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Trends in Computers: Automatic Control and Data Processing

PROCEEDINGS of the
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Los Angeles, Calif.
February 11 and 12, 1954

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Foreword

The Western Computer Conference and Exhibit, sponsored jointly by AIEE, IRE, and ACM, was held at the Ambassador Hotel in Los Angeles, February 11 and 12, 1954. This was the second Western meeting initiated by the Joint Computer Conference Committee. The theme of the Conference was "Trends in Computers: Automatic Control and Data Processing."

The three phases of the Conference — exhibits, scheduled papers, and informal discussion groups — were all well attended by the more than 1,000 registrants. A number of unregistered visitors also toured the exhibits. Twenty-three booths displayed major equipment, all relating to the theme. Two technical sessions ran in parallel each afternoon of the conference, and the twenty papers presented covered a variety of equipment and systems useful in scientific, engineering, and business fields. The full text of these papers is presented in this Proceedings. The discussions which followed the presentations, however, are not. The decision to omit summaries of discussions and questions was based on two considerations: first, editing and compiling a sufficiently accurate and detailed report of a discussion to be of real value to the reader almost invariably delays seriously the publication of the Proceedings; second, representatives of a number of companies indicated that they could participate more freely if no transcription were made. For the same reasons, the five Discussion Group sessions were not recorded, nor were summaries written. A note listing topics and names of panel members, and describing the general organization of the groups is included on the following page, however, because of the enthusiastic reception accorded these sessions.

The registration fee entitles each registrant to one copy of the Proceedings. Additional copies may be obtained from any of the sponsoring societies:

American Institute of Electrical Engineers	The Institute of Radio Engineers, Inc.	Association for Computing Machinery
33 West 39th Street New York, New York	1 East 79th Street New York, New York	2 East 63rd Street New York, New York

Discussion Groups

Five Discussion Groups met at the same time on the morning of February 12 to consider the following topics:

1. Unit Control in Retail Operations

Chairman - RICHARD G. CANNING	University of California at Los Angeles
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HARRY BROUGH	Shell Chemical Company
HENRY NOEBELS	Beckman Instruments Inc.

3. Numerical Control of Machine Tools

Chairman - J. O. McDONOUGH	Massachusetts Institute of Technology
JOHN L. BOWER	North American Aviation, Inc.
R. LOWELL HAND	Lockheed Aircraft Corporation
C. H. STEVENSON	Douglas Aircraft Company

4. Maintenance Requirements for Business Computers

Chairman - FRANK C. CARLIN	Lockheed Aircraft Corporation
ROGER L. SISSON	Computer Research Corporation
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5. Mathematical Methods in Management Programming

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ALAN S. MANNE	Rand Corporation
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The Discussion Groups were organized in a somewhat unorthodox fashion, with emphasis on participation by the audience rather than on presentation of prepared material or discussion among panel members.

The first step toward this objective was to eliminate any reporting of what was said. Those who were not prepared to speak for publication but were free to express their ideas informally were thus able to contribute. The second step was to allot only a small part of the time — in some cases about an hour of the two and a half hour session — to prepared material, leaving most of the session for informal remarks from the floor. The third step was to enlist the help of Dr. Martin Anderson, Head of the Conferences and Special Activities Department, University Extension, U.C.L.A., who discussed with panel members and chairmen methods of encouraging wide participation in the Groups.

As we go to press, a number of comments received indicate that an exceptionally free exchange of ideas by a large proportion of those attending was achieved. The reaction to this year's Discussion Groups will probably influence the decision whether similar sessions shall be included at future meetings.

PROCEEDINGS OF THE WESTERN COMPUTER CONFERENCE

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WELCOMING ADDRESS

D. H. Lehmer
University of California
Berkeley, California

I have been asked to extend a word of welcome to all participants in this, the fourth West Coast Conference devoted solely to electronic computers. It is my pleasant task also to congratulate those who have worked so hard to make this conference possible.

As you know, this two-day meeting is sponsored by three national organizations, the AIEE, IRE, and ACM via the Joint Computer Conference Committee. This is the second such conference undertaken by this committee to be held in the West. The previous conference, held a year ago in Los Angeles, was so successful in every way that the Steering Committee ran very little risk in sponsoring a similar program.

The main objective of such a conference is the dissemination of information and this general objective is approached from three directions. First of all, we have the papers being presented, which have not only the audio output of today and tomorrow but also the printed output in the form of the Proceedings of this conference. Those of you who have seen the Proceedings of the computer conference a year ago know what an absorbing and interesting volume it is. Secondly, we have tomorrow morning five different discussion groups meeting. These bring to light certain facts and principles that are not included in the regular papers and give a chance for the interplay of conflicting ideas in the indeterminate middle ground of machine development. Lastly, we have the exhibits, in which the more tangible aspects of computing are displayed. All three approaches are intended to allow the designer and the user of computing equipment each to present his own point of view and to learn something from his fellow conferee.

The topic of this conference, Trends in Computers: Automatic Control and Data Processing, reflects the fact that the computer art has progressed a great deal in the past few years. The topic a few years ago would have been just "computers." Our next speaker, Mr. McDowell, is going to set the stage for the conference in his keynote address and I will not discuss the topic more than just to say that it brings to this conference not just the old guard in the computer field but a large number of newcomers, whose interest is stimulated by the new applications that are being made of modern computers. It is perhaps not unimportant to say in welcome to these newcomers a few words as a sort of backdrop to the stage setting. I realize that the term "old guard" is often used today in a derogatory way but nevertheless I will run the risk of such an identification in presenting one or two ideas based on living the history of computing machines of the past decade.

If there is one thing that we can learn from the history of the past ten years it is that progress was made chiefly by the interchange of ideas. Those projects which stubbornly stuck to their original concepts prospered less than those whose ideas came from several sources. The veritable exponential growth of computing is due to the lessons learned from the pioneering projects. I will not illustrate these remarks, but nearly every one of you can think of examples. The availability of information on computers was fortunately high in the critical years. This fact was due largely to the economic situation. Until recently, the driving force in the computer field has been the U. S. Government. Much of the know-how we possess today in the computer field first appeared in government reports, which were made freely available in almost all cases. This enlightened policy (which is also being implemented by today's conference) is now in some danger. With the gradual withdrawal of government support and at the same time the acquisition of new fields such as those discussed in this conference there arises the very real danger that channels of information will be closed for reasons of "corporate security". Even in the present conference there has been some of this trouble forced upon the Program Committee. I feel that the restriction of information will have a levelling off effect upon what has in the past been an exponential curve. This problem is at least as serious as that of the smooth transition from the governmental support and pump-priming (to use a very old phrase now coming back) to full-blown commercial and industrial exploitation.

A third problem is one of which those of us who are engineers rather than mathematicians are perhaps not cognizant. In the past decade the mathematician has played a peculiar role in machine development. His interest in solving physical problems has been the driving force to the design and construction of many a machine or even machine component. The new look in the direction of data processing is not an inviting one to the well-trained mathematician.

With no offense meant, there is a world of difference between a C.P.A. and a Ph.D. in Mathematics. There are some interesting mathematical problems in the fields of operations analysis and programming but these are not very wide fields as mathematical fields go. And so it seems to me that with the elimination of mathematical interest in the wider extension of the computer we again run the risk of levelling off from another angle.

With these perhaps too somber backdrops I leave the more essential stage setting to our next speaker.

Again in behalf of the Joint Computer Conference Committee my best thanks to those who have labored for this conference and my cordial welcome to all assembled.

WILL ELECTRONIC PRINCIPLES MAKE POSSIBLE A BUSINESS REVOLUTION

W. W. McDowell
Director of Engineering
International Business Machines Corporation

I am very appreciative of the opportunity which your committee has afforded to me to speak to this great audience of scientists, engineers and business people attending the 1954 Western Computer Conference. You gentlemen have accomplished much in a relatively short time. You will accomplish even more in the future.

Your work is one with which I am obviously closely associated. It is one that is very dear to my heart. I am a firm believer in the fact - as Dr. Huntoon said last year, "You ain't seen nothing yet" in the field of automatic and semi-automatic machines for the control of factory and office.

Your committee deserves great commendation for the program which they have arranged for this conference - Automatic Control and Data Processing. To the lay person I suspect these are thought of as two distinct subjects, which for the most part must be dealt with separately. To most people, automatic control implies something that deals with engineering or manufacturing problems, while the other deals primarily with accounting and statistical information - the problems which are present in an office. To date, I suppose that in a very broad sense this is true, but I wonder if they are not much more closely allied than many of us might realize.

You are all, of course, well aware that an automatic control system may require a considerable amount of data processing ability. A number of papers which will be presented today on flight control systems will point out this need. On the other hand, so-called data processing systems often result in some form of automatic control. We will later hear a paper from Dr. Oliver Whitby, which will describe some of the devices which are required in order to make data processing systems more automatic from the standpoint of the control of a business.

We will hear more at this conference about automatic control of machine tools. In the developments which have been accomplished to date, with which I am familiar, the automatic control applies to the cutting element on the machine tool. An operator must change the tool when it becomes dull. I am in no sense belittling the development in this area, but merely pointing out that the automatic part of it extends only to a certain point.

Is this example of the machine tool so much different - from the standpoint of automation - than a data processing system, which is programmed to perform a complex production control problem? In this instance the machine automatically makes certain decisions based on many complicated factors, and it is fair to state, I believe, that the machine has performed a very difficult automatic control problem.

In other words, I am thoroughly convinced that automatic control and data processing really go hand in hand, that you ordinarily do not have one without the other, that in developing an effective system they both play a very important and essential part. The two have now become so entwined that in the future it will be difficult to logically separate them.

It is for these reasons that I feel the agenda for this conference is so appropriate.

As I stated earlier, tremendous strides have been made in the application of computers and electronic equipment to industry and business. Time will not permit mentioning of all of the papers which will be given at this conference, but the fact that you are able to talk with authority about so many control and data processing systems as applied to business and industry is in itself proof of the strides which have been made. There will be much more done as time goes on. Each year business machines will become more and more complete and perform in a more efficient manner.

In general, and for probably obvious reasons, the machines which have been developed to date have proceeded on the basis of adapting electronic principles to form a new machine concept which tries to duplicate the results now being obtained. Thus, when a study is made to see what an electronic business machine may do in the way of providing improved efficiencies the only basis on which a study can be made, either on the part of management of the business, or on the part of an engineer, is on the data and concepts currently available and the procedures currently followed.

In most instances, business management is able to present a very clear cut and convincing picture of exactly what functions and results are required. Their Methods people, as a result of studying procedures for many years, are well acquainted, based on their concept of the needs of business, with exactly what a new machine should do. Many of the rules and procedures were evolved as a result of an extremely detailed and careful analysis of the basic problem, but many many others were formed by tradition, on what apparently had happened in the past, or on opinion as to the essentials for a particular business.

This situation is, I think, bound to be present in any large, well-established organization. I am not suggesting this in any critical manner, but as an inevitable product of growth in any business. I am certain that it exists in IBM.

This approach to the application of electronic principles to business problems has produced and will continue to produce astounding results. Unfortunately, however, there are many studies made which show that the projected savings are marginal or where a more or less "brute force" method must be used to justify the investment.

And yet, because of the versatility of electronics it is not obvious why such should be the case. Why are so many of the complex business problems apparently incapable of being effectively solved by the electronic business machine?

I think that one of the principal reasons may be that we are trying to ask a scientific machine to solve a non-scientific problem. We are trying to ask the machine to operate under a set of rules which, in many instances, are not consistent with its logical nature. We are saying that these are the rules of business, now you make the machine - adhere to them.

In contrast to this, one cannot help but wonder, however, how much more might be accomplished were it possible to find some means of scientifically studying and analyzing business needs on the same scientific basis as the machines and the components within the machines have been studied and developed. It is obviously a very complex subject, particularly since all businesses deal with customers of one type or another, and customers cannot be patterned as can machine tools. On the other hand, there is just beginning to be a feeling within industry that business procedures can be dealt with in a far more scientific manner than has been done in the past.

You are all familiar with the developments which have taken place, for instance, in oil refining, or in automotive production. Both of these operations evolved around a new scientific concept for getting results. They were far reaching and play an important part in our economy today.

Very little of this sort of thing has been done on the office side of business, probably because management has been unable to visualize a plan which would justify the investment costs. Also, business problems are undoubtedly far more involved than those of the automotive production line.

Yet, as businesses grow larger, the problem of handling office routines and management controls is becoming more and more difficult. More and more clerical people are added each year, and as they increase in numbers, the problems of communication, organization and control increase geometrically. The more people who are added, the more complex must be the controls to control them.

I wonder if the time has not come when it is essential that some means be found to incorporate into a business the same type of radical and bold new approach which was demonstrated in the automobile production line, or in the oil refinery. I have a very strong feeling that something of this sort can be done, and further, that when a plan is evolved, the electronic principles which you have or know about will make it possible to develop the machines which will really fit the plan. I do not feel, however, that this can be done by the development engineers and scientists alone.

In order to achieve this objective there must be a willingness on the part of business to look at its problems and way of doing business in the same scientific manner as that used by the men developing the machines.

What I am really trying to suggest is that a new kind of partnership is needed -- a partnership between the development engineer and the business engineer. Perhaps the latter should be thought of as a business research engineer, a man who has the ability to analyze in a scientific manner the procedures and inter-relationships which are essential in order to conduct a successful business.

This thought is not new, but I wonder if we are giving it the proper emphasis. It is certainly somewhat akin to "operations research" which we are beginning to hear about. I think it is also akin to the thought which Dr. Hobson presented to this conference last year when he said, and I quote:

> "It is a curious fact that, while tremendous advances have been made within industry to increase the efficiency of operations in the major functional areas - production, research, marketing, etc., - equivalent advances have not been made in the techniques for handling the routine facts of business operations. The volume of factual data mounts - the need for factual analysis grows greater - the demand for precisions continues unabated. But, by and large, management had had to meet the problem with the same mechanical aids used by a growing army of administrative and clerical employees. The 'clerical problem' is becoming a matter of great concern in industry. This situation gives a sense of urgency to the widening applications of high-speed electronic equipment on industry's data handling problems and their information processing systems. The possibilities appear to be tremendous - the result far-reaching. If the rate of progress continues for some time in the future as it has since World War II, it is conceivable that future business historians will know this period as the beginning of the 'administrative revolution.' If the trend continues, a new factor in the management equation will most certainly have been created."

Perhaps, also the theory of games has a place in this thing I am talking about. Again I do not know enough about it to chart any clear course. I do know, however, that when we have been faced with what appears to be an insurmountable problem that we have always found the means of chopping our way through it.

Is there any reason to feel that with sufficient study, and with the right kind of people, that startling new concepts of business might not be evolved which would cut at the heart of this problem?

Let me give you an example of the sort of thing I am talking about - oversimplified, but none the less illustrative.

We have in IBM what might be considered a rather complex production control problem. As would naturally be expected, we are using our punch card equipment to provide as nearly as possible an automatic solution to this problem. Because of the numbers of parts which we must control and the changes which inevitably occur during the course of a production cycle, we must use what we consider rather clumsy methods in performing our day-by-day planning operation. When we developed the 701 Electronic Calculator, which, as many of you know, is quite a powerful and fast machine, we went to work to try to program our production control problem on it.

To our amazement, we found that we were unable to evolve a satisfactory set of formulas which would permit us to obtain an overall machine solution. There is no question in any of our minds that if we secure the right type of people and continue to work on this problem, a procedure can be found, but it is very probable that the solution will affect much more than just this particular job. It may well result in changes in our method of handling orders, our basic planning operation, the numbers of machine tools which are available, inventory policies, etc. Furthermore, when we get through we may find that the 701 is not properly balanced for this data processing application.

The same type of analysis can be made on costs, budgeting, order control, purchasing, planning and many others. In most instances, each application cannot be considered by itself. Its relationships and effect on related activities must also be carefully thought out. The solutions from the point of view about which I speak are tough, but I am thoroughly convinced solutions can be found.

The same might be said with respect to customer relations. Because we are dealing with personalities it cannot be as positive or scientific. There is every reason to believe, however, that with proper study and scientific analysis an improved relationship with customers can be found - one that would be more efficient and would readily fit machine solutions. An example of a new concept of customer relations is the "super market." I am not suggesting that all groceries should be super markets, but that there are ways to make significant advances in efficiencies and, at the same time, be susceptible to better machine solutions.

It was not so many years ago that airplane design was carried out without much reliance on scientific computation. Not too much was known about the factors which would lead to the safest and most efficient airplane. I suspect that even if a giant calculator had been available twenty years ago, it would have remained idle because no one knew enough about the behaviour of aircraft to intelligently apply problems to the machine. But today calculators aren't big or fast enough for them - all because the scientists and engineers in the aircraft industry have learned how to deal with the factors which affect airplane design.

Can't this same sort of thing - with enough thought and study - exist in the concept of a business?

For the most part businesses do not have people who are scientifically trained to take this approach. Methods people within industry are doing a marvelous job and their services are indispensable but, unfortunately, most of them are not trained to deal with problems of this sort.

To do this work, a new type of scientist is required. Probably a basic engineering education is desirable, and in addition an excellent grasp of mathematics. He must be research minded. Large numbers are necessary. Such men are not available today and, therefore, must be trained. A number of universities have recognized this need, and I understand are in the process of developing courses which will assist in the training of people who can intelligently deal with this problem.

This program will cost a lot of money, but if business management can be convinced that an approach of this sort may result in real savings, the money will be found. Business management does not question the spending of many millions of dollars in research and development of new devices and products. Only a few years ago, however, this concept was not so widely held. Here, as with product research, the benefits must be shown.

I appreciate that the value of this type of research is hard to pinpoint. It is extremely difficult to understand. At the present time, the results which can be expected may be nebulous. It is a long range affair. Everything else, however, that we in this country, at least, have approached in a scientific manner has paid off handsomely. Again, is there any reason to believe that this type of research problem cannot also pay off handsomely?

The reason why I particularly wanted to speak to this group on this subject is that you can play a major role in explaining the need for this kind of research. You are, in one way or another, constantly in contact with business throughout the country. If you believe at all in this concept and its importance, you are in an excellent position to tell the story. You can show management how vital this step is. If you can sell the idea it will have a double-barreled effect on the work in which you scientists and engineers are primarily interested. First, it will help to make more businesses aware of the possibilities of more efficient solutions to their problems. Second, and the more important - and the one which will pay off the biggest dividends - through this scientific analysis will evolve methods which will be more compatible with the techniques which you have for the building of business machines.

This possibility is well illustrated in the current trend towards the "systems concept" for the development of weapons. A plan of this sort - a scientific balance between all phases of the problem will inevitably lead to the most efficient results.

Is it not far more likely that this same overall scientific approach will also in the case of business machines, provide the most efficient and significant solution?

This whole concept may be considered by many to be in the class of the wildest of dreams. For my own part, however, I believe that the same systematic scientific analysis of business problems will yield the same beneficial results that have been achieved in industry, science, medicine and many other fields.

Those of you who do feel, with me, that there is something here, can do, I believe, a tremendous amount of good by talking about it to your associates in the scientific and business world and find a way together to tackle this problem head on. Its bigness and the lack of trained men should not be discouraging. Once we are convinced of its merit, the means will be found to accomplish it.

May I thank you again for making it possible for me to be present here with you today.

TRENDS IN ELECTRONIC BUSINESS DATA SYSTEMS DEVELOPMENT

Dean E. Wooldridge
The Ramo-Wooldridge Corporation
Los Angeles, California

Mr. Chairman, Ladies and Gentlemen.

When I began a week or ten days ago to think seriously about preparing for this talk, I came up with the conclusion that it is probably considerably more difficult now than it was a few years ago for a luncheon speaker to prepare a talk on the application of modern electronic techniques to business and industry. It seems to me, relatively speaking, only yesterday that any one of us who found himself in the position of giving a luncheon talk to an audience such as this could be pretty certain of attracting and holding the audience's attention if he only took time the preceding evening to make a few simple calculations to permit the recital during the talk of how much faster electronic equipment could add 2 and 2 and get 4 than a good human mathematician with a pencil and paper. Then it seems to me that, as soon as this luncheon-talk thesis was worn out, we found ourselves in another era in which the popular subject for luncheon talks was quite different, but still easy from the point of view of the speaker.

The topic for the second era of speech-making grew naturally out of the over-selling we had done in the first era. In this period our speeches usually started something like this: "Ladies and Gentlemen. In recent months you have heard from other speakers of the exciting discoveries and inventions that lie just over the horizon. Well, I'm sorry to tell you, but you have been misled by overenthusiastic visionaries who don't appreciate the practical problems. The sober fact of the matter is that these fantastic new developments probably won't occur at all. If they do occur, they are at least twenty years away. Now, let me tell you why."

Well, I don't intend to be entirely facetious in these remarks. If it was a mistake to employ such thesis in luncheon talks, then I must admit that I participated in the mistake, because my own public and semipublic remarks on this general subject were at least partially in accordance with the developing styles as I have defined them. Actually, I think that it was natural for us to be fascinated by the bright and attractive horizons we could see stretching out ahead of us when we first became aware of the tremendous potentialities of the application to business and industry of electronic data-handling and digital-computer techniques. As a consequence, perhaps we did more talking about the pot of gold at the end of the rainbow than about the ruggedness of the path leading there. Then, when experience in attempting to design apparatus and make it work caused us to realize that there were some serious problems standing in our way, it was again natural for us to concentrate our remarks on this aspect of the situation for a time.

However, for today's talk to this group, it would be completely out of order for me to choose either the bright-promise or the view-with-alarm thesis that I have just described. In the first place, it is now early 1954, and there has been a lot of water over the dam in the last several years. In the second place, today I am speaking to a group of professionals in the business. All of you, I am sure, share with me a firm faith in the potential of this field, so it would be wasting your time and mine to tell you about that. I think, too, that those in this room probably know better than anyone else what the practical problems are that remain standing in your way. Consequently, it has seemed to me necessary to choose an entirely different topic. My topic, as a matter of fact, is going to be fairly limited. My remaining remarks will be applicable to only one of the many aspects of the whole field of electronic business-data systems, although it is one which in my mind, at least, is an important feature of the field. I am going to talk about the systems analysis part of the job that has to be done in the application of the newer electronic techniques to business data handling problems. By systems analysis, I mean the processes through which we must go in order to perform a suitable marriage between the requirements of the business establishment and the techniques of the electronics engineer so that the procedures and equipment that are devised will solve the problems of the business establishment rather than a set of imaginary problems which the engineer thinks the business establishment should try to solve. Sometimes, as we all know, these are quite different things.

Now, I must freely admit at the outset that, with respect to this matter of systems analysis, I have a prejudice. My prejudice is that probably it is not going to be very well done -- that both the quantity and the quality of the talent and effort that are put into this aspect of the business data systems field are going to fall rather far short of what they ought to be. I've arrived at that prejudice by means of observations that I have had an opportunity to make during recent years in another field, which, however, is similar enough to the field of electronic business data systems that the experience developed there should have some applicability here. The field to which I refer is that of electronic systems for military application. Military electronic systems compare favorably with electronic business data systems with respect to the difficulty of the problems that must be solved, and the complexity of the equipment that must be developed. In addition, the evolutionary development of this field is appreciably ahead of that of major electronic business data systems, in the sense that there has now been time for a number of major military electronic systems to be developed, to be manufactured, to be put in the field, and to fail to work very well. I can say, without the slightest fear of being proven wrong, that by and large the quality of the systems analysis that has gone into weapons systems development has been disappointing, even among some of the organizations that are known to possess high-caliber scientists and engineers. There appears to be an illusory sense of simplicity about systems analysis that at times fools even the best engineers and scientists.

The typical situation is that at the beginning of a major project an analytical approach is indeed brought to bear to attempt to determine what the influence of the tactical problem is upon the characteristics of the major subsystems that have to go together to solve it, but when the scientists and engineers are really only about half way through with the systems analysis that needs to be done, they develop a feeling that they completely understand the problem, and they divert their attention to the invention and development of new components and devices. As a result, when the military system finally comes out, a little bit of hindsight which somebody generally exerts at that time reveals that it could have been ever so much more effective with respect to the tactical job that it was designed for, if only there had been a little more continuing attention paid to the systems analytical portion of the task before the program was so thoroughly committed to hardware development.

This is the source of my prejudice with respect to systems analysis. As I have said, I believe that the mistakes that have been made in the military field are apt to carry over into the business field. Indeed, I have a feeling that the business data systems field is more susceptible to such mistakes and that, in fact, all of the ingredients are here present to permit us to develop some awfully fine equipment that will bring a tremendous efficiency to the performance of precisely the wrong tasks. The problem is more complicated than in the military case, for two or three reasons. In the first place, it is generally easier to specify the objective in the instance of a military weapons system. The things that we attempt to do in warfare are pretty primitive. We can describe most military weapons systems by saying that they must consist of means for seeing an enemy and observing what he is doing, making calculations on the data that are achieved in this way, and finally using these calculations to provide some kind of navigating or guidance instructions for a vehicle that is sent out after the enemy and caused to explode in the vicinity of the target.

But it is pretty difficult to describe as simply as this the function that must be performed by the typical electronic business data system. Here we must deal with complex requirements that have been developed for many years -- sometimes several hundreds of years -- by large numbers of people who have been engaged in one phase or another of business and industry. These procedures, techniques, and requirements have been developed partially on the basis of the actual logical needs of the business or industry and partially on the basis of prejudice and tradition, so that at the outset the systems analyst in the business data systems field is confronted with quite a difficult assignment of defining the problem. This task is complicated by virtue of the fact that the scientists and engineers, who engage in trying to devise apparatus and procedures for such purposes, have generally not had much experience or interest in business as such. They don't really know the language, and they get into trouble because the language sounds too much like that which they do know, which helps them to come to the conclusion, more prematurely than in the military systems case, that they understand the business problem before they really do. As a result they are apt to design equipment for solving what they imagine to be the problems of the business rather than the problems the business really has.

Having tried to establish as carefully as possible what my prejudice is and how I came by it, I now come to the obvious next step -- looking into the state of the art as it exists today to see if I can find evidence to prove that my suspicion is correct, and that mistakes in the systems analytical direction are being made in the field that we are talking about today. It's never really very hard to find proof for your own point of view, if you start out by being prejudiced and then simply sort out the evidence accordingly. Consequently, I have indeed been able to turn up a number of examples of the kinds of mistake to which I'm referring that are being made today and probably will be made tomorrow. The examples I shall give will be simple ones, but I think they will illustrate the kinds of pitfall about which I have been talking that, I believe, will clutter up the paths for all of us who engage in the development of electronic business data systems.

Here's one example. Most of us who have been engaged in this business for a number of years have had occasions to make analyses of existing business data or accounting systems in an attempt to prove that some of the electronic techniques we espouse can be put together to do the job better and more efficiently. Some of these existing systems make use of a punched card as the fundamental unit of storage information. A common mistake, in the analysis of a punched card system with a view toward the replacement by electronic techniques, is to assume that the amount of data-sorting and collating in the new system would need to be the same as that performed in the punched card system. The point missed here is that the limited amount of material that can be carried on a punched card frequently results in the necessity for creating more than one card in order to carry all the information pertinent to a single account. Much of the processing arises only because it is necessary to merge the several cards in an account in some steps of the procedure and arrange them in separate decks in others. If the electronic system, which probably employs magnetic tape recording, is planned for the same amount of processing, then proper use will not be made of the much higher capacity for unit storage that is provided by magnetic recording techniques.

Another example of imperfect systems planning also has to do with the analysis of an existing data-handling system for possible replacement by newer techniques. One of the characteristics of many current business data systems is that, while most of the transactions of the business can be properly mechanized, there remains perhaps 5 or 10 per cent of all of the business transactions that do not lend themselves to the kind of mechanization that is available. As a result these exceptional cases are not mechanized but are handled by the improvisation and employment of judgment by human clerks and operators. Even though the percentage of such transactions is small, it is not unusual to find that their handling accounts for as much as 50 per cent of the operational cost of the entire business data system. Nevertheless, I know of at least one analysis of such a data system, for possible replacement by newer techniques, where the procedure was to lay out a design of an electronic system that would simply duplicate exactly the functions and procedures of the current data system, without attempting to mechanize the exceptional transactions. This in spite of the fact that, as was shown later by a competing analysis, a more careful design of the programming procedures and apparatus would have permitted the exceptional cases as well as the usual cases to be handled automatically. When this increased versatility of the newer electronic techniques was ignored, the very best the electronic system could do, even though the equipment were to cost nothing, and require no maintenance or human operators, would be to decrease the operational cost of the data-handling by a factor of 2. By paying proper attention to the handling of the 5 or 10 per cent of exceptional transactions, currently responsible for 50 per cent of the cost of the system, the designer had a vastly improved potential for increasing the over-all efficiency and economy of the new system.

Another example of a kind of problem to which the systems analyst should pay more careful attention than I expect him to has to do with the preparation of reports. The preparation of reports is not the simplest function of a business data system. Therefore, the frequency of the reports and the kind and detail of information they contain deserve the most careful attention of the system designer. It is important, in laying out the new system, that the schedule and procedures employed in the preparation of the reports be properly adapted to the actual needs of the business. If you ask the business executive about his requirements, the chances are that he will tell you he needs something like the kind of report service he is now getting. However, if you investigate more carefully, you may find that the present service is in part characteristic of the particular kind of mechanization that was available at the time the business data system in use was originally set up. The actual need may be quite different. For example, the possibility, with the newer electronic techniques, of obtaining rapidly on demand important information out of the storage system of the equipment might well preclude the necessity for large numbers of periodic reports. Here again, it could be a serious mistake, in attempting to apply the new techniques, to copy the equipment performance specifications that were appropriate to the old.

This example of reports permits me to comment on one aspect of the systems analysis problem in electronic business data handling that I am sure is quite similar to a corresponding aspect of systems analysis for a weapons program. Perhaps the best way I can make the point is to state that, in the weapons systems field, a company doesn't do well if it doesn't learn very early that it is a bad mistake to assume that the customer really knows what he wants. Inasmuch as the concern that I represent is engaged in business with the military and hopes to continue, I must hasten to amplify this statement. The military customer usually does know what he wants when it comes to a tactical or military description of his requirements. The difficulty arises when an attempt is made to do a job of translation, still within the military, from the tactical description of the need to a set of technical specifications. The military people may not have complete up-to-date information on the newer techniques that are available, and they may not completely understand the old ones. So the first thing that a competent contractor does when he gets a set of specifications from his military customer is to get off in a corner with his own best analytical talent and see whether these specifications really represent what he believes the military tactical requirements to call for. Nine times out of ten there are discrepancies, and the contractor, if he knows his business, goes back to his military customer and works out changes in the specifications to properly reflect the actual military requirements. I think that we have the same kind of problem in the business data systems field. The matter of reports was a good example. As I suggested, the business executive, if asked, would probably specify schedules and types of reports similar to those he has been getting, whereas his actual needs might be quite different. This doesn't mean that the executive is not an intelligent man, but most of us get accustomed to thinking in rather superficial terms about many of the operational details of our regular activities; sometimes it is not natural or easy to analyze carefully our basic requirements.

There are many interesting examples of how we can go astray if we accept too literally the definition of requirements given us by the business customer. Some of us have on one occasion or another looked over the operations of a department store, with a view toward installing electronic techniques by means of which inventory control and charge accounting could be concurrently mechanized, thereby making it possible for the store to operate more efficiently, with fewer white-collar workers. Here we quickly encountered a problem that is common to so many business data system studies -- that of getting the input data into the system. Hence, we find ourselves thinking about point-of-sale recorders of some form, by means of which a customer transaction can be entered into the machine automatically at the time that the transaction occurs. At this point we may very well run into a difficulty -- an assertion on the part of a highly-placed, well-informed, widely-experienced executive of the department store to the effect that there is a basic requirement that a sales slip bearing the customer's signature be kept on file as evidence of each charge-account transaction. This has a major bearing on the kind of mechanization we can employ, for it greatly restricts such approaches as the use of keyboards or coded sales tabs by the clerks for entering transactions into the storage system. The pertinence of this example is that, in the course of our own investigations, we have encountered at least one highly-placed, experienced, successful executive in a major department store who assures us that this assertion about the necessity for keeping signed sales slips in the record is nonsense -- that there exists no such basic requirement. I don't know the right answer to the question, but, if I were going very far in the direction of designing equipment for use in department stores, I'd make it a point to find out.

Another example comes from the insurance business. In one nationally-known, successful insurance company that we once considered for automation techniques, we were told that it is essential to maintain historical records of the policyholders' transactions for a number of years into the past, so that, say, Mrs. Jones could find out how much interest she had paid on an insurance loan back in 1945. In another equally prominent, nationally-known insurance company, however, we were told that not only was this not a requirement, but that this company kept its records for only one year, and had gone so far as to have successfully tested the practice in the courts. An item like this could make a tremendous difference to the designer of electronic data systems.

I have probably belabored the subject long enough. I have been talking about a prejudice of mine, and have actively tried to substantiate that prejudice. I trust you realize that, if you have accepted my points of view, you are now left on the horns of a dilemma. According to my predictions, the mistake many of us will make will be to assume prematurely that we understand the business problems we are trying to solve, and therefore design, and put together apparatus and procedures that won't quite handle the actual problems. But after we have made this mistake once or twice, if we still have jobs, and if our company is still in existence, there's the danger of over-reaction, of assuming that the customer really knows what he wants and designing equipment accordingly. As a result, our system may again fail to sell because a cleverer competitor, who has delved deeper into the business man's statement of his requirements and discovered that they are not quite what he thinks they are, has turned up with a simpler and more efficient system.

But I don't really mean to imply that we can't win, no matter what we do; nor do I mean to sound pessimistic in my predictions. Not only is this a tremendous field, but I believe that by and large those of us who are in the field are going to do a pretty fair job of progressing in the directions in which we want to move. Even though I predict that our performance is going to be less than perfect, I am confident that we will still find our way to the sizable pot of gold that we are all sure is to be found at the end of this particular rainbow.

AN EXPERIMENTAL DIGITAL FLIGHT CONTROL SYSTEM

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Introduction

Development of aircraft with large ranges in speed and altitude has resulted in a need for autopilot systems with optimum control characteristics over a wide range of conditions and with very high accuracy and resolution. In designing a digital flight controller to pilot a highly maneuverable aircraft whose flight conditions are constantly changing, an investigation has been made into the necessary and desirable control characteristics. This paper describes the control equations resulting from this investigation as well as the special purpose breadboard model computer which is being tested and analyzed in conjunction with an analog flight simulator (see Figure 1).

The breadboard model computer-controller has been built for the sole purpose of proving that digital flight controlling is possible and advantageous over conventional analog methods. No effort has been made to package the unit or to make it flyable. Even though the machine has a fixed program, it is flexible enough to permit considerable freedom in choice of control equations and parameters for research study, as will be described later in the text.

The flight controller will direct the aircraft in three modes of operation: (1) Altitude control, (2) Attitude control, (3) Pitch rate control. These modes of operation must have good stability and fast response (Technical Report, Project 1, Phase 1 under Air Force contract AF 33(616)-273 entitled "Preliminary Investigation", classified Confidential, describes the necessary control and stability criteria for a linear system). An increase in the speed of response is provided through programming a nonlinear control function. At the same time the airframe must be guarded against excessive maneuvers that might bring the airframe into unsafe stall or structural load conditions. Therefore, limiting the airframe maneuvers so as not to exceed safe stall and load limits has been provided. These nonlinear controls, so difficult to perform in analog computing systems, lend themselves directly to a digital control system. The fire control command signals to the flight control system are usually exceedingly noisy. Therefore, the last nine pieces of data are digitally weighted and added to provide a smoothed input. Investigations show that digital smoothing by means of weighting discrete readings is more advantageous than comparative analog filtering methods.

Development of Control Equations

When the digital flight controller is functioning to maintain pitch rate control, the error signal commanding a change in control surface position becomes (definition of symbols will be found in the Appendix):

$$\Delta = \lambda = k_e(\dot{\theta}_D - \dot{\theta}_o) \qquad (1)$$

$$\text{where } \lambda = K_{\dot{\theta}}(\dot{\theta}_D - \dot{\theta}_o) \qquad (2)$$

Pitch rate control is furnished by the inner or primary loop of the basic control system illustrated in Figure 2. When operating in the pitch rate control mode, the command is $\dot{\theta}_D$ and the outer loops are broken at the attitude error input. The pitch rate command signal $\dot{\theta}_D$ will be provided by the fire-control computer; a discussion of the smoothing necessary on this signal will be found later in this paper.

When the digital flight controller is operating to maintain attitude control,

$$\Delta = \lambda = k_e\left[k_7(\theta_D - \theta_o) - \dot{\theta}_o\right] \tag{3}$$

$$\text{where} \quad \lambda = K_\theta(\theta_D - \theta_o) - K_{\dot{\theta}}\dot{\theta}_o \tag{4}$$

Attitude control is furnished by the primary loop plus the position feedback θ_o as illustrated in Figure 2. When operating in the attitude control mode, the command is θ_D and the outer loop is broken at the altitude error input. The error in attitude multiplied by the proper gain $K_\theta/K_{\dot{\theta}}$ becomes the new desired pitch rate.

When the flight controller is operating to maintain altitude,

$$\Delta = \lambda + k_7 k_e \theta_o = k_e\left[k_7 k_f(h_D - h_o) - \dot{\theta}_o\right] \tag{5}$$

$$\text{where } \lambda = K_h(h_D - h_o) - K_\theta \theta_o - K_{\dot{\theta}}\dot{\theta}_o \tag{6}$$

Altitude control is furnished by the entire system as illustrated in Figure 2. The command as shown is h_D . Since Δ is used in nonlinear control and in maneuver limiting, it is essential that Δ becomes zero in the steady state. For this reason the term $-k_7 k_e \theta_o$ is intentionally omitted from Δ and will be introduced in equation 8.

The equations for the three modes of operation may be combined into one equation for convenience:

$$\Delta = k_e\left[k_7 k_f(h_D - h_o) \;\textcircled{1}\; + k_7(\theta_D - \theta_o) \;\textcircled{2}\; + \dot{\theta}_D \;\textcircled{3}\; - \dot{\theta}_o\right] \tag{7}$$

where ① stands for altitude control
② stands for attitude control
③ stands for pitch rate control

The symbols ① , ② , and ③ have the value 1 if the particular control applies, and have the value 0 if the control does not apply. Equation 7 can be shown to reduce to equation (1), (3), or (5) as the mode of control changes.

In order to maintain a steady-state flight path, integral (or trim) control must be provided. The desired control surface position then becomes

$$\delta_d = \Delta + k_{12} \int_{t_{-\infty}}^{t_o} \Delta dt - k_7 k_e \theta_o \textcircled{1} \tag{8}$$

where ① = 1 for altitude control and ① = 0 for attitude and pitch rate control. The integral term $k_{12} \int_{t_{-\infty}}^{t_o} \Delta dt$ will provide the trim control necessary to fly the aircraft along a steady-state flight path. The term $-k_7 k_e \theta_o$ ① maintains the proper damping during altitude control and is necessary since the rate gyro signal does not provide the required sensitivity.

The nonlinear control function which the digital flight controller will provide to improve the speed of response of the aircraft while still maintaining the desired damping will be programmed as follows (see Figure 3):

$$\delta_D = \delta_d \quad \text{if} \quad k_8 < \Delta < k_9 \tag{9}$$

$$\delta_D = k_{10} \quad \text{if} \quad k_8 \geq \Delta \tag{10}$$

$$\delta_D = k_{11} \quad \text{if} \quad \Delta \geq k_9 \tag{11}$$

As can be seen from equation 7, Δ defines the transient error, which ultimately determines the desired control surface position. As used in equations (9), (10), and (11), the magnitude of Δ determines when the nonlinear control action is desirable.

At the same time this programming and computing is taking place to determine the proper control surface position, the necessary limiting to keep the aircraft maneuver within safe stall and load bounds is being calculated. The basis for the stall limiting scheme is to make certain that the lift available will always keep the plane aloft; accordingly

$$qs\, C_{L_{max}} \geq n_z mg \tag{12}$$

And the basis for the load limiting scheme is to make certain that the load will not exceed the critical load and snap the aircraft's wings off; therefore,

$$n_{z_{lim}} \geq n_z \tag{13}$$

The following equations will permit maximum response while keeping the maneuver within the safe load and stall limits by predicting the expected response as a function of the limited command signal $\bar{\Delta}$, where

$$\bar{\Delta} = \Delta \quad \text{if } \Delta < k_{13} \tag{14}$$

$$\bar{\Delta} = k_{13} \text{ if } \Delta \geq k_{13} \tag{15}$$

$$d_s = qk_a - k_b m_1 = k_1(qS\,C_{L_{max}} - n_z mg) \tag{16}$$

$$d_g = k_4 - k_b = k_2(n_{z_{lim}} - n_z) \tag{17}$$

$$d_L = d_g \text{ or } d_s \text{ , whichever is smaller} \tag{18}$$

$$k_c = k_5 + k_6\,\bar{\Delta} \tag{19}$$

$$k_d = 1 \text{ if } \Delta < 0 \text{ or if } k_b < 0 \text{ or if } d_L > k_c \tag{20}$$

$$k_d = \frac{d_L}{k_c} \text{ unless } k_d = 1 \text{ as per equation (20)} \tag{21}$$

The error signal to the control surface servo, defined by

$$\varepsilon_i = \delta_e - k_d\delta_D \tag{22}$$

will move the control surface according to equation (22). The variable multiplier k_d computed as defined by equations (20) and (21) and illustrated in Figure 4 is utilized to limit the aircraft to safe maneuvers. An examination of Figure 4 discloses that the aircraft response will not even begin to be limited unless, first, the aircraft is close to critical stall or load limits, or, second, the command signal $\bar{\Delta}$ will carry the aircraft to the critical limits before limiting might otherwise be obtained. If the command signal $\bar{\Delta}$ is small and the aircraft is operating near the critical stall limits, maneuverability without danger is assured; Figure 4 demonstrates that fact.

δ_D as defined in equations (9), (10), and (11) to provide nonlinear control, must be modified so that stall and load limits can be accurately applied. Therefore, equations (9), (10), and (11) become:

$$\delta_D = \delta_d \quad \text{if } k_d \neq 1 \text{ or if } k_8 < \Delta < k_9 \text{ and only if } k_{10} < \delta_d < k_{11} \tag{23}$$

$$\delta_D = k_{10} \text{ if } k_d = 1 \text{ and } \quad k_8 \geq \Delta \quad \text{ or if } \quad k_{10} \geq \delta_d \tag{24}$$

$$\delta_D = k_{11} \text{ if } k_d = 1 \text{ and } \quad \Delta \geq k_9 \quad \text{ or if } \quad \delta_d \geq k_{11} \tag{25}$$

These decision equations make it possible to eliminate the nonlinear control action whenever limiting resulting from adverse stall and load conditions is imminent.

The equations to be solved by the breadboard digital flight controller computer have, therefore, been established as shown in Figure 5. These control equations are modified slightly when the flight control system is functioning in the fire control mode. The input command is then $\dot{\theta}_{DN}$, i.e., $\dot{\theta}_D$ with noise. To eliminate as much of the undesired noise as possible $\dot{\theta}_{DN}$ is smoothed and becomes $\dot{\theta}_D$ in the above control equations.

Therefore, $\dot{\theta}_D$ is the sum of the last nine pieces of information summed with the proper weighting constants.

$$\begin{aligned} \dot{\theta}_D(t_o) = {} & C_o\dot{\theta}_{DN}(t_o) + C_1\dot{\theta}_{DN}(t_{-1}) + C_2\dot{\theta}_{DN}(t_{-2}) \\ & + C_3\dot{\theta}_{DN}(t_{-3}) + C_4\dot{\theta}_{DN}(t_{-4}) + C_5\dot{\theta}_{DN}(t_{-5}) + C_6\dot{\theta}_{DN}(t_{-6}) \\ & + C_7\dot{\theta}_{DN}(t_{-7}) + C_8\dot{\theta}_{DN}(t_{-8}) \end{aligned} \tag{26}$$

where t_o is the present instant, t_{-1} is the previous instant, t_{-2} is the next to the previous instant, etc. These weighting constants may be easily altered without introducing any new components in the computer. This digital filter will enable a rather complete survey and analysis of the effect of various weighting functions.

Computer

The breadboard computer built for this project does all the necessary computation described in Figure 5 as well as the following: scan the input disks; convert the resulting information from reflected-code into true binary numbers; compute the smoothed value of $\dot{\theta}_D$; and convert the output into a voltage of continuous step function nature.

The computer is a serial machine. Its computation cycle is broken down into 63 word-times; each word-time consists of 20 clock pulses. Thus, a computation cycle consists of 1260 clock pulses.

The computer has three arithmetic registers. Two of these registers (F and G) are 20 bits long. The third register (E) is eight bits long. In addition to these registers the computer has a magnetic drum memory which (1) stores all constants on a permanent memory channel, (2) has one seven word re-circulating line which stores the trim-integral as well as some temporary data, (3) has two delay lines 8 words long used primarily for smoothing the fire control computer signal, and (4) has an additional short delay line used to convert reflected-code numbers into true binary representation. All of these registers will be further described in the following paragraphs.

In order to better understand the operation of this unit let us examine each function separately.

Input Scanning and Conversion

All data utilized by this computer is scanned from 13 commutator disk assemblies. Six of these assemblies consist of two disks in series for better resolution. The computer scans these inputs one at a time serially, least significant digit first, by means of a diode matrix. The scanned data of all 13 inputs eventually appears in one single flip-flop I_r , in reflected-code.

It is well known that a number could not be read off directly in a true binary form (where each digit represents a power of two) from a moving commutator disc because it is impossible to get all the digits concerned to change at exactly the same instant. Thus, for example, if the number were to change from 15 to 16, any number between 0 and 31 could be read due to misalignment of one or more brushes. To avoid this difficulty, the reflected binary code was developed by the Bell Telephone Laboratories. This code has the feature that a change of one increment in the total number represented requires a change of only one bit.

Several methods for decoding such a reflected code have been devised in the past. However, these methods either convert the whole number in parallel (that is, all bits are observed simultaneously), or most significant digit first (that is, the most significant digit is observed and operated upon first and the least significant digit last). It is well known that a serial digital computer has to operate least significant digit first, and out of this consideration the following method for decoding a reflected-code, least significant digit first, has been devised.

If the count of 1's of higher significance than the digit under consideration in the reflected-code number is odd, the digit should be inverted; if it is even, the respective digit should stay unchanged. (The word "invert" amounts to substituting a "0" for a "1" and vice versa).

The following arrangement will convert a number according to the method just described, where the number circulates timewise, least significant digit first. Figure 6 is a block diagram showing the elements of the decoder.

The reflected-code number to be converted is carried serially, least significant digit first, in flip-flop I_r . A delay line feeds the reflected-code number from this flip-flop I_r into another flip-flop I_0 so that flip-flop I_0 carries the reflected-code number at least one word-time later than it was represented in flip-flop I_r .

Flip-flop I_a carries the reflected-code number delayed by one additional clock-period from flip-flop I_0 , thus trailing I_0 by one clock-time.

Flip-flop I_c is a single-stage binary counter which changes its configuration every time a "1" is in flip-flop I_r or in flip-flop I_0 . Flip-flop I_c has to start out in the "0" configuration and will automatically leave itself in the "0" configuration after a word has been converted.

This conversion is done in two word-times. During the first word-time I_c counts the 1's in the reflected-code number and determines whether the count of 1's is even or odd. During the second word-time, without resetting, the same flip-flop counts the 1's in the reflected-code number again. The complete reflected-code number is also delayed by one clock-time through flip-flop I_a . The decoded output will be the configuration of I_a if I_c is in the "0" configuration; the output will be in the inverted condition of I_a if I_c is in the "1" configuration.

Smoothing of $\dot{\theta}_{DN}$

Smoothing of $\dot{\theta}_{DN}$ is accomplished by effectively multiplying the last nine data points of $\dot{\theta}_{DN}$ by constants and summing these products to obtain the smoothed value. The computer accomplishes this function in the following manner: the last eight data points are stored in a precessing re-circulating line A , eight words long. This line is automatically kept up to date by replacing a data point every computation cycle, which is equivalent to a revolution of the drum or 63 word-times. This method automatically replaces the oldest data in that line with the newest and advances the relative position of the information in it by one word every computation cycle.

During each computation cycle the data in the eight words of A is either added or not added to another re-circulating line B . The eight products of these data points times their respective weighting constants are thus formed in B. No attempt is made to include algebraic sign at this point. If the machine is operating on pitch rate control, the products in B are either added or subtracted into an arithmetic register during the beginning of the following computation cycle. Then the latest data of $\dot{\theta}_{DN}$ is multiplied onto this sum. The above computation results in the smoothed value of $\dot{\theta}_D$ in this arithmetic register. If the machine is operating on altitude or pitch control, terms $k_7 \, k_f(h_D - h_o)$ ① or $k_7(\theta_D - \theta_o)$ ② are respectively computed in the arithmetic unit during this time.

Constants

All constants are stored in a special channel K , on the magnetic drum. The weighting constant digits are always stored in the first digit of a word-time in the K channel. The other spots in this channel are used to store all other constants used throughout the computation. The ease with which the constants can be changed is the main reason for storing them in this manner. In the upper right-hand corner of the computer (see Figure 9) a set of toggle switches is located which enables the operator to arbitrarily change information in the K channel, one bit at a time, by simply setting the switches to the desired word and digit number. A "1" or "0" can then be recorded by setting an additional switch and depressing a push-button. A lock and key is provided on the recording circuit to prevent any unauthorized "knob-twisters" from altering any information in this channel. Such mis-information might be difficult to detect if not suspected. These switches also enable the operator to trigger his oscilloscope at any desired time as selected by the switches.

It should be pointed out that this K channel on the drum can be eliminated once all these constants are established and built into the computer permanently.

Control Computation

The computer follows the equations given in Figure 5. The timing of the computer is so arranged that each word of information used for computation is scanned off the input disks at the proper time so that it can be used immediately when available. Because of this feature, it should ultimately be possible to eliminate the magnetic drum memory altogether.

All computation necessary to determine k_d , namely equations (14) through (21) of Figure 5 are performed utilizing a ten-digit word. This ten-digit word is sufficiently accurate for that purpose. Machine-wise this ten-digit word is achieved by splitting, at specific times, the G-register into two ten-bit registers and performing these operations simultaneously with other operations in the remaining arithmetic registers. As a result considerable computation time is gained. The miscellaneous comparisons described in Figure 5 are performed whenever the necessary information is available, and the resulting decisions are sometimes stored in flip-flops until they can be utilized.

Output

The output of the computer is ε_i as illustrated in equation (22). It is easy to see that ε_i can be of very large magnitude when a large input command is given. The control surface is rate and position limited, consequently, starting with the third least significant digit, only seven binary digits are converted into a DC voltage output. If ε_i is of a magnitude larger (or smaller) than the maximum (or minimum) that can be represented by these seven binary digits, the computer reaches the decision to substitute for it the maximum(or minimum) expressed by these seven digits. This information is then stepped into seven flip-flops which keep it for one computation cycle until newer information is available.

The method used to convert from a binary number to a voltage is well established (see Figure 7). The binary number is shifted into an output register made up of seven flip-flops. Each flip-flop has a voltage output which is accurately clamped to a high voltage E_1 or a low voltage E_0 , depending on whether the flip-flop contains a binary 1 or binary 0 . The output voltages of each flip-flop are indicated by A_1 through A_7 , where A_1 is the voltage output of the flip-flop containing the most significant digit and A_7 is the voltage output of the flip-flop containing the least significant digit. A_1 through A_7 will take on voltages equal to E_1 or E_0 depending on whether the particular flip-flop contains a 1 or 0 . Figure 7 illustrates the resistance network which forms the output voltage E_{out} . It can be shown that each binary digit will receive a voltage weight proportional to its significance in the binary number in the network output, or:

$$E_{out} = \frac{1}{3}\left(A_1 + \frac{A_2}{2} + \frac{A_3}{4} + \frac{A_4}{8} + \frac{A_5}{16} + \frac{A_6}{32} + \frac{A_7}{64}\right) \qquad (27)$$

From studies made on this type of conversion system, it is known that a linearity of ±1 percent is readily obtainable in the conversion from binary number to voltage. It is desirable to calibrate the system so that E_{out} will be zero when the output register holds a binary number which represents zero error signal.

Acknowledgements

This work was performed at the J. B. Rea Company under contract with the Air Force Armament Laboratory at Wright Air Development Center. The electronics for this experimental model was designed by Mr. Arthur P. Untrauer.

Appendix

Definition of Symbols

C_i	weighting constants for the digital filter
$C_{L_{max}}$	$= f(M)$, maximum lift coefficient
d_s	weighted difference between lift and load
d_L	$= d_g$ or d_s , whichever is smaller
d_g	weighted difference between critical load and actual load
g	gravity acceleration
h_D	desired altitude
h_o	measured altitude
k_a	$= k_1 s\, C_{L_{max}}$
k_b	$= k_2 n_z$
k_c	the limiting value of d_L , the factor which permits the airframe to obtain maximum response for all flight conditions
k_d	limit factor on the desired control surface position
k_e	$= K_{\dot{\theta}} = f(q)$, pitch rate gain factor
k_f	$= \frac{K_h}{K_\theta} = f(TAS)$, altitude gain factor
$k_1 k_2$	scaling factors

k_3	$= \frac{k_1}{k_2} g$
k_4	$= k_2 \, n_{z_{lim}}$
k_5	absolute margin of safety for critical stall and load conditions
k_6	the weighting term on $\bar{\Delta}$, used in predicting how close the aircraft may come to critical load or stall conditions
k_7	$= \frac{K_\theta}{K_{\dot{\theta}}}$, pitch attitude gain factor
k_8 k_9	the lower and upper bounds of Δ respectively, which decide when nonlinear control action will be utilized
k_{10}	maximum positive control surface deflection
k_{11}	maximum negative control surface deflection
k_{12}	trim coefficient
k_{13}	limit for Δ for determination of k_c
L	lift force, qs C_L
M	Mach number
m	aircraft mass
m_1	$= k_3 m$
n_z	$= \frac{L}{mg}$, load factor in g's
$n_{z_{lim}}$	maximum allowable structural load limit
q	dynamic pressure
s	wing area
TAS	true airspeed
t_o	time at which the present computation is being made
Δ	desired control surface position before trim, nonlinear control action, load or stall limits have been included
$\bar{\Delta}$	limited value of Δ for determination of k_c
δ_D	desired control surface position including the nonlinear control function but before load or stall limits have been considered
δ_d	desired control surface position including trim before nonlinear control or load or stall limiting have been considered
δ_e	control surface position
ε_i	error signal to the control surface servo
θ_D	desired pitch attitude
θ_o	measured pitch attitude
$\dot{\theta}_D$	desired pitch rate
$\dot{\theta}_{DN}$	desired pitch rate with noise
$\dot{\theta}_d$	effective desired pitch rate
$\dot{\theta}_o$	measured pitch rate

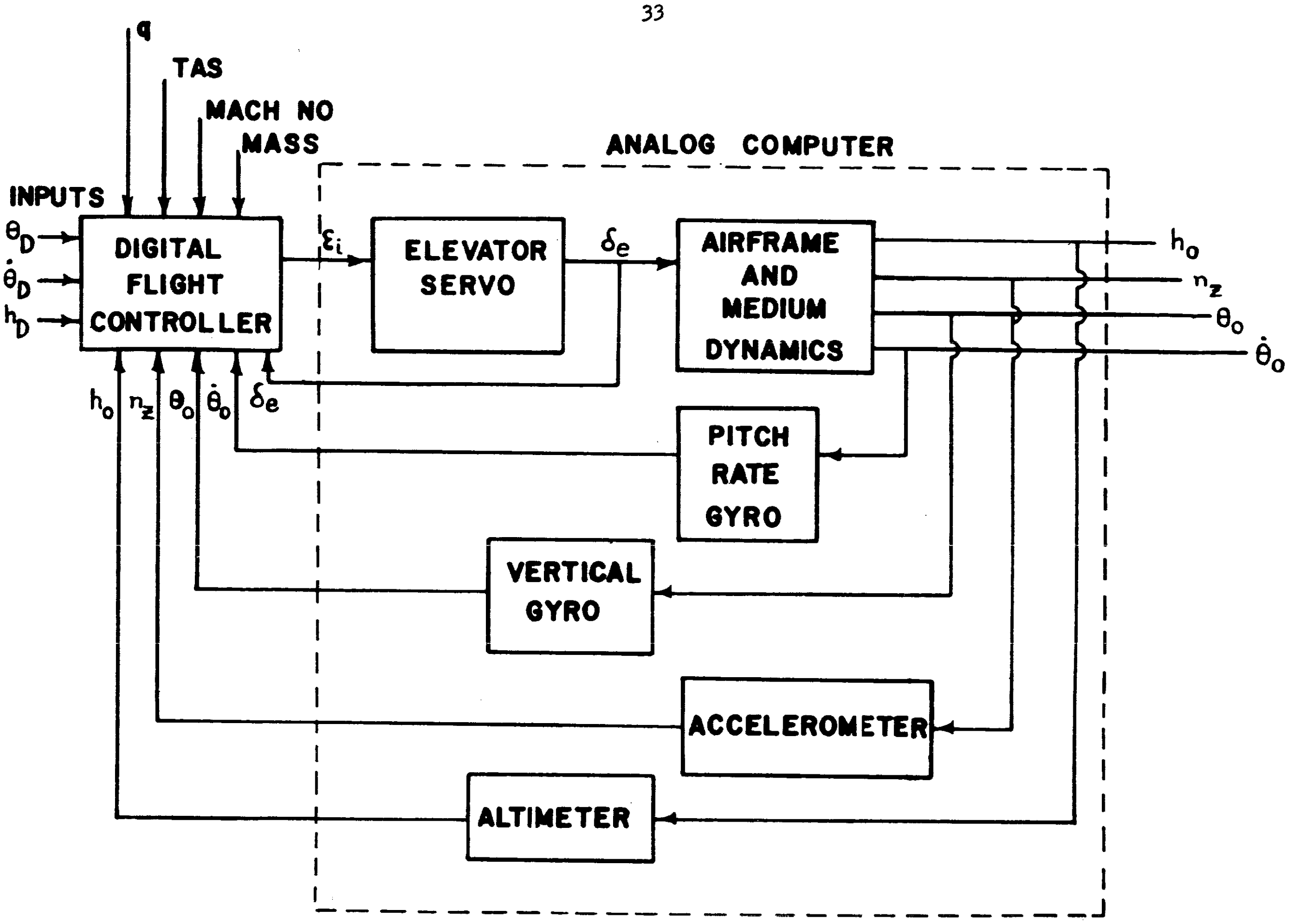

Fig. 1. Simulation mechanization for the digital flight controller

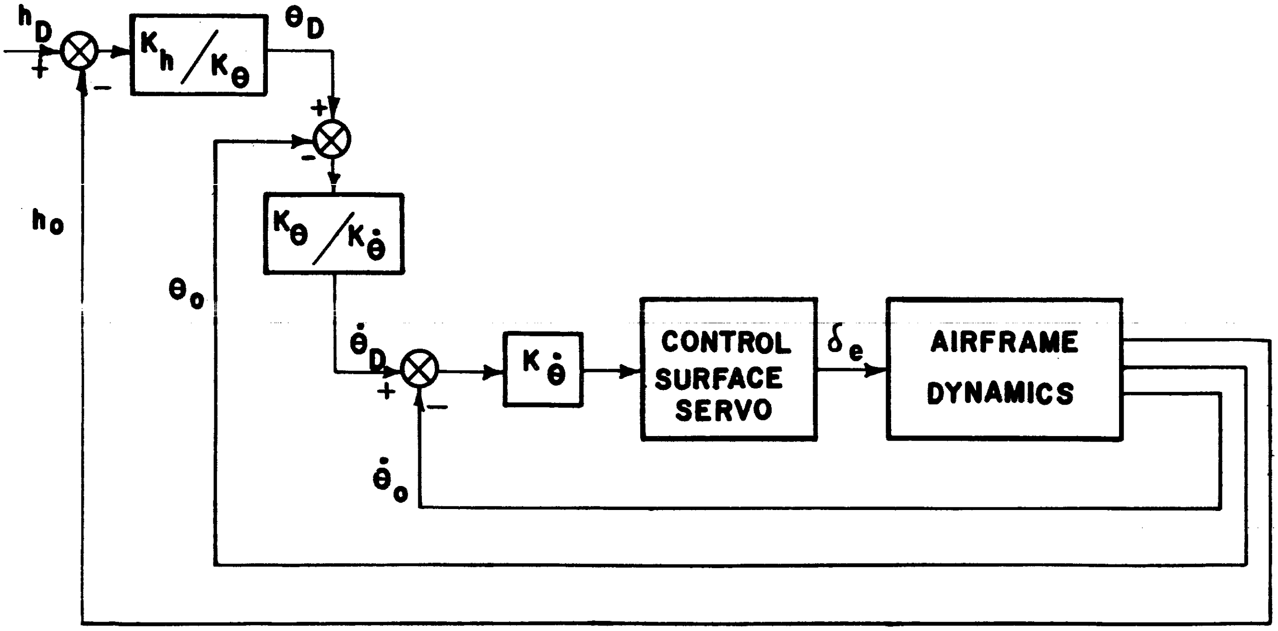

Fig. 2. Basic control system in block diagram form

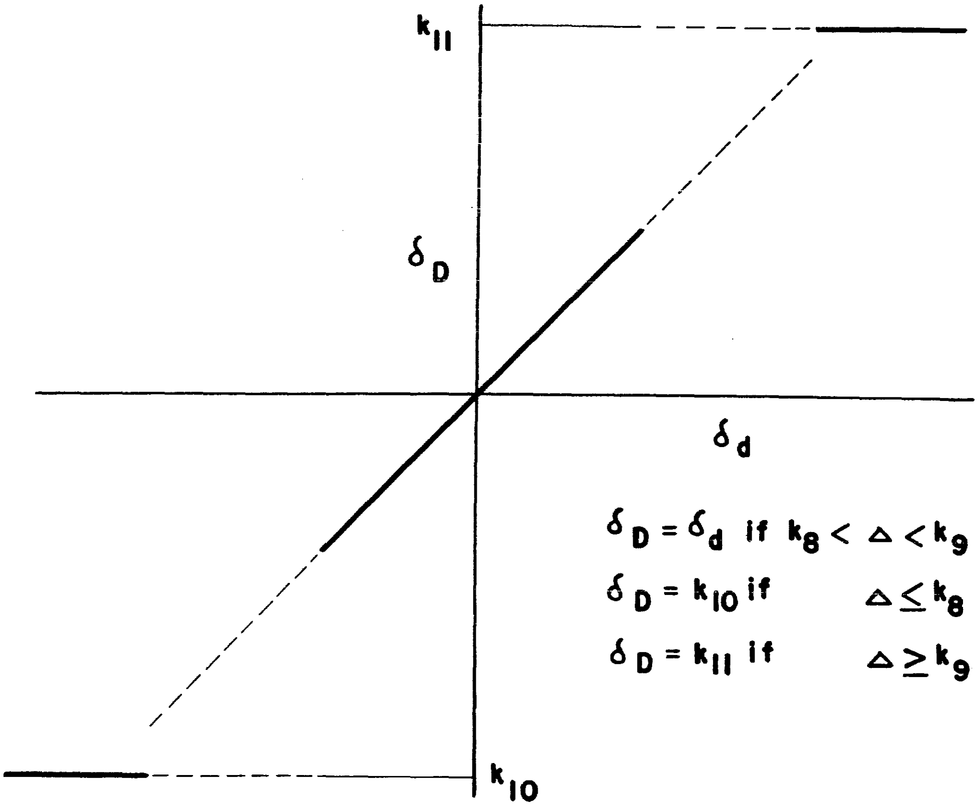

Fig. 3. Programmed nonlinear control

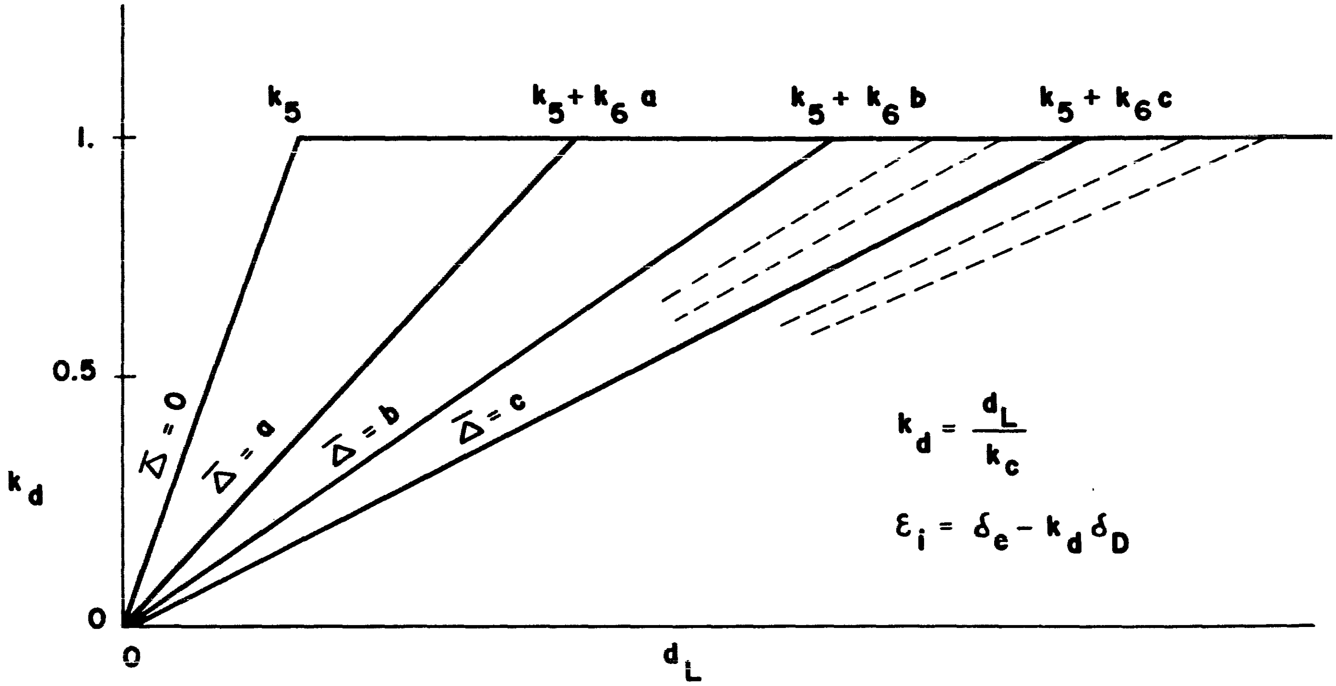

Fig. 4. Structural load and stall limiting factor

$$\Delta = k_e\left[k_7 k_f(h_D - h_o) \text{ ① } + k_7(\theta_D - \theta_o) \text{ ② } + \dot{\theta}_D \text{ ③ } - \dot{\theta}_o\right] \quad (7)$$

$$\delta_d = \Delta + k_{12}\int_{t_{-\infty}}^{t_o} \Delta dt - k_7 k_e \theta_o \text{ ① } \quad (8)$$

$$\bar{\Delta} = \Delta \quad \text{if } \Delta < k_{13} \quad (14)$$

$$\bar{\Delta} = k_{13} \text{ if } \Delta \geq k_{13} \quad (15)$$

$$d_s = qk_a - k_b m_1 \quad (16)$$

$$d_g = k_4 - k_b \quad (17)$$

$$d_L = d_s \text{ or } d_g \text{ , whichever is smaller} \quad (18)$$

$$k_c = k_5 + k_6 \bar{\Delta} \quad (19)$$

$$k_d = 1 \text{ if } \Delta < 0 \text{ or if } k_b < 0 \text{ or if } d_L > k_c \quad (20)$$

$$k_d = \frac{d_L}{k_c} \text{ unless } k_d = 1 \text{ per above} \quad (21)$$

$$\varepsilon_i = \delta_e - k_d \delta_D \quad (22)$$

$$\delta_D = \delta_d \text{ if } k_d \neq 1 \text{ or if } k_8 < \Delta < k_9 \text{ and only if } k_{10} < \delta_d < k_{11} \quad (23)$$

$$\delta_D = k_{10} \text{ if } k_d = 1 \text{ and } k_8 \geq \Delta \text{ or if } k_{10} \geq \delta_d \quad (24)$$

$$\delta_D = k_{11} \text{ if } k_d = 1 \text{ and } \Delta \geq k_9 \text{ or if } \delta_d \geq k_{11} \quad (25)$$

Figure 5. Control Equations

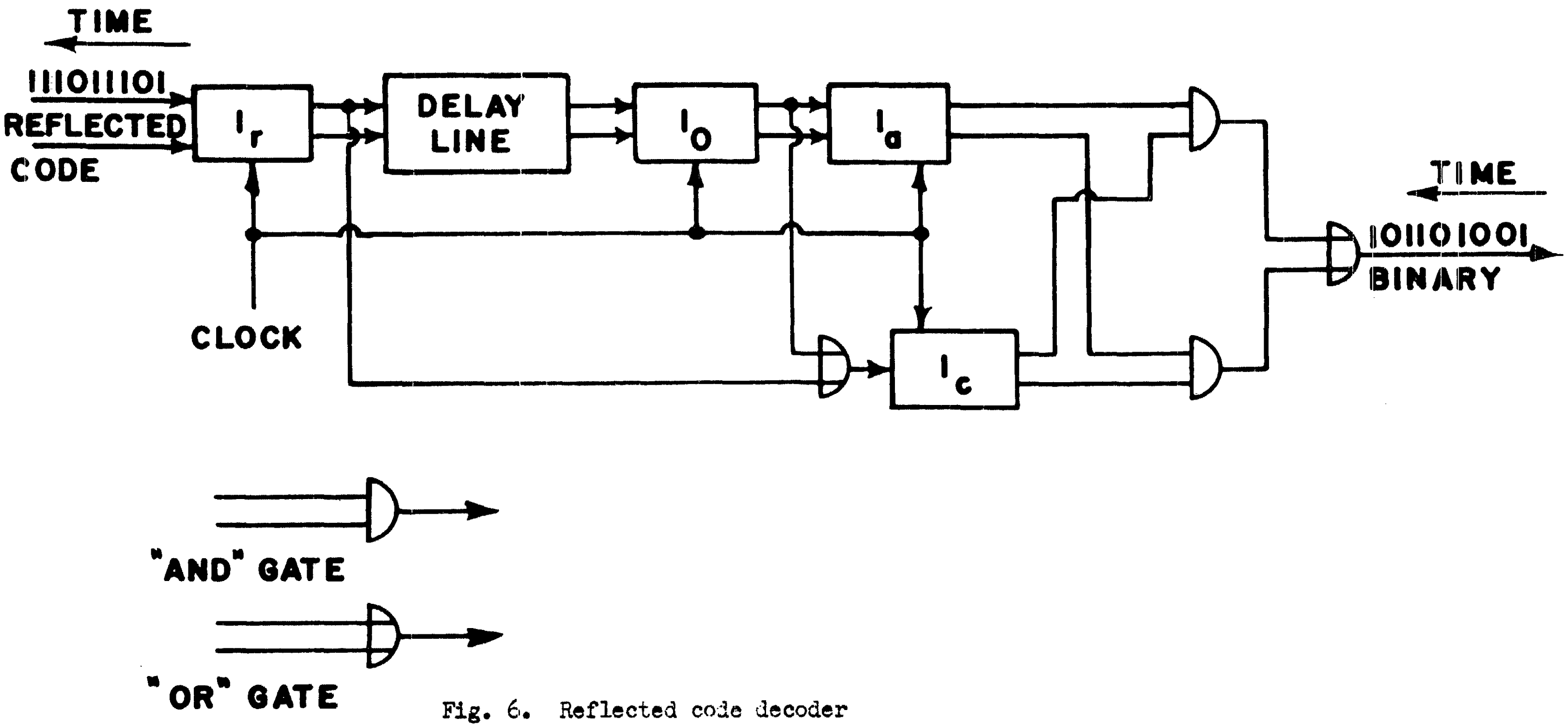

Fig. 6. Reflected code decoder

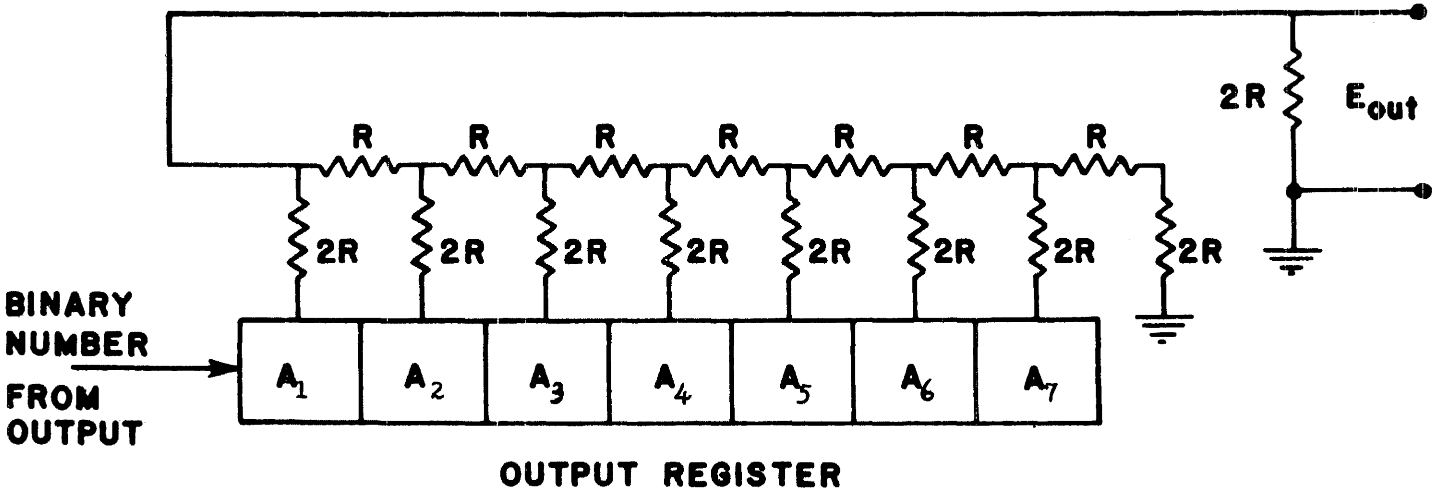

Fig. 7. Binary to d-c voltage converter

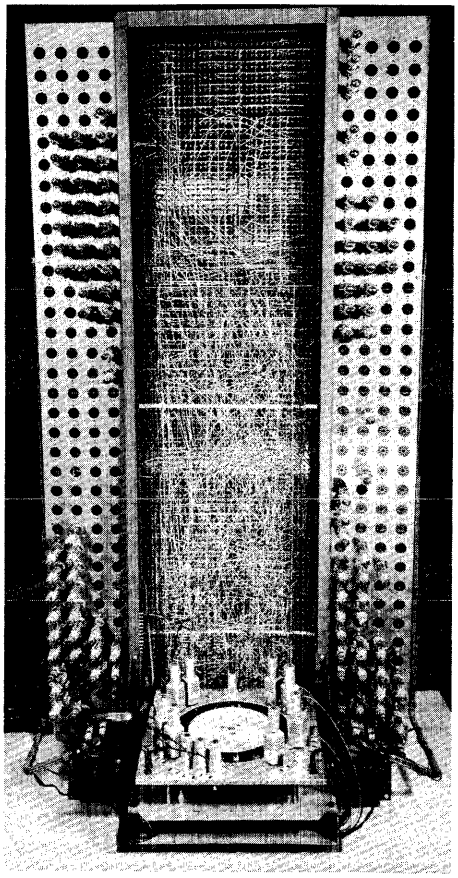

Fig. 8. Front view, the digital computer including the magnetic drum memory

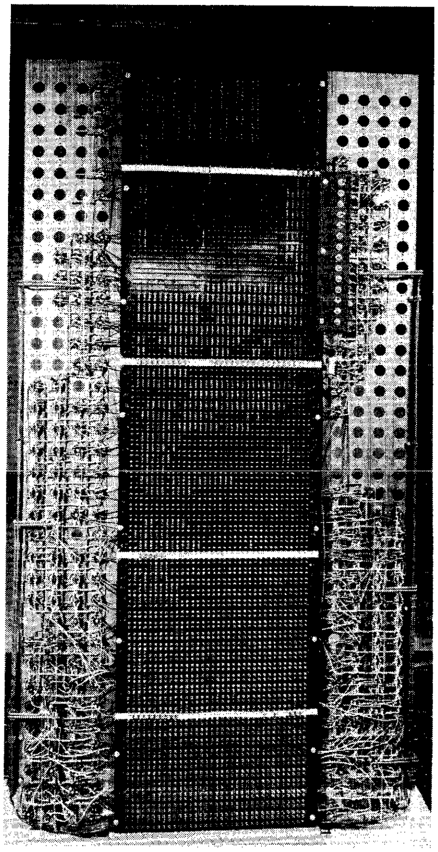

Fig. 9. Back view, the digital computer showing the diode matrices

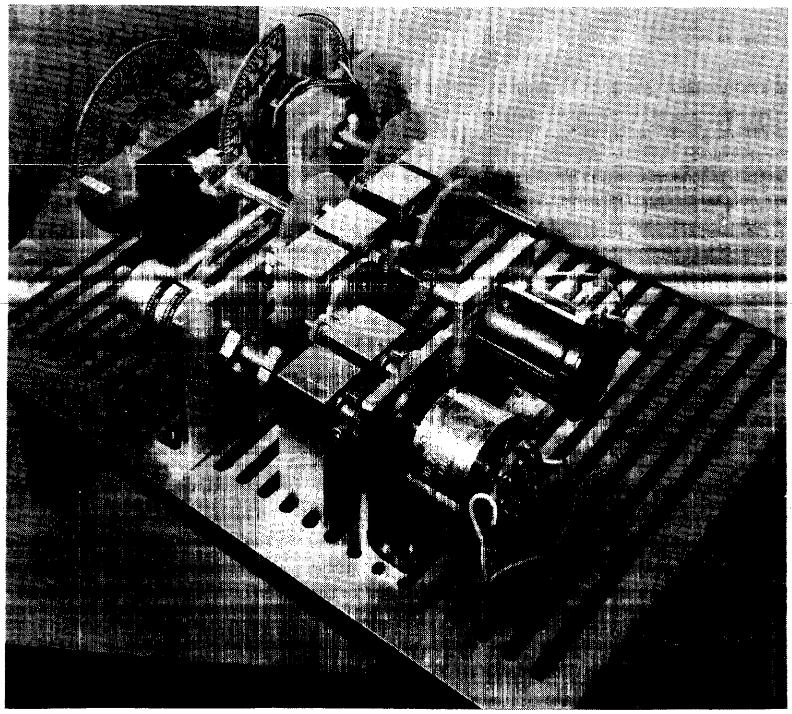

Fig. 10. The analog-to-digital servo converter

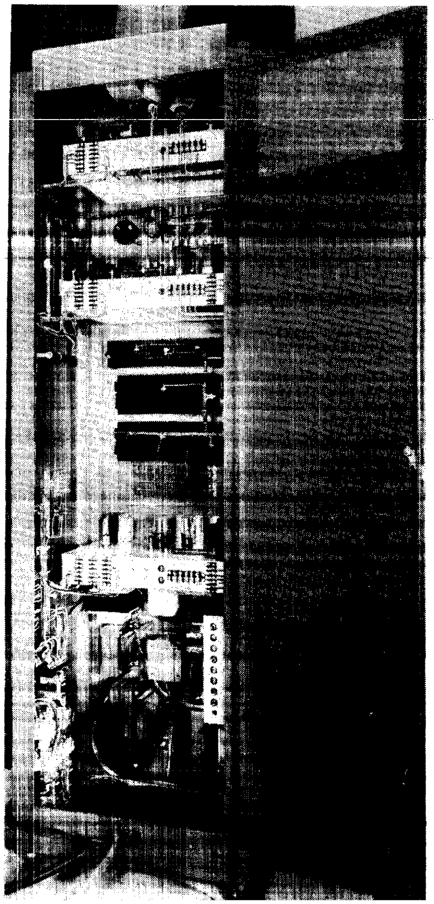

Fig. 11. The power supply

THE DIGITAC AIRBORNE CONTROL SYSTEM

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After World War II the field of digital computers began a period of rapid growth, primarily because their application to scientific computation provided increased accuracy and computational speed, as well as tremendous versatility which analog computation could not provide. It was only natural that designers of airborne military systems would also consider the application of digital techniques as their advantages over the analog techniques became apparent. However, the initial development of digital techniques had produced computers of such enormous size and complexity that their inclusion in airborne systems was in general considered to be impractical. The outstanding feature of the Digitac[1] system is the development of a small compact digital computer that is used as the computational and control element of an airborne system, without sacrificing the versatility of a general purpose digital computer. This unique development was successfully culminated by the excellent performance of the digital computer during the flight test program of the system.

Work began on the Digitac Airborne Control System in October, 1948, under a contract with the Armament Laboratory, Wright Aeronautical Development Center. The purpose of the work was the application of the hyperbolic position determination principle to a high precision automatic navigation system. Loran and other hyperbolic guidance systems were developed during the last war for guidance of aircraft and naval vessels. However, most of these hyperbolic guidance systems involved manually operated equipment and the use of special charts for position determination, and they did not provide the accuracy necessary for precise automatic navigation. The Digitac contract called for a completely automatic system which used hyperbolic navigation. No restrictions were placed on the type of equipment or components required for the system and every encouragement was given to consider any possible novel approaches which might lead to an advanced system.

The program was started with a study phase which was followed by equipment development and construction, and finally culminated in a system flight test program. In this paper we wish to outline the over-all system aspect of the development, but some details concerning the digital computer and flight test results will be included. Details of the computer, the autopilot coupler, and the flight test program will be presented in papers given at the 1954 National IRE Convention.

In a hyperbolic guidance system, such as the Digitac system, the position of the aircraft is determined with respect to three ground transmitters whose locations are accurately known. The master or common station operates with two slave stations in a manner to provide the effect of two pairs of ground stations. The time difference of arrival between pulses from each pair of ground stations

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[1] The word Digitac stands for Digital Tactical Airborne Computer and was applied to the system after the decision was made to use a digital computer.

establishes two hyperbolic lines whose intersection provides a fix for the aircraft. Thus, a set of ground stations establishes a coordinate grid which provides position signals for any number of aircraft in the service area.

A system analysis of the problem indicated that new developments would be required in practically every part of the system in order to meet the precise requirements for automatic navigation. A hyperbolic coordinate system has an inherent divergence of coordinates which leads to a purely geometric error which increases with the range from the ground stations. This fact indicated that one of the crucial points in the system would be the measurement of time differences to a sufficient precision to achieve the desired positional accuracy. Specifically, the time differences had to be measured automatically with an over-all accuracy of one part in 30,000 or about ±.02 microseconds. Early in the study program a digital system was developed for accomplishing this measurement using pulse counting techniques and a novel vernier interpolation scheme (reference 1). This system counted the number of 2 mc pulses occurring in the interval to be measured and then an interpolation was carried out by a pulse counting vernier technique which provided a measurement with an error less than that mentioned above, without exceeding the 2 mc counting rate. The time measurement equipment required no precision components other than a two megacycle crystal oscillator and a pulsed oscillator of similar frequency. The answer for the time measurement was in digital form so that it could be used directly by a digital computer.

Since the time measurements were provided with an accuracy of one part in 30,000, the computer for this system was required to use this data in determining position without loss of accuracy. This in addition to the fact that the time measurement data was already in digital form emphasized the desirability of developing a digital computer for these accurate computations. There are many other advantages of digital computation for airborne systems, however, which eventually led to its choice. These may be summarized as follows:

1. The computational accuracy can be chosen so that it is not a limiting factor in the accuracy of the system.

2. The basic nature of a digital computer allows the problem being solved to be modified at any point in the system development without equipment changes in the computer. It is entirely feasible to make a radical change in the problem during the development and flight test stage, while the computer is in production or even after the computer is being used in the field. The analog computers that had been used in airborne systems were completely incapable of this type of flexibility.

3. The flexibility of problem solution inherent to a digital computer means that in combination with different inputs and outputs one standard computer can be used for many systems and thus provide a degree of standardization and interchangeability that has been previously unavailable.

4. The ability of a digital computer to make decisions provides, for example, the capability of automatic navigation through a series of way points in approaching a target and provides for navigation back to any specific point after the mission is completed.

5. Finally, one of the most attractive advantages of a digital computer is its ease of mass fabrication which is due to the use of many similar subassemblies and to the lack of precision components.

This list of advantages of digital computation is not new to anyone familiar with digital equipment; however, they take on a new meaning for airborne control systems since they provide advantages which heretofore have been unavailable. In addition to these advantages, there are a number of others which are important in the tactical use of the Digitac system.

Upon completion of the study phase in which it was decided to develop a digital computer, an active development phase began in which two complete airborne systems and one set of three ground stations were constructed. The greatest portion of the development program was devoted to the airborne equipment; therefore, only this part of the system will be described here.

The block diagram of the airborne system is shown in Figure 1. The purpose of the receiver, decoder, and time measurement equipment is to supply the basic navigational information as two time differences. The result of these measurements are groups of 2 mc pulses which are counted by the input register and then this information is shifted in serial form into the computer. The information obtained from the aircraft's instruments for the heading, altitude and airspeed is converted to binary form (reference 2) and used in turn to parallel set the input register which shifts this information into the computer.

The digital computer was designed as a general purpose machine in order to obtain the maximum amount of flexibility. This allowed the construction of the computer to begin long before the system equations were in satisfactory form. The computer is a serial binary machine using a magnetic drum memory, a 100 kc clock pulse rate, and words composed of 16 binary digits plus sign. The computer performs addition, subtraction, multiplication, division, check sign, as well as transfers to and from the input-output equipment. The magnetic drum has a total storage capacity of 1110 words and one 6-word circulating register was provided for fast access storage. A floating address reference system (reference 3) is used to simplify the control equipment.

Extensive use of germanium diodes was made in gating circuitry to reduce the number of vacuum tubes to a minimum. The use of these techniques, as well as novel circuitry and logical design allowed the construction of a digital computer with a total of 250 vacuum tubes.

The pilot's display provides steering signals on a pilot's director indicator, as well as signal lights to indicate the state of the system operation. The autopilot coupler converts the binary steering signal to a shaft position necessary for input to the autopilot.

Figure 2 is a photograph of the input-output equipment showing typical chassis on extenders to facilitate maintenance. Figure 3 is a photograph of the digital computer. The total number of tubes in the airborne equipment is 434 and the total volume is 12 cubic feet including power supply. No attempt was made to subminiaturize the equipment as it was constructed as a research model and it was not intended as a prototype.

A parallel effort to the equipment development was the system analysis and formulation of equations in a manner suitable for digital solution. It was immediately apparent that the transformation from hyperbolic to rectangular coordinates is a cumbersome and lengthy problem. Various schemes were considered to simplify this transformation, one of which was the use of a pre-programmed course. This required precomputed constants to be stored for points at two-mile intervals along the course from which a simple transformation can be made. However, this was abandoned in favor of an iterative type of solution from which position may be determined at any point in the service area. In each cycle the previously computed velocity and positional data are used to compute a predicted position. The current time measurements are then used, together with the predicted position and the measured altitude, to obtain a new value of position. This iterative technique was chosen as it provides a simple and rapid solution for position and it converges quickly if the trial values are reasonable.

Figure 4 shows a simplified block diagram of the program in which the major steps of the computation are shown. Normally, the course of computation proceeds by the path outlined with the heavy arrows, in which the time measurements are usable and the position, the smoothed wind, the ground velocity, and the steering signal are computed. If the computer determines that the time measurements are not usable, then the dead reckoning branch is taken and the ground velocity is determined from the previous smoothed wind and the measured airspeed vectors. Since this computation is much faster than the normal navigation, any weapon systems computation would normally be done in this branch, thus utilizing otherwise dead time so that the total computation time is constant for the normal and the dead reckoning branches. Dead reckoning is forced to occur every 32 iterations in order to insure the weapons computation at repeated intervals. The trigonometric functions required are computed by polynomial approximations and square rooting is done by using Newton's iterative technique. The other branches shown in Figure 4 are entered to do the final weapons computation and to change the destination when the present way point has been reached. The over-all computation time for the normal or the dead reckoning branches of the routine is 0.5 seconds.

The digit rate of the computer is not accurately controlled; however, it is necessary to know the iteration time precisely in order to determine an accurate ground speed. This is accomplished by using a part of the time measurement equipment to measure the magnetic drum speed each iteration cycle from which the iteration time can be accurately computed. This feature means an over-all saving of airborne equipment as a frequency regulated 400-cycle supply is not required.

For the system flight tests a C-47 aircraft with an E-6 autopilot was chosen. Several approaches were considered for tying the digital computer into the autopilot control system and the method chosen is illustrated in Figure 5. This technique uses the steering signal to modify the autopilot heading angle input from the gyro compass while the autopilot operates to maintain a fixed heading. This method of coupling has the advantage of inserting the steering signals without interfering with the normal autopilot control loop. A detailed description of this coupler will be given in a later paper.

A fairly complete laboratory checkout of the system and the program was made by using the computed steering signal converted by the autopilot coupler to vary the heading input to the computer in a manner that would be equivalent to having an aircraft with zero response time. Then by putting into the computer an appropriate airspeed and forcing it to dead reckon, it could be made to navigate through a series of way points and in effect "fly in the laboratory." This technique proved to be a very valuable one in checking out the program as well as the performance of the computer. During these tests an automatic plotting board was tied to the computer so that the computed position could be plotted for these laboratory tests.

The flight test program began in June 1952 and continued for a period of fourteen months. It was conducted in the Metropolitan Los Angeles Area with the ground stations located at Playa del Rey, Baldwin Hills, and the Hollywood Hills. In addition to these points, a number of other accurately known locations in West Los Angeles and the Santa Monica Mountains were used as check points to determine the system accuracy. During the initial flight tests a very thorough checkout was made of all the components of the system and when these were working satisfactorily a series of complete system tests were begun. These tests were climaxed by a number of completely automatic flights in which the system was used to navigate the aircraft through a series of four way points. Very satisfactory results were obtained with normal navigation and in addition, the dead reckoning was shown to be very accurate. As a comparison, the aircraft was guided by having the pilot follow steering signals presented to him on a Pilot Director Indicator, as well as by completely automatic control through the autopilot coupler. This latter technique proved to be considerably superior as it was smoother and more accurate than manual control, and therefore was used throughout most of the flight test program. The computer iteration time of 0.5 second did not lead to any control difficulties, in fact it was shown that stable control was possible with longer iteration times.

During this flight test program, the advantage of a general purpose digital computer was demonstrated, as its flexibility allowed many dozens of program changes to be made. These program changes were necessary to correct unforeseen difficulties which became apparent only as a result of the flight test program.

During the flight test program it was necessary to record large quantities of information in order to evaluate the system operation. The advantage of digital computation was again apparent in that all the quantities desired for recording were readily available in the form of binary numbers within the computer. Equipment was developed to display up to 15 binary numbers on a 5-inch cathode ray oscilloscope and to photograph these numbers with a 35 mm. camera. With this technique it was possible to extract groups of numbers at intervals of once per iteration cycle, or at a much slower manually selected rate. This technique provided a valuable tool for determining the operational performance of the computer and the system.

The Digitac system is an excellent example of a system's approach to a complicated problem in which the choice of a general purpose digital computer allowed the equipment design and construction to proceed even though the formulation of the system equations was not yet completed. In the future this flexibility will be exploited by using one type of general purpose digital computer for each class of airborne problems, such as navigation, fire control, etc. This will result in a considerable reduction in the maintenance and spare parts problem for the Air Force. The Digitac system has pioneered in the development and flight testing of airborne digital computers and has demonstrated that their use in navigation systems results in advantages previously unavailable. It is safe to predict that in the future the airborne digital computer will be used extensively in military systems.

REFERENCES

1 D. W. Burbeck and W. E. Frady, "Precision Automatic Time Measurement Equipment." IRE-06, 20 February 1952; Paper presented at the Institute of Radio Engineers National Convention in New York, March 5, 1952.

2 A. D. Scarbrough, "An Analog-To-Digital Converter," M-50, 3 August 1953; Paper presented at the Wescon IRE, August 19-21, 1953, at San Francisco, California.

3 A. Zukin, "Automatic Program Control Utilizing a Variable Reference for Addressing." Paper presented at Electronic Computer Symposium, April 30-May 1, 1952, at the University of California at Los Angeles.

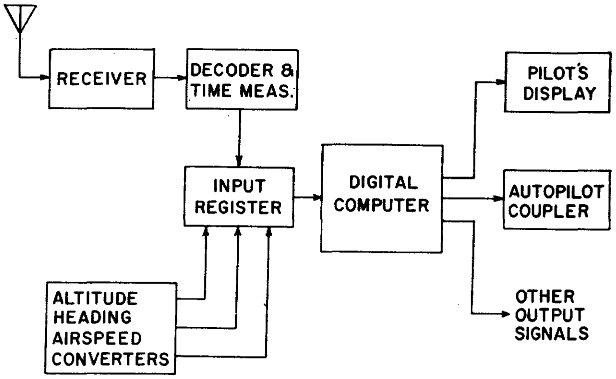

Fig. 1. System block diagram

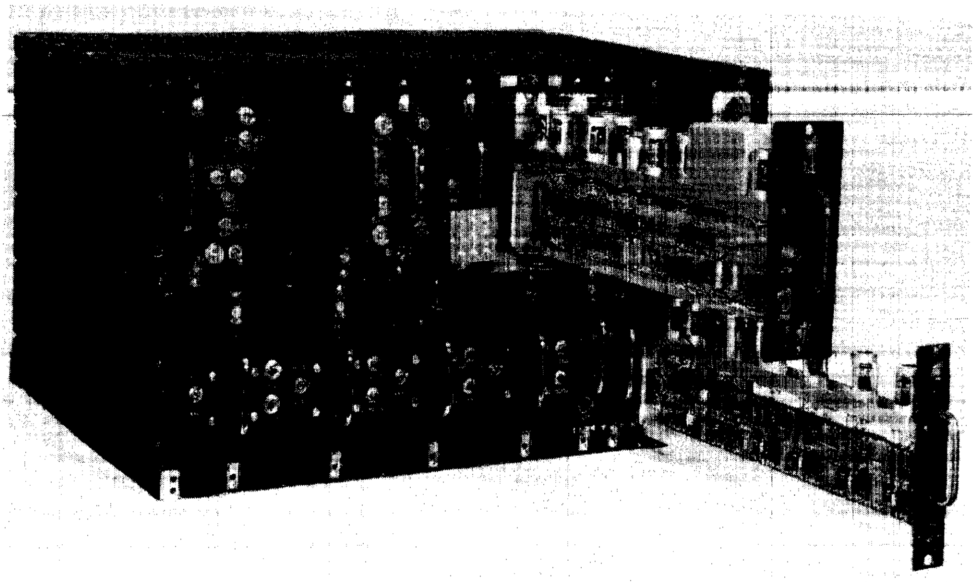

Fig. 2. Input-output equipment showing typical chassis on extenders

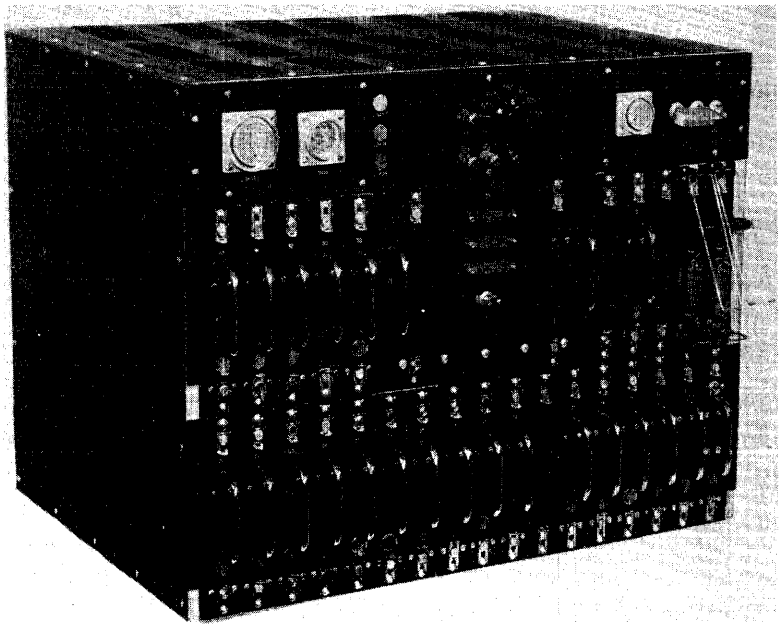

Fig. 3. The Digitac Computer

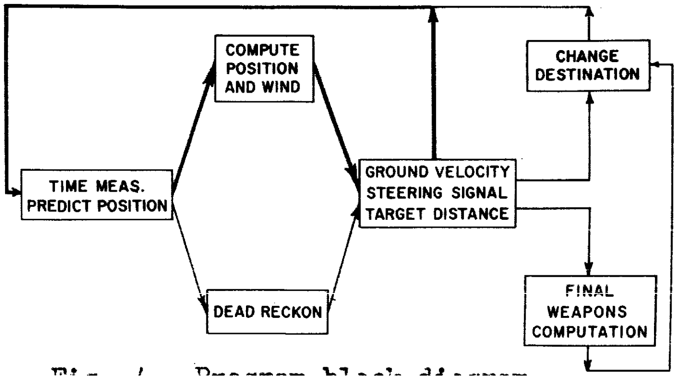

Fig. 4. Program block diagram

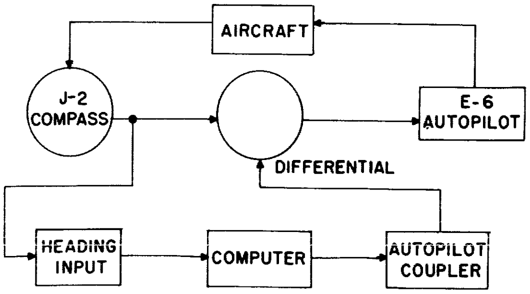

Fig. 5. Block diagram of the computer autopilot tie-in

APPLICATION OF OPERATIONAL DIGITAL TECHNIQUES TO INDUSTRIAL CONTROL
(Abstract)

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In many industrial applications, the instrumentation of control functions with operational-digital components rather than conventional analog or programmed digital types evidences advantages. New techniques have been developed and previously published techniques extended so that now a family of converters, packaged magnetic multipliers, dividers, and function generators are available.

Two examples are presented. First the instrumentation of a digital second-order rate-control mechanism is discussed. Also, measurement techniques and control instrumentation as specifically applied to a cement-making installation to survey and control its manufacturing processes are considered.

A DIGITAL-ANALOG MACHINE TOOL CONTROL SYSTEM

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Introduction

The research objectives of the Lewis Flight Propulsion Laboratory of the National Advisory Committee for Aeronautics include fundamental investigations of aircraft flight propulsion systems. A portion of the research deals with the experimental investigation of the optimum design parameters of the blades of compressor and turbine rotors. In the conduct of this program a series of rotors must be constructed on which the blade shapes have been systematically varied. Problems involved in the fabrication of these experimental blades are similar to those encountered in the fabrication of three dimensional cams. The blades (figure 1) have a general airfoil cross section and in many cases present a high degree of longitudinal twist and taper. Usual production techniques for their manufacture cannot be used at the Lewis laboratory because there are relatively few blades of a given design. The required expenditure of time and personnel to fabricate a single set of experimental blades was such that a program was undertaken to study the problem of automatizing a machine tool in such a manner that complete blades might be automatically fabricated directly from their original mathematical descriptions.

The surface of the complete blade is defined by coordinate data describing the plan profiles of three sections along the blade length, together with the angular displacements of each section measured around a common axis (figure 2). The initial problem is to prepare these original discrete data points defining the sections in a form acceptable to the control mechanism and to store these data in some medium that would permit moderate access time with a high degree of reliability. IBM card storage of the data was chosen for this operation.

This machine tool control program was therefore divided into the following objectives:

1. To develop a technique for preparing the coordinate or dimensional data describing the profile to be machined in the form of punched card intelligence.

2. To devise a technique whereby a small amount of the total defining data might be held sequentially in a secondary storage in order to provide for immediate and simultaneous access for conversion to a form acceptable to the control mechanism.

3. To develop a device for interpolating between the discrete data points to generate a continuous profile represented as a mechanical position.

4. To develop a magnetic recording system where the output of the interpolating device might be recorded as a continuous signal on magnetic tape, thereby allowing repeated operation of the control system in the absence of the interpolating device.

5. To modify a standard machine tool and equip it with power servos to enable it to reproduce the continuous interpolator output signals as recorded on magnetic tape.

A detailed discussion of each of the above developments would, of course, be outside the scope and purpose of this single paper. The discussion to follow will be limited to the two-dimensional case and will emphasize objectives 1, 3, and 4. Extensions of the described techniques to the three-dimensional case will become obvious to the reader. The purpose of this paper is to serve only as a general description of the composite machine tool control development. It is the author's belief that this system represents a perfectly general machine tool control which is directly applicable, without modification, to many machine tool automation problems.

Data Preparation

As previously stated, the profile one desires to generate in metal is defined by discrete data points. The fact that one desires to generate a continuous profile through these data points imposes the necessity of devising some sort of interpolation technique to generate this continuous profile.

Interpolation Equations

Two schemes to perform this continuous interpolation were investigated. The first device was an analog computer which generated a third degree polynomial of the form

$$r = r_0 + a\theta + b\theta^2 + c\theta^3 \tag{1}$$

Here r and θ are the defining polar coordinates of the desired profile and r_0, a, b, and c are constants. The values of the constants were chosen such that the polynomial passed through four successive data points (figure 3). The interpolation formula was then used to generate a continuous profile in the interval between the two middle data points. At the completion of the interpolation for one interval, the constants r_0, a, b, and c were reevaluated for the succeeding interval and the resulting formula was used to continue the generation of the profile. This process was continued until the complete profile of the blade was generated.

Equation (1) can be generated by interconnecting three mechanical integrators[1] (figure 4) and providing them with successive integrand inputs of $6c$, $2b$, and a. The problem then becomes one of expressing the coefficients a, b, and c in terms of the original digital coordinate data.

The coefficients of the interpolation equation could be determined by solving four simultaneous equations in terms of the coordinates of the four points. Considerable simplification will result, as will be evident later, if the points are chosen at equal intervals of the polar angle. The coefficients may then be evaluated in terms of the first, second, and third differences of the radius vectors of the four selected points. Because of the simplification in equipment, the equal interval mode of operation has been chosen for the development described in this report.

The Newton-Bessel[2] interpolation equation is a third degree polynomial whose coefficients are expressed in terms of numerical quantities derived from a difference table of $r = f(\theta)$. This difference tabulation is shown in figure 5.

For interpolation in the interval $W = W_0$ to $W = W_1 = W_0 + \delta W$, the Newton-Bessel equation is

$$f(W_0 + \theta\delta W) = f_0 + \theta\delta f_{1/2} + \frac{1}{2}\,\theta(\theta-1)\delta^2 f_0 + \frac{1}{6}\,\theta(\theta+1)(\theta-1)\delta^3 f_{1/2} \qquad (2)$$

For interpolation in the interval $W = W_{-1} = W_0 - \delta W$ to W_0 the corresponding interpolation formula is

$$f(W_{-1} + \theta\delta W) = f_{-1} + \theta\delta f_{-1/2} + \frac{1}{2}\,\theta(\theta-1)\delta^2 f_{-1} + \frac{1}{6}\,\theta(\theta+1)(\theta-1)\delta^3 f_{-1/2} \qquad (3)$$

Here $f(W)$ is the function to be generated. W is the independent variable. θ, however, as used in equations (2) and (3) is a parameter of W and is defined only in the interval from $0 \leq \theta \leq 1$. Therefore the continuous function of W may be generated by successive functions of θ made up of unit excursions from 0 to 1. This is shown graphically in figure 6.

If formula (3) is differentiated and θ is set equal to 1, it yields

$$(\delta W)f'(W_{-1} + \delta W) = (\delta W)f'(W_0) = \delta f_{-1/2} + \frac{1}{2}\,\delta^2 f_{-1} + \frac{1}{3}\,\delta^3 f_{-1/2} \qquad (4)$$

and if formula (2) is differentiated and θ is set equal to zero, it yields

$$(\delta W)f'(W_0) = \delta f_{1/2} - \frac{1}{2}\,\theta^2 f_0 - \frac{1}{6}\,\delta^3 f_{1/2} \qquad (5)$$

The difference between these two expressions is $-1/6\delta^4 f_0$. Therefore as W increases through W_0, a change $\Delta f'_0$ given by

$$(\delta W)\Delta f'(W_0) = -\frac{1}{6}\,\delta^4 f_0 \qquad (6)$$

has been made in f' in order to change from the interpolation formula appropriate to the interval W_{-1} to W_0 to that for the interval W_0 to W_1. The corresponding changes in the second and third derivatives are

$$(\delta W)^2 \Delta f''(W_0) = 0 \qquad (7)$$

$$(\delta W)^3 \Delta f'''(W_0) = \delta^4 f_0 \qquad (8)$$

Without further belaboring the mathematics of the interpolating mechanism, let it be sufficient to say that the coefficients of the third degree interpolation polynomial may be written in terms of the tabulated numerical values of the first and higher differences of the dependent variable. It may be stated that in order to proceed through successive interpolation intervals only one piece of difference information need be introduced for each interval.

Data Preparation

For the interpolation scheme just described, it is necessary that the original data defining the desired profile be transformed into coordinates defining the locus of the machine tool's cutter trajectory around the desired profile, at equal intervals of the polar angle. This data transformation is carried out on an IBM type 604 computer, wherein the slopes at each data point are computed using a five point interpolation equation. From this slope intelligence, plus knowledge of the cutter radius, a new series of coordinate data points describing the cutter trajectory are computed. Five point interpolation techniques are again applied to these new data points to yield radius vectors of the cutter trajectory at equal intervals of the polar angle from a pole chosen within the section profile. From these equally spaced computed radius quantities, their fourth difference data are derived. These fourth difference data are punched in the IBM cards. Also punched in the cards is the desired position of the cutter at the end of each interpolation interval. This information is used to prevent the accumulation of errors in the interpolating device.

Digital to Analog Conversion

An IBM 523 Summary Punch is used to read the cards in sequence and transfer the decimal digital data from the cards in the form of electrical pulses to a diode converter where the intelligence is converted to binary-decimal data and temporarily held in a relay storage. Precision resistance elements are introduced into one leg of a self-balancing bridge by this relay storage where the mechanical analog of the original punched card intelligence becomes the accumulated angular position of the bridge balancing servo motor. This mechanical position is the analog of the fourth difference data and is in a form suitable for introduction to the interpolator. Card cycling of the Summary Punch is controlled by the interpolator at a rate in excess of one card per second. Data is introduced and held in relay storage in advance of its treatment by the interpolator. Error circuits which measure the generated error at the end of each interpolation interval are installed in the computing circuit so that the possibility of accumulated error is completely eliminated. This error correction is made in the derivative of the interpolation function so that the error arising in one interpolation interval will be compensated for in the interval to follow. The maximum error that can be present is therefore that developed during a single interpolation interval.

Analog Computer

Three mechanical integrators constrained as shown in figure 4, with provisions for changing the displacements of the integrand input to two of them by the amounts shown in equations (6) and (8) as W passes through each tabular value, will generate a continuous function. This interpolation scheme has the advantage of generating a continuous function through each interpolation interval with only one piece of stored information, this being the fourth difference. Figure 7 shows an experimental assembly of the interpolator. Precision Kelvin-type ball-disc integrators with servo coupling were used to generate the interpolation polynomial.

Spline Interpolator

A second technique for performing the required continuous interpolation between the discrete data points describing the cutter locus is shown schematically in figure 8. This device consists essentially of a servo positioned spline which is positioned at four equally spaced points whose displacements are proportional to four successive radius vectors along the cutter locus. The spline passes between four knife edges; each knife edge being carried on a nut which is displaced by the angular rotation of a precision, servo-motor driven jack screw. Each servo-motor drives its knife edge to a position proportional to the coordinate magnitude punched in the IBM card. Four, three-digit decimal numbers representing first difference data of the dependent variable are punched in each card and read out of relay storage simultaneously to position the spline displacing knife edges.

A servo-positioned probe (figure 9), carrying a high voltage follows the spline without physically touching it, by using the voltage drop across the spark gap between the probe and the spline as a control signal. This gap length is approximately 0.003 inch. The probe is caused to scan the length of the spline by means of a constant velocity cam whose integrated angular position is proportional to the polar angle while the probe is displaced in the variable r by means of the spark-controlled servo to follow the curvature of the spline. One revolution of this cam represents a 20° excursion of the polar angle.

To provide a continuous output from this interpolator, two identical splines, each driven by four positioning servos, are provided. This permits card data to be read out of relay storage into one spline's positioning servos, while the other spline is being followed. A shifting device permits the probe to shift from one spline to the other in a negligible time.

The interpolation cycle (figure 9) proceeds as follows:

1. Assume that the right-hand spline is positioned and static at displacements R_0, R_1, R_2, and R_3.

2. As the "θ" cam rotates, the probe follows the spline through the interval R_1 to R_2.

3. During this cycle data is read into the left hand spline's servos and the spline is displaced to values R_1, R_2, R_3, and R_4.

4. When the probe has traveled from R_1 to R_2, it shifts to the left hand spline which is also displaced at R_2, and proceeds to follow up the left

hand spline to R_3. This sequence is then repeated and one new radius vector is introduced and one old radius vector is discarded with each interpolation interval. A photograph of the actual spline interpolator is shown in figure 10.

In this system the response of the spark-controlled servo is sufficiently good so that the accuracy of this type of interpolation system is limited only by the linearity of the balancing potentiometer used in each knife edge positioning servo. 1/10 percent linearity potentiometers have been used quite satisfactorily in the interpolator now in operation at the Lewis laboratory.

The mathematical analog of the computer interpolator and the spline interpolator are, for practical purposes, the same. One process generates a third degree interpolation polynomial through four successive data points, while the second system produces a faired profile through the data points through the use of the deflection curve of a tempered spline passing through the four data points.

Experience has indicated that 10° increments of the polar angle are the largest increments giving satisfactory performance in the interpolators just described. The selection of the size of this increment is, of course, a function of how well $r(\theta)$ can be expressed as a third degree polynomial, thus making the fourth differences small.

Magnetic Recording System

Although the entire system so far described is capable of operating directly into a machine tool's power servos by means of synchro coupling, it was deemed advisable to devise a system which would permit the independent operation of the computing machinery and the machine tool. For this reason a magnetic tape recording system was developed to permit the integrated angular rotations of the outputs (r and θ) of either interpolator to be recorded on magnetic tape, thereby necessitating only the playback electronics and the power servos to be in the immediate vicinity of the machine tool.

The recorder, around which this system is built, is an Ampex Sterophonic tape recorder using 1/4 inch tape (figure 11). It is designed to operate a tape speed of $1\frac{7}{8}$ and $3\frac{3}{4}$ inches per second and provides for the simultaneous record and playback of two channels of information. As was previously stated, the output of the interpolator is the mechanical position of two shafts whose integrated angular rotation represents the excursions of the variables r and θ.

A block diagram of the recording system is shown in figure 12. The r and θ outputs of the interpolator drive the recording control transformers $1CT_1$ and $1CT_2$ whose stators are excited by a three phase 60 cycle voltage. This three-phase voltage serves as the phase reference signal on playback and therefore a signal representing one phase of this three-phase stator voltage is recorded on tape track No. 1.

The rotor voltages of the recording control transformers are constant amplitude signals whose phase varies as a function of the rotor's angular position referenced to their stator winding's exciting signal. The phase varying from $1CT_1$ modulates a 1000 cycle phase shift oscillator signal and is added to the phase varying signal from $1CT_2$. This composite signal, containing intelligence defining the integrated angular position of the interpolator outputs representing the excursion of the variables r and θ, is then recorded on tape track No. 2.

On playback (figure 13) it is desired to position the control transformers $1CT_3$ and $1CT_4$ in accordance with their recorded position intelligence. To do this it is first necessary to recover the original three phase reference signal. One phase of this signal, recorded on tape track No. 1, is passed through three power amplifiers where the signal is shifted 0, 120, and 240 degrees to reproduce the original three-phase signal to excite the stator windings of the playback control transformers. The multiplexed signal on tape track No. 2 is separated into its two components (a 60 cycle signal and a 1000 cycle modulated signal) by means of low and high pass filters. The output of the low pass filter and the rotor signal of $1CT_4$ are compared phasewise to indicate the mechanical following error. These two signals are amplified and clipped before comparison, thereby yielding a square wave error signal which is reshaped to a 60-cycle sine wave to provide a suitable error signal for a conventional positioning servo, stabilized with velocity feedback. The five watt servo motor associated with this channel drives the rotor of $1CT_4$ to minimize the error signal and thereby mechanically reproduces the original recorded signal representing the variable r.

The second component of the multiplexed signal representing the variable θ is mechanically reproduced in a similar manner, however, the 60-cycle modulated, 1000 cycle carrier is first demodulated before it is clipped and compared with the clipped rotor voltage of $1CT_3$.

These low power read-out servo motors M_1 and M_2 (figure 13) are connected in cascade with the power servos driving the machine tool's controls in the variables r and θ. A 12-inch Monarch Engine Lathe was adapted to accommodate the power positioning servos. The work piece is held in a four jaw chuck which is rotated in the variable θ. A motor driven milling head (figure 14) is mounted on the lathe's cross-slide and is positioned in the variable r.

Concluding Remarks

In conclusion let us consider the composite system and review its operation (figure 15).

1. The original coordinates of the section to be machined are processed with IBM machinery to obtain the coordinates of the cutter locus at equal intervals of the independent variable. The fourth or first difference values of the dependent variable (depending upon the type of interpolator being used) are computed and these values are punched in IBM cards.

2. Each difference card is sequentially read in an IBM Summary Punch as a three digit decimal number which is then temporarily held in relay storage.

3. The relay storage converts this stored intelligence into a mechanical position by means of self-balancing bridge circuits and introduces these data into an analog interpolator, where a continuous function is generated through the discrete data points.

4. The interpolator output provides two continuous angular rotations whose integrated angular positions represent the magnitudes of the variables r and θ describing the machine tool's cutter locus.

5. The interpolator output is converted into a frequency modulated electrical signal and recorded on magnetic tape.

6. On playback, the controls of the machine tool are caused to duplicate the mechanical position recorded on the magnetic tape by means of power servos operating in a closed loop with the tape read-out servos.

This type of control is readily adapted to any machine tool using rack or lead-screw coordinate control. No modification of the interpolator is required concerning the type of coordinate system, the range of the controlled variables, or the size of the piece being machined, for the device operates from normalized data. The scale factor is adjusted at the output end of the interpolator to conform with the size of the machined member and the pitch of the particular machine tool control elements.

The interpolator, in association with its correction and reset circuits presents a total accumulated error of about 0.1 percent for a complete interpolation cycle. The maximum operating speed in the variable r is approximately ten inches per minute, the limiting factor here being a proper balance between the data input and interpolation cycles. It is the author's belief that this system represents a perfectly general machine tool control requiring a minimum of data preparation and equipment auxiliary to the machine tool.

References

1. Crank, J.: The Differential Analyzer, Longmans, Green & Co., 1947.

2. Whittaker, E., and Robinson, G.: The Calculus of Observations, Chapter One, Blackie & Sons Ltd., 1944.

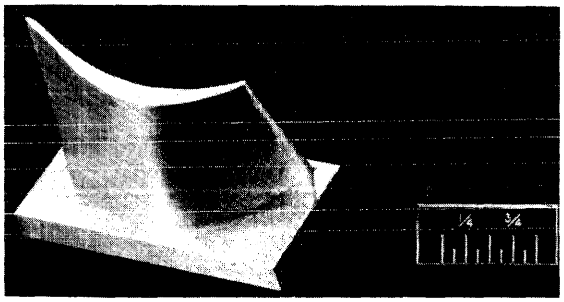

Fig. 1. A typical blade geometry

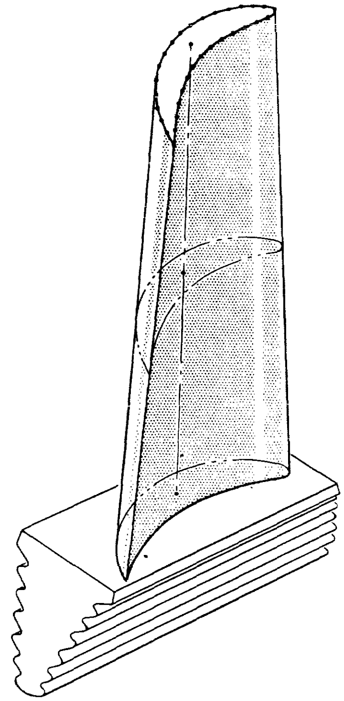

Fig. 2. A blade surface defined by coordinate points describing the profiles of three of its cross sections

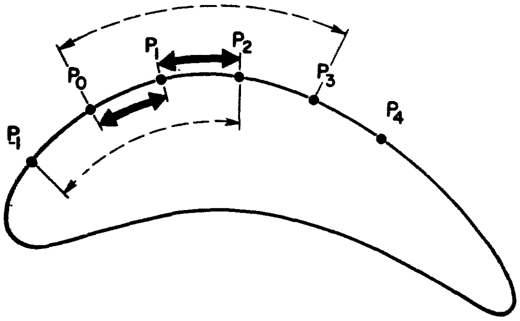

Fig. 3. Information points for interpolation intervals P_0 to P_1 and P_1 to P_2

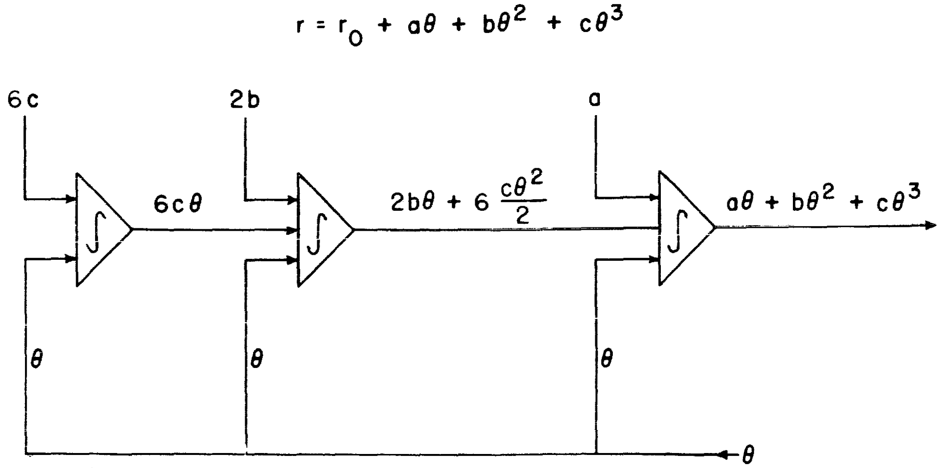

Fig. 4. Connection of three integrators to generate the polynomial $r = r_0 + a\theta + b\theta^2 + c\theta^3$.

θ	$f(\theta)$	δ	δ^2	δ^3	δ^4
W_{-1}	$f(W_{-1})$		$\delta^2 f_{-1}$		
		$\delta f_{-1/2}$		$\delta^3 f_{-1/2}$	
W_0	$f(W_0)$		$\delta^2 f_0$		$\delta^4 f_0$
		$\delta f_{1/2}$		$\delta^3 f_{1/2}$	
W_1	$f(W_1)$		$\delta^2 f_1$		$\delta^4 f_1$
		$\delta f_{1\frac{1}{2}}$		$\delta^3 f_{1\frac{1}{2}}$	
W_2	$f(W_2)$		$\delta^2 f_2$		$\delta^4 f_2$
		$\delta f_{2\frac{1}{2}}$		$\delta^3 f_{2\frac{1}{2}}$	
W_3	$f(W_3)$		$\delta^2 f_3$		
		$\delta f_{3\frac{1}{2}}$			
W_4	$f(W_4)$				

Fig. 5. Method of tabulating higher differences of $r=f(\theta)$

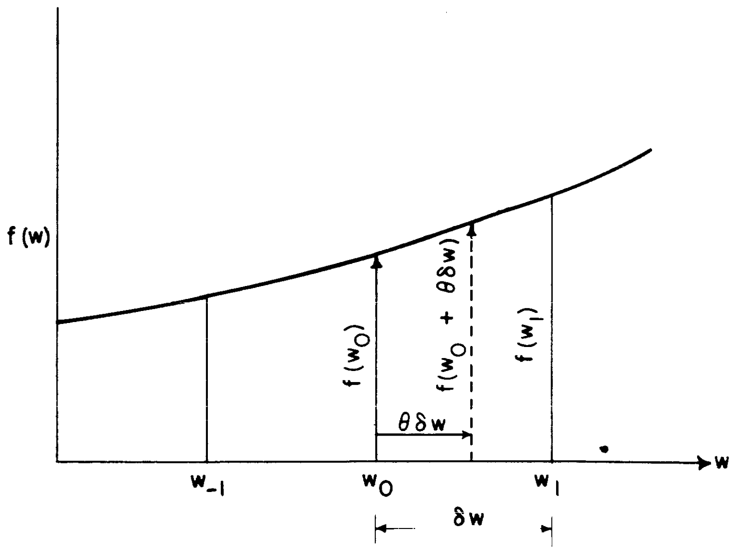

Fig. 6. A graphical description of the interpolation formula

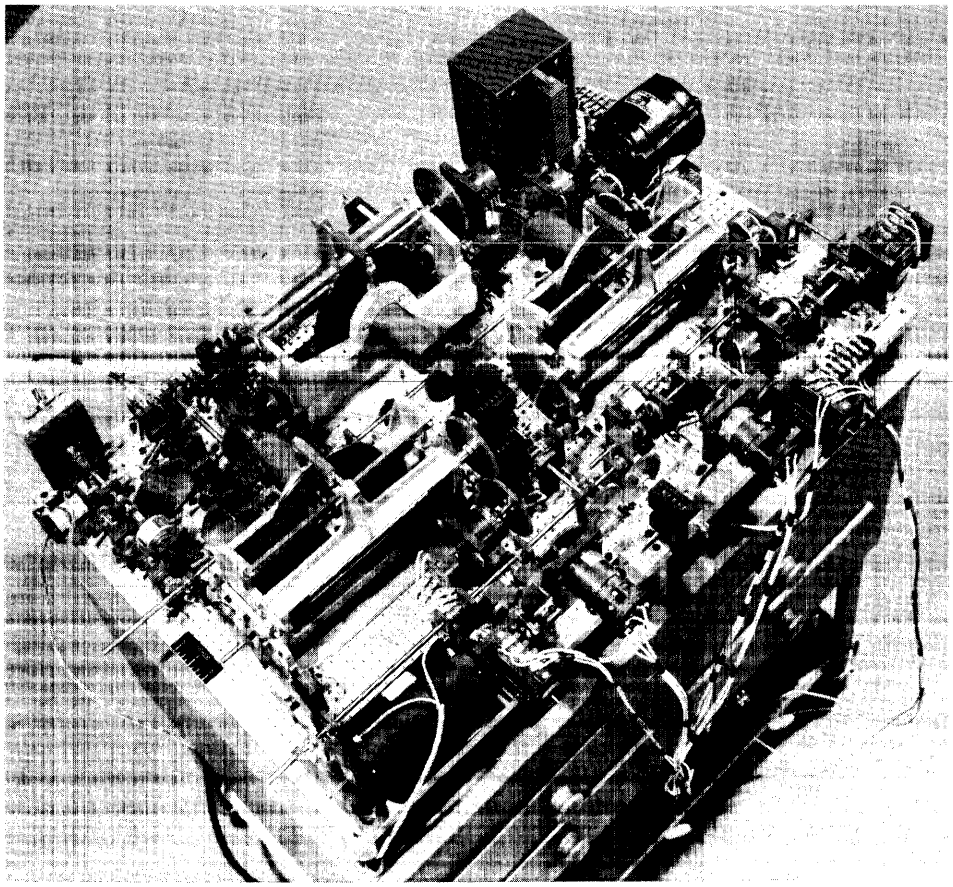

Fig. 7. Experimental assembly of the analog interpolator

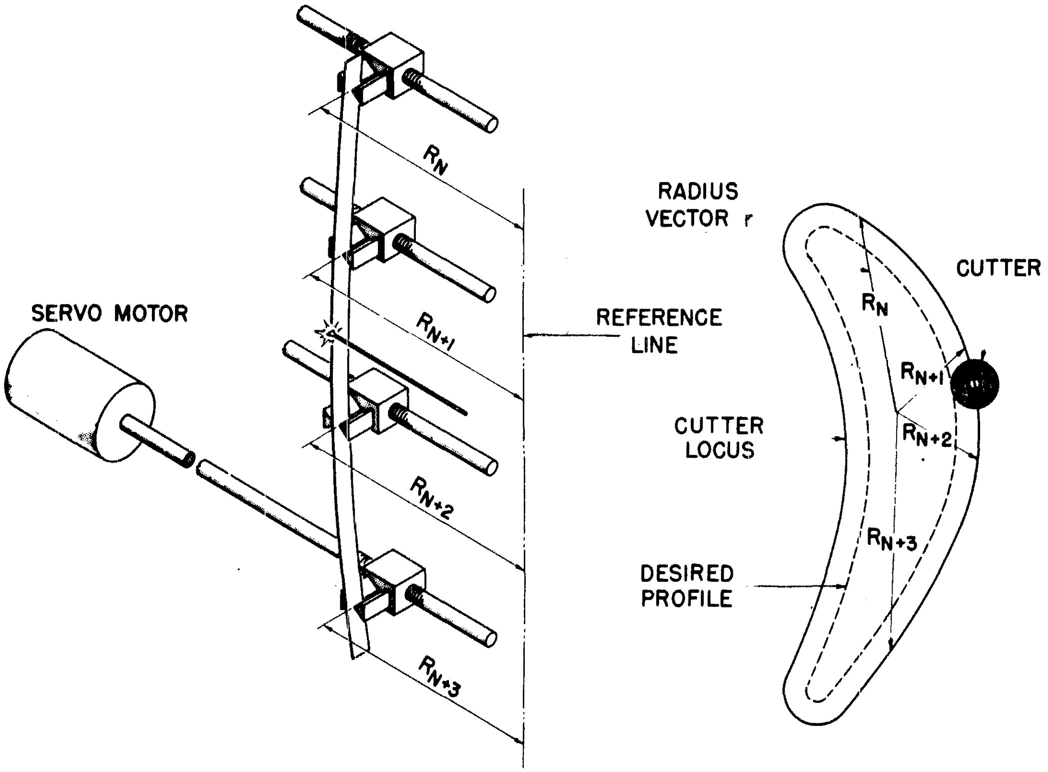

Fig. 8. Method of forming a continuous function through four data points with a servo-positioned spline

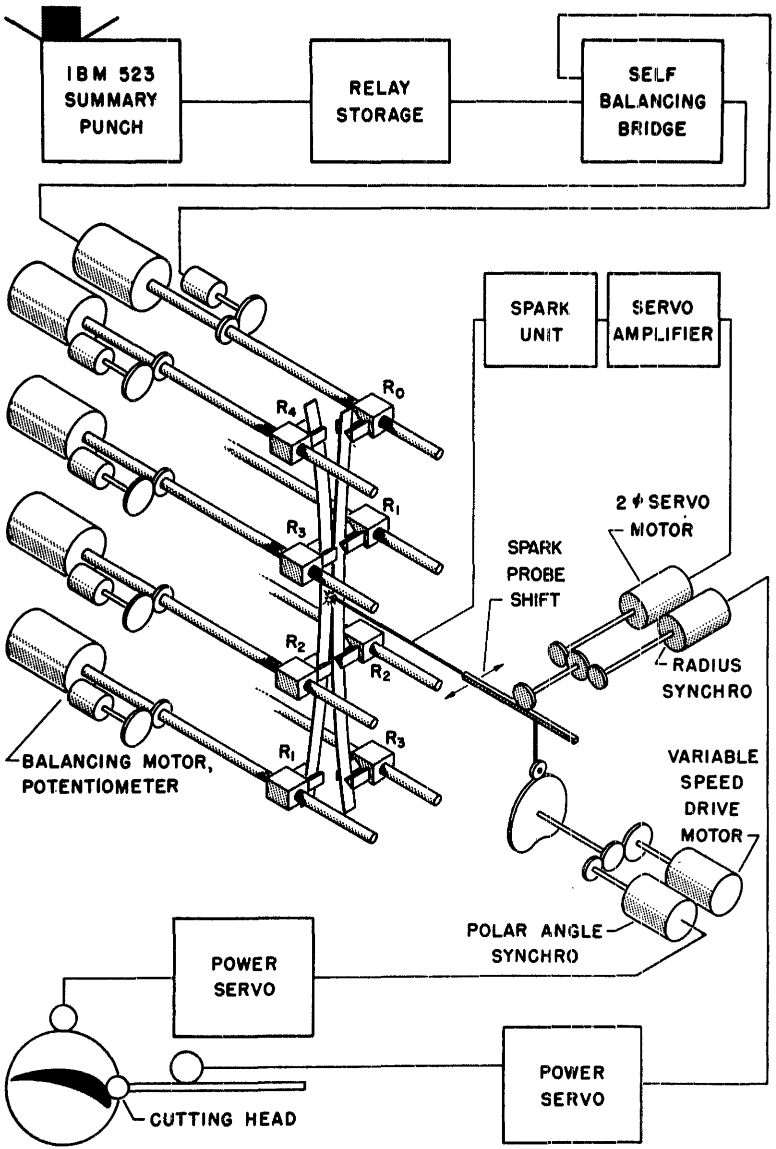

Fig. 9. Composite system of the servo-positioned spline interpolator

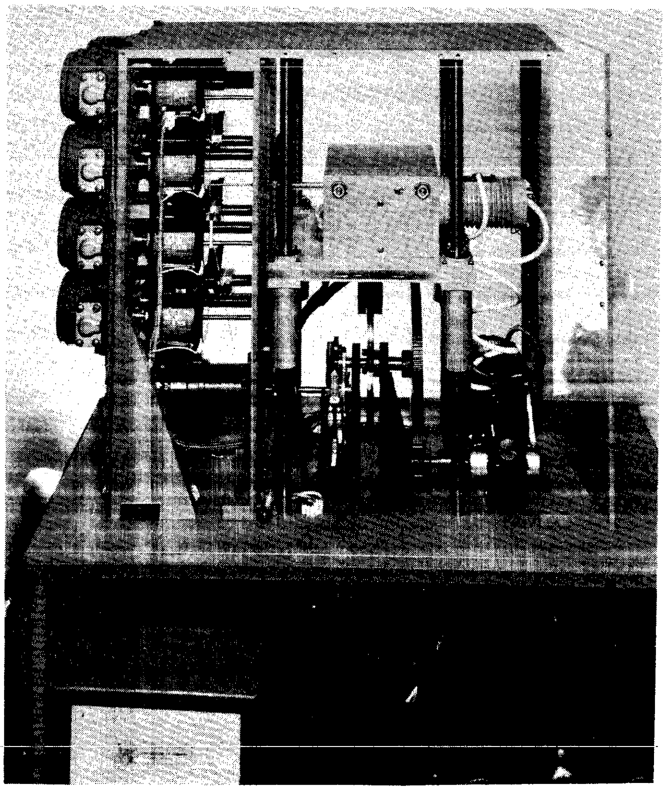

Fig. 10. Photograph of the spline interpolator

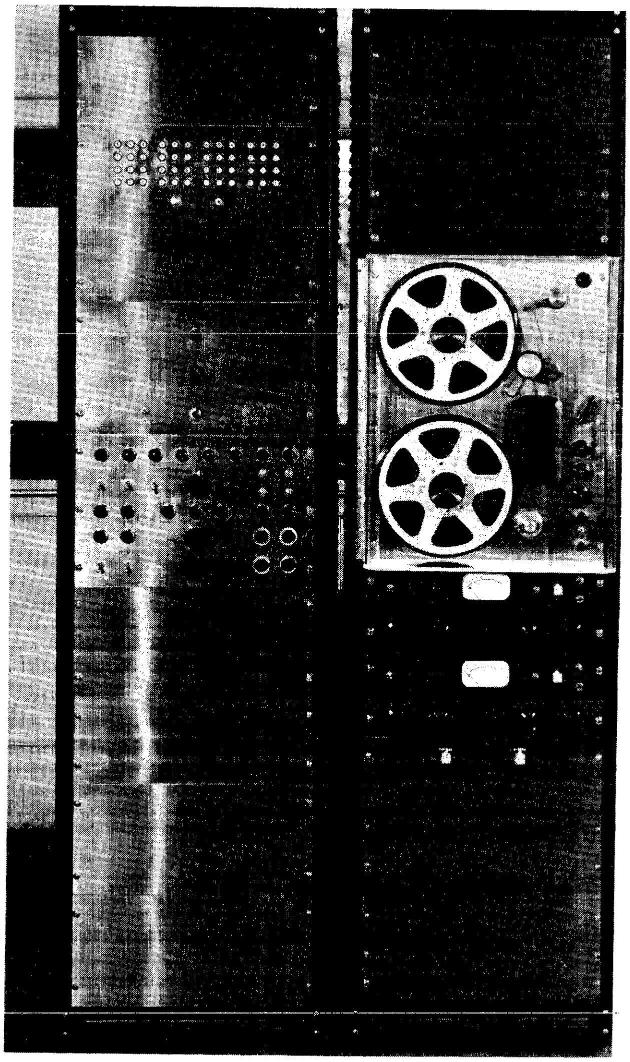

Fig. 11. Relay storage, master control station, and power servo electronics (left rack), magnetic recorder and associated electronics(right rack)

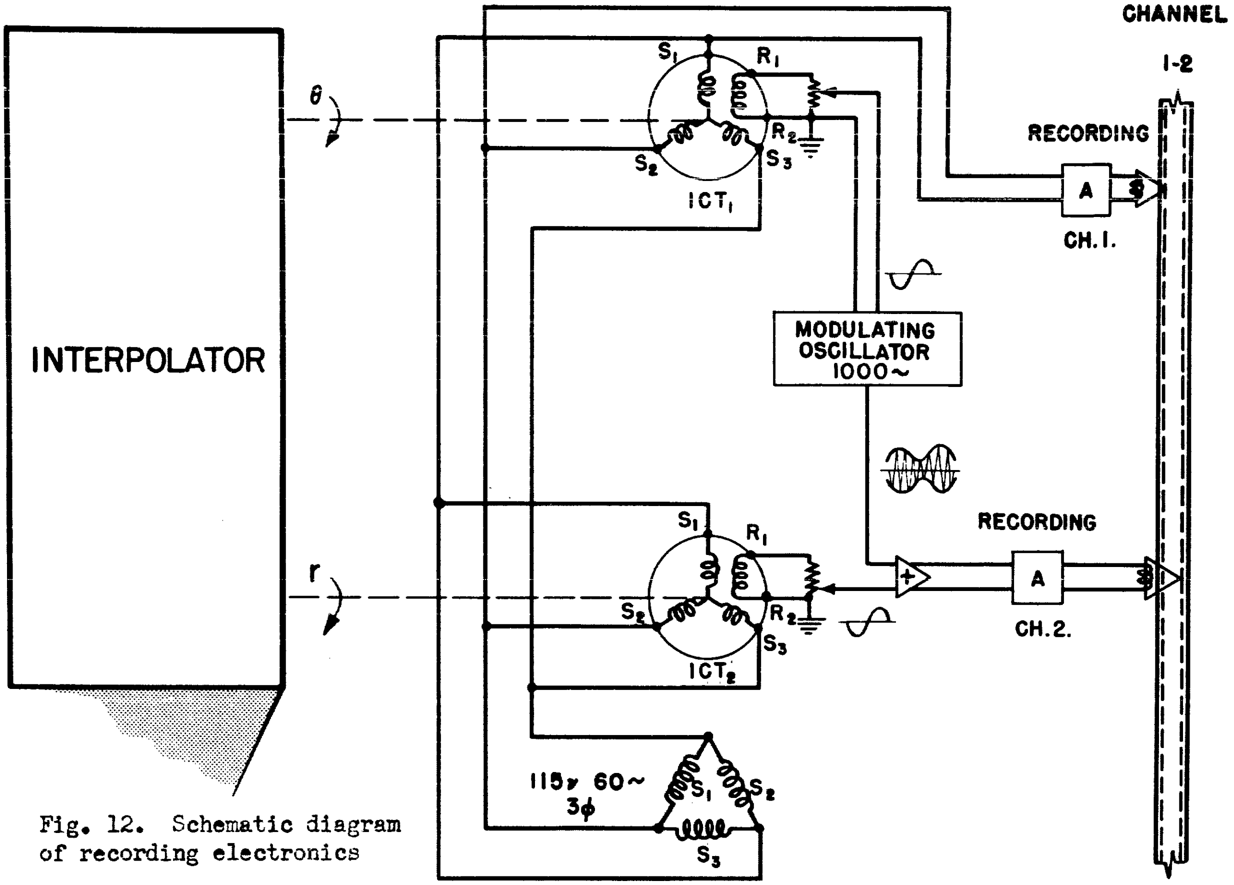

Fig. 12. Schematic diagram of recording electronics

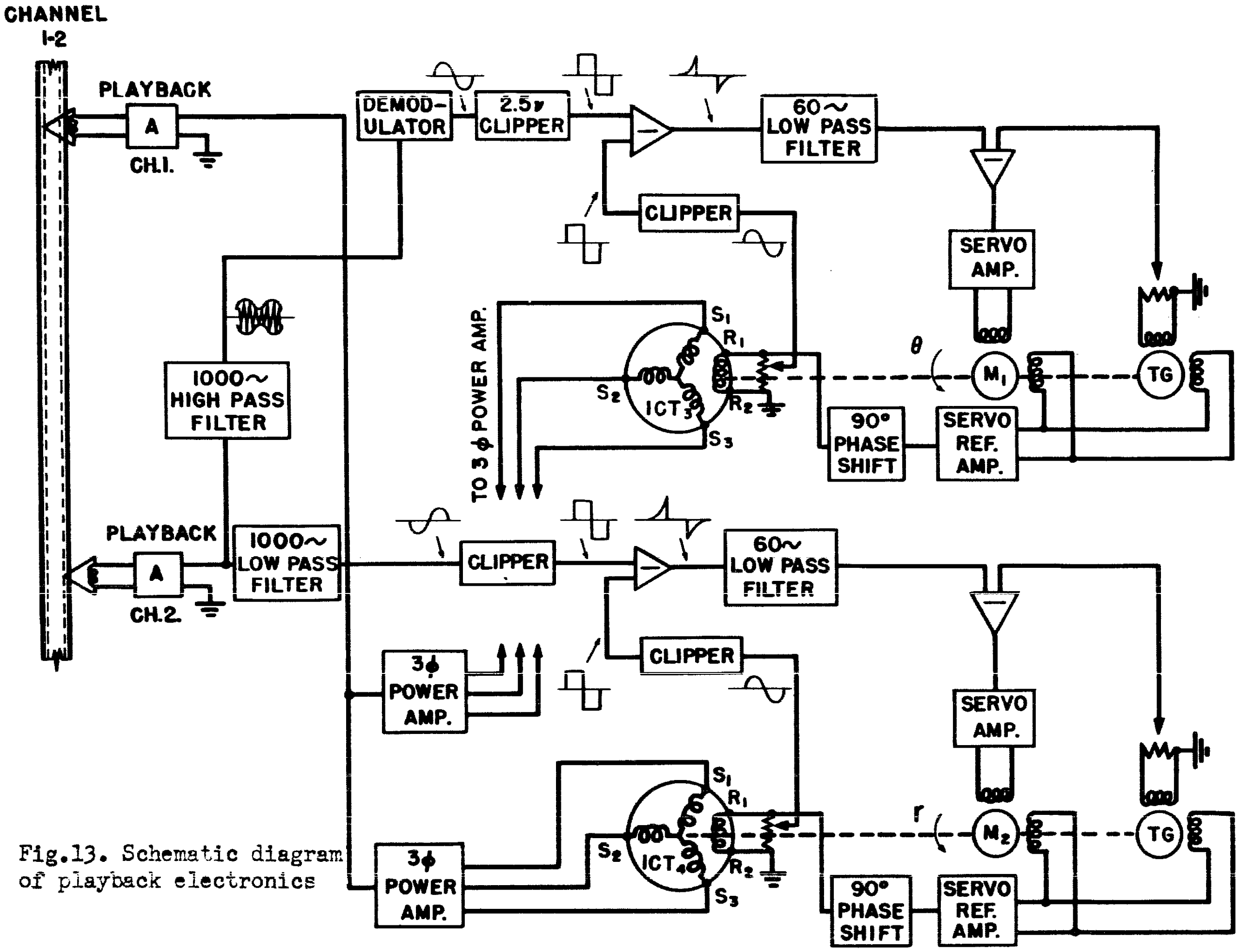

Fig.13. Schematic diagram of playback electronics

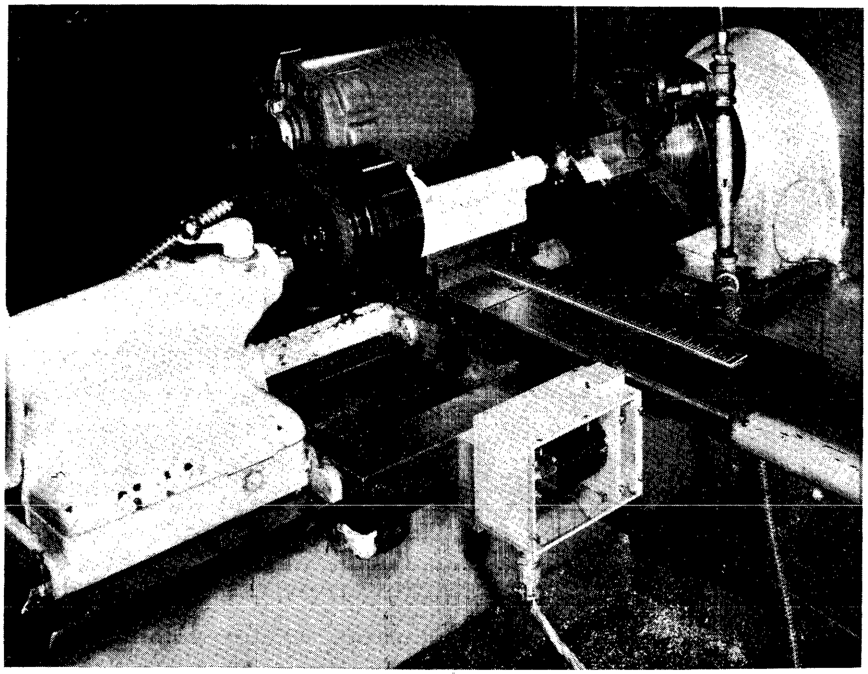

Figure 14. - Adaptation Of A Motor Driven Milling Head To The Engine Lathe.

Figure 15. - The Machine Tool and Its Complete Control System. From Left to Right, Rack One Containing Relay Storage, Master Control Station, and Power Servo Electronics; Rack Two Containing Tape Recorder and Associated Electronics; IBM 523 Summary Punch; Spline Interpolator. 12" Monarch Engine Lathe. Power Servos May Be Seen To The Left and To The Rear Of The Lathe.

EXPERIMENTS WITH A DIGITAL COMPUTER IN A SIMPLE CONTROL SYSTEM

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Introduction

The use of digital computers as elements in control systems is rapidly becoming an accepted and effective practice. One important feature of such systems is that information is accepted by most digital computers only intermittently. On each sample of incoming data the computer performs a sequence of operations, and it is effectively unable to accept new data until it has finished operating on the old sample. Thus, such a mixed (digital-analog) system is a sampled-data system.

Pulsing and sampling techniques have been used in systems for some time, and often conventional methods sufficed to analyse these systems. However, when the sampling rate is decreased until it is not many times greater than the significant frequencies of the signal and the system, conventional analysis applicable to continuous-data systems fails to be adequate. Fortunately, some recent contributions (which will be referred to in this report) to the theory of sampled data and digital filters provided some useful analytical tools for the understanding of digital-analog systems. One difficulty with these theories is the lack of experimental evidence they have been subjected to.

The purpose of the investigations here reported upon was a limited experimental exploration of the relevant theories. It is emphasized that the studies conducted were fundamental in nature. No effort was made to represent a practical system configuration or to answer any specific problems that might have arisen in other investigations. The particular system configuration used was chosen because it was relatively simple and well understood as far as continuous-data operation was concerned. It was a convenient vehicle for the experimental verification of analytical results, and it also provided an opportunity to develop suitable laboratory techniques for testing a digital computer as an element of a system.

Experimental Setup

The facilities used to perform these experiments consisted of a developmental model of a general-purpose airborne digital computer and a conventional analog simulation facility. Figure 1 is a photograph of the experimental setup used. It shows, from left to right, a Goodyear electronic analog computer (GEDA), the digital computer and test equipment, a six-channel Midcentury recorder, and the laboratory power supply in the background.

The digital computer used for these experiments was the second laboratory model built for a particular control system being developed. This is a general-purpose binary digital computer with a magnetic drum memory. It is a serial machine operating at a pulse rate of about 160 kilocycles per second and using a word length of 17 binary digits. The input-output equipment[1] of this particular model can handle 9 different inputs and 4 different outputs. A conversion is performed on each revolution of the drum so that the complete input-output cycle, including one drum revolution used for calibration, takes 14 drum revolutions or 0.105 sec. In the experiments described only one input and one output was used, because the computer was a single-channel link. Actually, other inputs were utilized for such purpose as a convenient means for changing parameters of the program and other outputs were used to record certain intermediate quantities.

The analog equipment used was conventional and requires no detailed description. Actually, the equipment shown is part of a larger simulation installation; moreover, only a portion of the analog computer shown in Figure 1 was required for the experiments reported.

The basic system configuration chosen is chosen in Figure 2. The closed-loop transfer function of this system is the quadratic

$$\frac{C(s)}{R(s)} = \frac{1}{1 + s/K + \alpha s^2/K} \quad , \tag{1}$$

which has the resonant angular frequency,

$$\omega_n = \sqrt{\frac{K}{\alpha}} \quad , \tag{2}$$

and the damping ratio,

$$\zeta = \frac{1}{2\sqrt{K\alpha}} \quad . \tag{3}$$

The control loop of Figure 2 is very easy to solve analytically and gave us a continuous check on our work.

The parameters α and K selected will be noted later. The next step in the experiments was the insertion of the digital computer in the system by using the setup indicated in Figure 3. It is certainly clear that the mere insertion of a digital computer into the system will not help the performance. Quantization and other conversion errors at the input and output, as well as the sampling of data through the computer have unpleasant effects by themselves. These are not the reasons for using digital computers in real-time systems. In any particular case there might be several advantages of using digital techniques. The present aim will not be to point out the advantages, or justify the use, of a digital computer. Attention will be focused toward gaining a better understanding of mixed digital-analog systems. The system parameters are so chosen as to show the dynamic limitations and capabilities of a digital computer.

In the first set of experiments the computer performed no operations on the incoming data. The program merely transferred the input information to the output with an artificial delay to simulate computation time, had there been any computation. In the second set of experiments the computer carried out various programs designed to compensate the over-all performance of the mixed system. The analysis and the testing of these systems were conducted in parallel, and very good agreement was obtained between theory and experiment.

Background to System Analysis

In order to lay the groundwork for this investigation a summary is given of the methods used in analysing the system tested.

An investigation of the input-output conversion device of this digital computer indicated that the input conversion was very close to ideal sampling, while the output conversion could be approximated by clamping. Thus a system containing this digital computer may be treated as a sampled-data system by methods established in the literature.[2,3]

The analytical equivalent of the digital computer having no program consists of a sampler at the input, a clamp circuit at the output, and a time delay between input and output. The process of sampling a function is equivalent to the modulation by the function of a series of impulses spaced by the sampling interval T. (In this case T is 14 drum revolutions = 0.105 sec.). The series of impulses can be expressed as $u^*(t) = \sum_{n=0}^{\infty} u_0(t - nT)$. If a function f(t) is sampled, and the sampled function is denoted $f^*(t)$, then

$$f^*(t) = \sum_{n=0}^{\infty} f(t)\, u_0(t - nT) = f(t).\ u^*(t) \qquad (4)$$

Figure 4 shows the analytical "equivalent circuit" of the digital computer. Figure 5 shows the effect of each component of the "equivalent circuit" on a function f(t).

The modulation described by equation (4) cannot be expressed as a transfer function. However, it can be shown that the Laplace transform of (4) is:

$$F^*(s) = \frac{1}{T} \sum_{k=-\infty}^{\infty} F(s + jk\Omega), \qquad (5)$$

where $\Omega = \frac{2\pi}{T}$ = sampling angular frequency. Equation (5) shows that if a sinusoid of angular frequency $\pm\omega_1$ is sampled, the resulting sampled function contains all frequencies $\omega_1 + k\Omega$ (k being all integers). Thus, if a continuous signal has the spectrum shown in Figure 6a, in its sampled form the signal has the spectrum shown in Figure 6b.

From Figure 6 it is evident that if the signal contains any frequencies greater than half the sampling frequency ($\Omega/2$) the complementary frequencies generated by sampling will overlap, and it would be impossible to recover the signal information. This is Shannon's sampling theorem.

If the original signal (Figure 6a) contains no frequencies greater than $\Omega/2$, then this signal could be recovered from the sampled signal by use of an ideal low-pass filter of bandwidth $\Omega/2$. Ideal filtering can be approximated only at the expense of time delays or phase lags so that a compromise must be struck in a closed loop system. The clamping of the digital computer output serves as a low-pass filter and attenuates to some extent the complementary frequencies generated by sampling.

Figure 8 shows that clamping holds each sample (impulse) until the next sample is obtained. The unit impulse response of clamping is a rectangular pulse of duration T, which can be expressed as $u(t) - u(t - T)$ where $u(x)$ is a step function at $x = 0$. Thus the transfer function of clamping (Laplace transform of impulse response) is $\frac{1}{s} - \frac{e^{-sT}}{s}$.

The transfer function of the time delay of γT seconds is merely $e^{-s\gamma T}$, so the digital computer can now be replaced by an impulse modulator and a "box" having the transfer function

$$G_1(s) = \frac{e^{-s\gamma T}(1 - e^{-sT})}{s} \quad . \tag{6}$$

In these experiments a simple analog loop with control function $G_2(s)$ was used (Figure 7a). The digital computer was inserted in the loop as shown in Figure 7b. The equivalent circuit of the latter is shown in Figure 7c. In part (d) $G_1(s)$ and $G_2(s)$ are combined into a single transfer function $G(s)$ and the impulse modulator is transferred to the other side of the subtractor. This is permissible since the order in which the processes of modulation (sampling) and addition are performed may be changed:

$$\begin{aligned} e^*(t) &= e(t)\ u^*(t) = \left[r(t) - c(t)\right]. u^*(t) = \\ &= r(t)\ u^*(t) - c(t)u^*(t) = r^*(t) - c^*(t) \quad . \end{aligned} \tag{7}$$

The system behavior can be defined as the relation of the controlled function $c(t)$ to the reference function $r(t)$. However, it is clear from the diagram 7(d) that $r(t)$ never enters the system, only $r^*(t)$ does. We can relate $c(t)$ to $r^*(t)$ or $c^*(t)$ to $r^*(t)$. Both relations (derived in references 2, 3, and 4) are helpful in the analysis and are as follows:

$$\frac{C^*(s)}{R^*(s)} = \frac{G^*(s)}{1+G^*(s)} \quad , \tag{8}$$

$$\frac{C(s)}{R^*(s)} = \frac{G(s)}{1+G^*(s)} \quad . \tag{9}$$

where $G^*(s)$ is defined in terms $G(s)$ by Equation (5).

Equation (8) represents the transfer function between points "A" and "B" of Figure 7d. It is similar to the conventional expression for a closed loop transfer function, but yields values of the output only at the sampling instants, as $c^*(t)$ is merely a sequence of impulses at the sampling instants. The expression for the continuous output is Equation (9). Whereas Equation (8) is amenable to conventional analysis in terms of the open-loop starred transfer function $G^*(s)$, Equation (9) is not, because the numerator and denominator contain different transfer functions.

If absolute stability is of interest, only the denominator needs investigation, and either expression (8) or (9) can be used. This is not surprising because if $c(t)$ of a physical system diverges so will its samples; therefore, the condition of stability for $c(t)$ and $c^*(t)$ must be identical.

Certain properties of the $G^*(s)$ locus, which follow from the definition (2), are pointed out:

1. If the locus is plotted for frequencies 0 to $\Omega/2$, then the locus for frequencies $\Omega/2$ to Ω is the reflection about the real axis of the 0 to $\Omega/2$ locus.

2. The locus for frequencies Ω to 2Ω, 2Ω to 3Ω, etc. is the same as the locus for frequencies 0 to Ω.

Thus all characteristics of the $G^*(s)$ locus can be determined from the locus for frequencies 0 to $\Omega/2$. An example of a $G^*(s)$ locus and its relation to the corresponding $G(s)$ locus is illustrated in Figure 8.

In the systems tested

$$G(s) = \frac{K e^{-\gamma Ts}(1 - e^{-Ts})}{s^2(\alpha s + 1)} \quad . \tag{10}$$

The corresponding $G^*(s)$ function is defined in Equation (5) as

$$G^*(s) = \frac{1}{T} \sum_{k=-\infty}^{\infty} G(s + jk\Omega) = \frac{1}{T} \left[G(s) + G(s - \Omega) + G(s + \Omega) + \ldots \right] \tag{11}$$

If $G(s)$ has sufficiently low-pass characteristics, only the first term in (11) is important and

$$G^*(s) = \frac{1}{T} G(s) \tag{12}$$

will give a good indication of several factors of system behavior. For the particular values of α (the time constant) and γ (the delay time as a fraction of the sampling interval) used in the experiments the approximation (12) generally sufficed. If this had not been the case, two or three terms in (11) could have been used or the closed-form expression (developed in Reference 4) for $G^*(s)$ employed.

Description of Experiments and Results

As noted before, the analog portion $G_2(s)$ of the system was

$$G_2(s) = \frac{K}{s(\alpha s + 1)} \tag{13}$$

Two sets of the parameters, α and K, were selected. In one case, referred to henceforth as the "narrow-band" system ($K = 4.2$ sec.$^{-1}$, $\alpha = 0.42$ sec.), the closed-loop response with no digital computer had the resonant frequency of 0.5 cps and the damping ratio 0.38. In the other case, the "wide-band" system ($K = 8.9$ sec.$^{-1}$, $\alpha = 0.056$ sec.), the resonant frequency was 2 cps and the damping ratio 0.7.

Since in the digital computer a sampling time of $T = 0.105$ sec. was used, corresponding to a sampling frequency of $f_s = 1/T = 9.52$ cps, the band of the system into which it is inserted should be limited to at most $f_s/2 = 4.76$ cps. This is a theoretical limit and in a practical servo system one wants to stay below this band. For this reason the wide-band system (whose bandwidth is wider than its resonant frequency) become difficult to handle. Note that the absolute band is not the important criterion; rather it is the band relative to the sampling frequency. Conclusions regarding particular systems must be drawn with this in mind.

In what follows a brief description of the experiments will be given. A more detailed discussion is found in Reference 4, while the methods of digital compensation will be dealt with more extensively in another paper.[5]

The various systems tested were compared in several ways. Nyquist plots were used to study stability and open-loop characteristics; logarithmic amplitude and phase plots were studied for closed-loop performance. In all cases both analytical and experimental data were obtained and found in excellent agreement. The step-function responses of the systems were obtained only experimentally.

Narrow-Band System

The Nyquist plots for the narrow-band system are shown in Figure 9. The first curve is the open-loop locus of the all-analog system, $G_2(s)/K\alpha$; the other curves are the open-loop sampled loci of the mixed system, $G^*(s)/K\alpha$, with two different simulated computing delays. All curves are normalized to $K\alpha$. Intersection of the curves with the negative real axis gives the limit $-1/K\alpha$ for stability. The intersections are:

Case	Delay	$-1/K\alpha$	K_{lim}
Analog	0	0	∞
Mixed	3 Drum Revolutions	-.175	13.6
Mixed	13 Drum Revolutions	-.35	6.8

The experiments verified these limits accurately.

If K in each of the above cases were kept at 4.2, for which value the all-analog system has the resonant frequency 0.5 cps and the damping ratio 0.4, the maximum amplitude ratios would be: 1.36 for the analog, 1.95 for the mixed case with three drum revolutions of delay, and 4.0 for the last case. The lags introduced by the delay and the clamping device are mainly responsible for this deterioration. The sampling process itself has an almost negligible influence in this narrow-band system.

It is seen that as the delay increases, so does the maximum amplitude ratio. It is usually desirable to limit this ratio to a value between 1.0 and 1.6, depending on the particular system. One way of accomplishing this is by reducing the system gain K, but this makes the system bandwidth even narrower. Another way of getting better response is by compensation.

The use of linear analog circuits in the forward or feedback loop for system compensation is well known. The aim in the present study was to do the compensation by a program in the digital computer. In the narrow-band case with three drum revolution delay this was quite simple to do. Actually, little effort was spent on this problem, but a simple prediction type compensation was tried. It can be shown that a parabolic approximation through three points of a function i(t) produces a predicted output o(t), which would be equal to i(t + T) ideally. The formula of this prediction can be written in terms of a difference equation,

$$o^*(t) = 3i^*(t) - 3i^*(t - T) + i^*(t - 2T), \tag{14}$$

which can be readily programmed on a digital computer. The essence of analysis is the representation of such difference equation in terms of a transfer function.[6,7] However, the analysis will not be pursued here, only the test results will be given.

Insertion of the above program into the computer immediately improved the system performance. However, the compensating effect of this program was further adjusted ("optimized") experimentally by varying the constants 3 and -3, while keeping their magnitudes equal to each other. The observed system step response was used as a qualitative criterion of improved performance, resulting in the program

$$o^*(t) = 2.5i^*(t) - 2.5i^*(t - T) + i^*(t-2T). \tag{15}$$

The effect of this compensation on the Nyquist plot is shown in Figure 10. It is not surprising to see that the effect is similar to that of an analog lead network.

The step response curves corroborated tha above frequency analysis. Actually, as was later realized, a factor of two slipped into the program, and as a consequence the program not only compensated for having inserted the digital computer but did so inspite of an increase in K by a factor of two. Figure 11 compares the step responses of the all-analog system with K = 4.2 (dotted curve), of the mixed system without compensation and with K = 4.2 (dashed curve), and of the mixed system with prediction compensation and K = 8.4 (solid curve).

The maximum gain constant for stability, K_{lim}, was increased by compensation from 13.6 to 28 according to the analysis. Experimentally K_{lim} = 33 was obtained, and the minor discrepancy between theory and test is attributed to certain approximations employed in the analysis.

Wide-Band System

The Nyquist plots for this case are shown in Figure 12. One curve is the open-loop locus of the all-analog system, $G_2(s)/K\alpha$ (where $\alpha = 0.056$); the other curve is the open-loop sampled locus of the mixed system, $G^*(s)/K\alpha$, with a delay of 13 drum revolutions (or $\gamma = 13/14 \cong 1$). The milder case of 3 drum revolution delay was not considered for the wide-band case. Since the latter locus crosses the real axis at $-1/K\alpha = -2.2$, the maximum permissible K is 8.2 for stability. Thus, at the value K = 8.9, for which the all-analog system had a damping ratio of 0.7, this mixed system is already unstable.

Compensation for this system must not only restore stability but must also recapture a reasonable damping ratio. It is clear that a compensating program was much more difficult to design in this case. After considerable study using frequency analysis, a program configuration was found using six (rather than three, as in the narrow-band case) coefficients. The program with an initial set of selected coefficients immediately improved the system response. However, it was decided to further improve the system by experimental adjustment of these parameters. When working with as many as six parameters it was essential to develop a suitable step-by-step procedure of adjustments.

The transfer function of the program made it possible to change the computation process in such a manner that the poles and residues of the program appeared as numbers in the computer. Changing any of these parameters, therefore, had a predictable effect on the program and, thus, the system. The experimentally adjusted program changed the system characteristics as shown in Figure 13.

The stability limits for the various conditions are summarized in the table below.

System	Delay	Compensation	K_{lim}	
			Theoretical	Experimental
Analog	None	No	∞	----
Mixed	13 Drum Revolutions	No	8.2	8.2
Mixed	13 Drum Revolutions	Yes	27.4	26.8

The agreement between analysis and test results is seen to be excellent.

The closed-loop step responses are shown in Figure 14: the dotted curve is for the analog system with $K = 8.9$; the dashed curve is for the uncompensated mixed system with 13 drum revolutions of delay and $K = 8.2$ (the stability limit); the solid curve is for the compensated mixed system with $K = 8.2$. Although the original performance has not been restored, compensation has stabilized the system and produced a reasonable response. Furthermore, the computation for compensation took only a portion of the sampling time of 0.105 seconds, leaving time for other computations, which would be the justification of using the digital computer in the first place.

Conclusion

As a basic investigation this series of experiments can be considered successful. The test results agreed with theoretical results to a high degree of accuracy. This seems to be the first reported systematic investigation with a digital computer of theories concerning sampled-data closed-loop systems and their compensation by digital computer programs in situations where the dynamic limitations of the system are approached. Satisfactory methods were developed to handle the interconnection between digital and analog computing elements, to synchronize the computer program with the input-output sampling, and to vary appropriate parameters in the program. The dynamic limitations of a digital computer were explored as far as a particular system configuration is concerned. Finally, it was demonstrated that programs can be designed to achieve particular effects in the compensation of closed-loop system performance.

References

1. M. L. MacKnight and P. A. Adamson, "Multichannel Analog Input-Output Conversion System for Digital Computer," Convention Record of the I.R.E. 1953 National Convention, Part 7, Electronic Computers.

2. W. K. Linvill, "Sampled-Data Control Systems Studied through Comparison of Sampling with Amplitude Modulation," Transactions of the A.I.E.E., Volume 70, Part II, pp. 1779-1788; 1951.

3. J. R. Ragazzini and L. A. Zadeh, "The Analysis of Sampled-Data Systems," Transactions of the A.I.E.E., Volume 71, Part II, pp. 225-234; 1952.

4. T. J. Burns, J. D. Cloud and J. M. Salzer, "Experiments with a Digital Computer in a Simulated System," Technical Memorandum, TM-338, Hughes Research and Development Laboratories, Culver City, California; 1954.

5. John M. Salzer, "System Compensation with a Digital Computer," paper to be presented at the I. R. E. National Convention, Radio Telemetry and Remote Control; March, 1954.

6. William K. Linvill and John M. Salzer, "Analysis of Control Systems Involving Digital Computers," Proceedings of the I.R.E., Volume 41, No. 7; July, 1953.

7. John M. Salzer, "Frequency Analysis of Digital Computers Operating in Real Time," Proceedings of the I.R.E., Volume 42, No. 2; February, 1954.

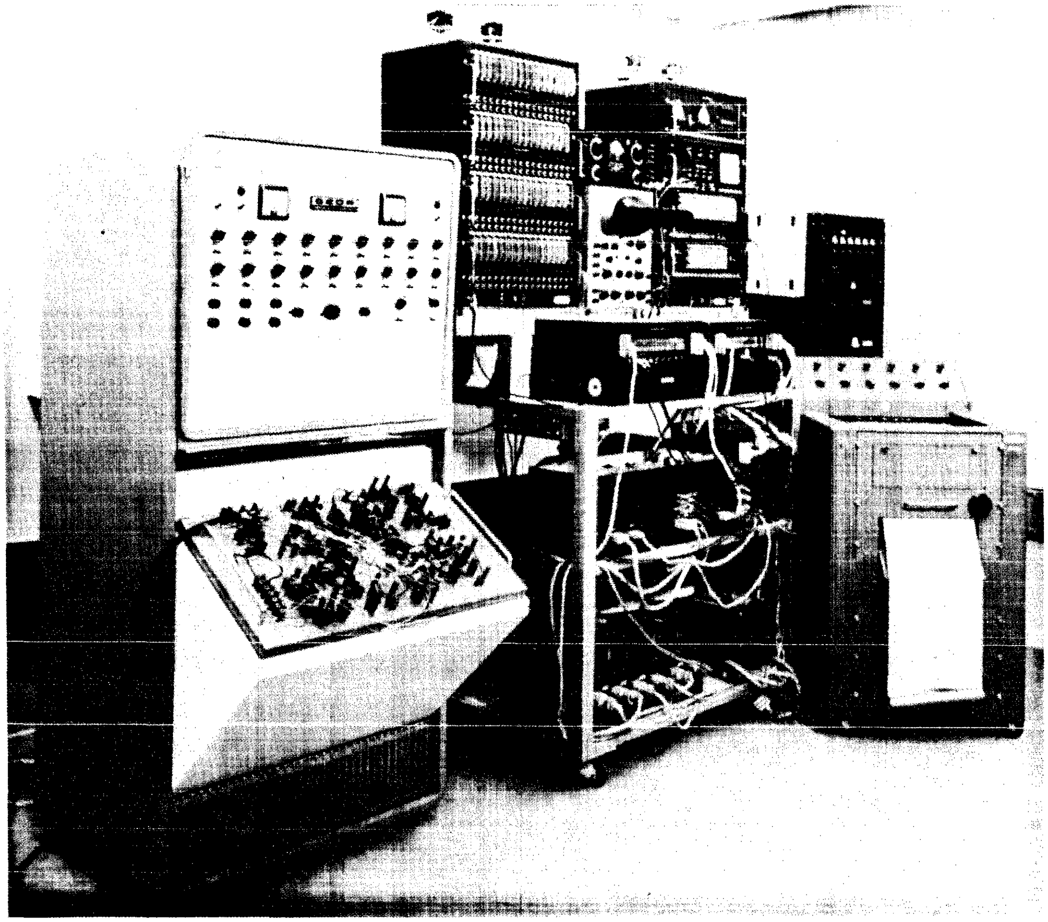


Figure 1 Photograph of Experimental Setup

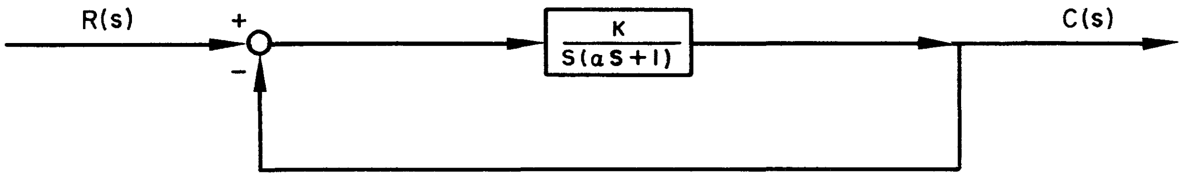


Figure 2 Analog System

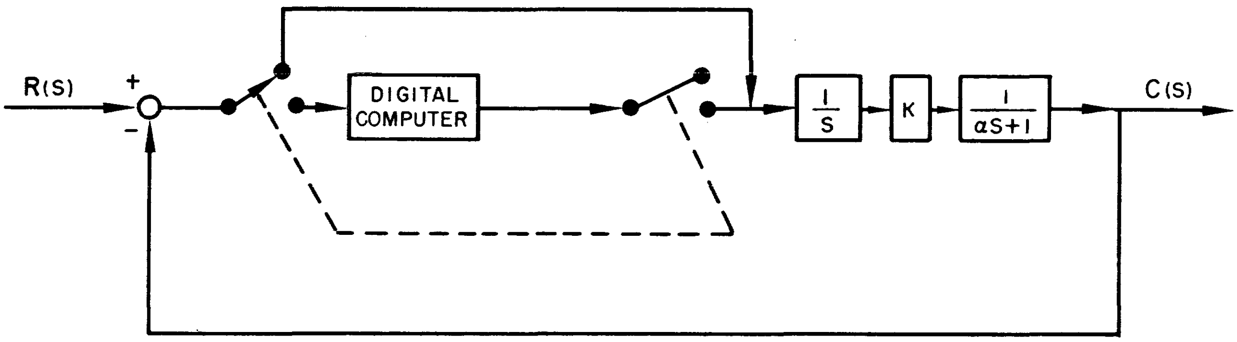


Figure 3 Simulator Setup for Analog and Mixed System Tests

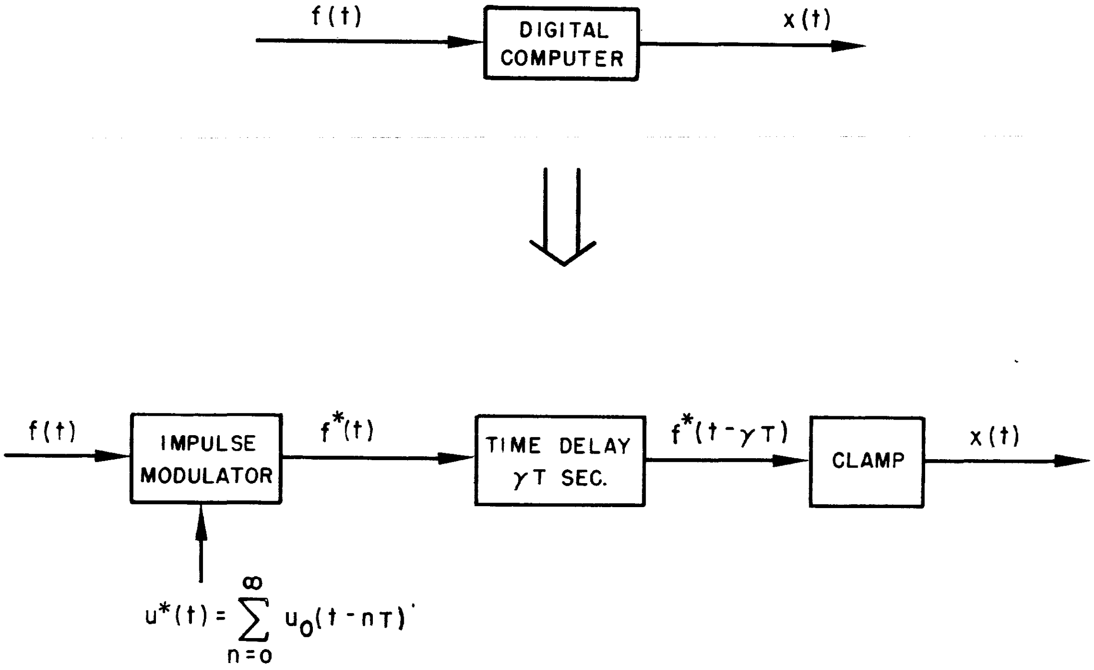


Figure 4 Equivalent Circuit of Digital Computer

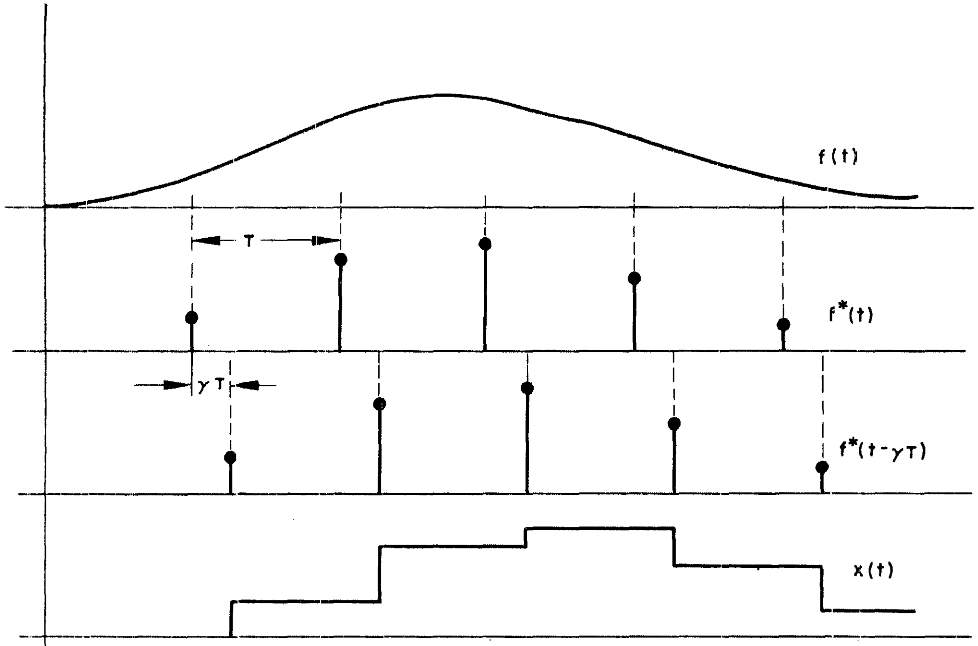
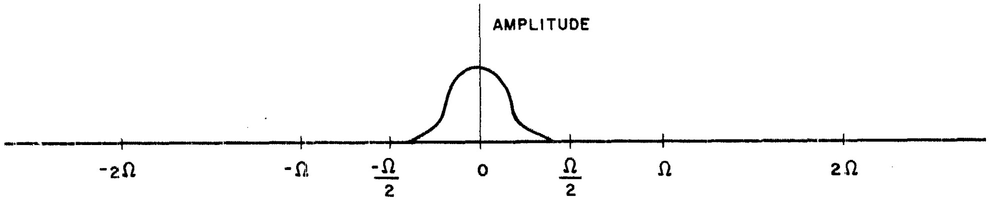
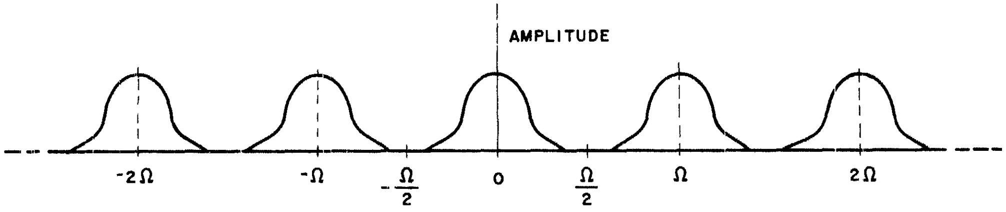


Figure 5 Effect of Digital Computer on a Continuous Function

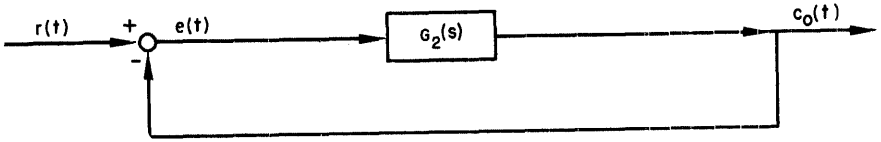


(A) SPECTRUM OF SIGNAL BEFORE SAMPLING

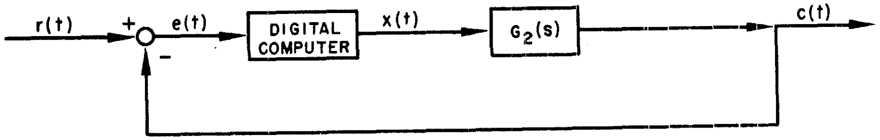


(B) SPECTRUM OF SIGNAL AFTER SAMPLING

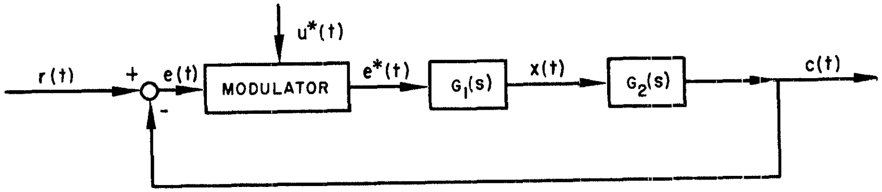
Figure 6 Effect of Sampling on the Amplitude Spectrum of Signal



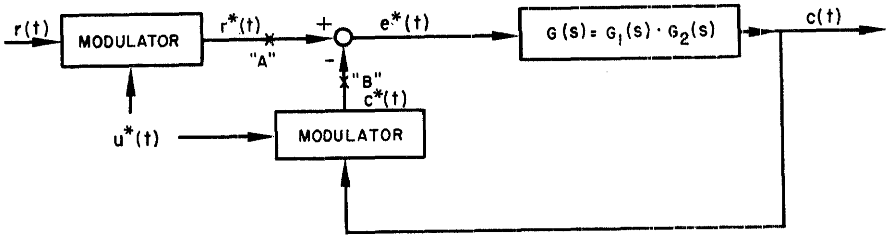
(A) SIMPLE ANALOG LOOP



(B) INSERTION OF DIGITAL COMPUTER INTO THE LOOP



(C) EQUIVALENT REPRESENTATION OF SYSTEM IN (B)



(D) ANOTHER EQUIVALENT REPRESENTATION OF SYSTEM IN (B)

Figure 7 Representation of System Studied

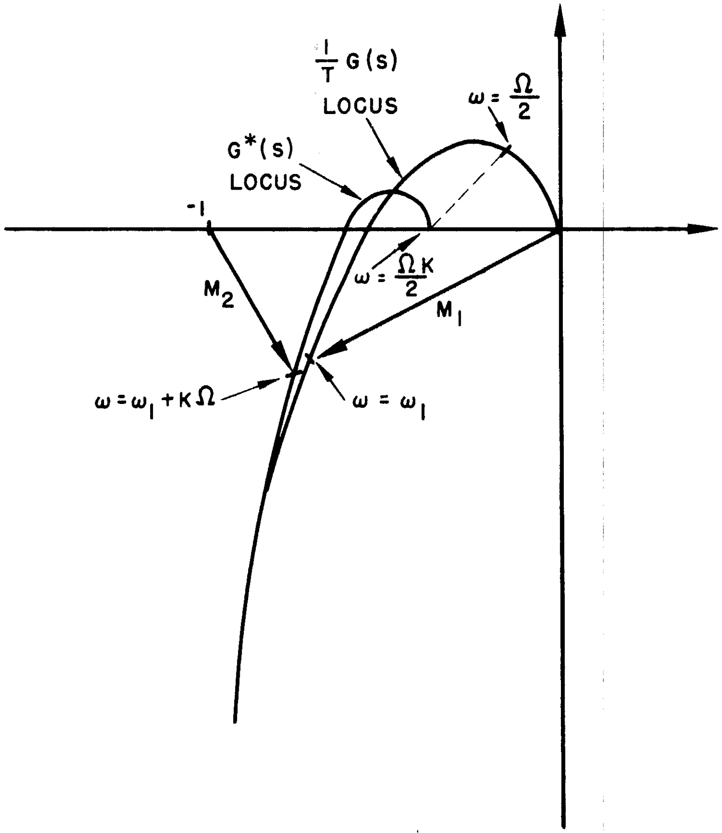
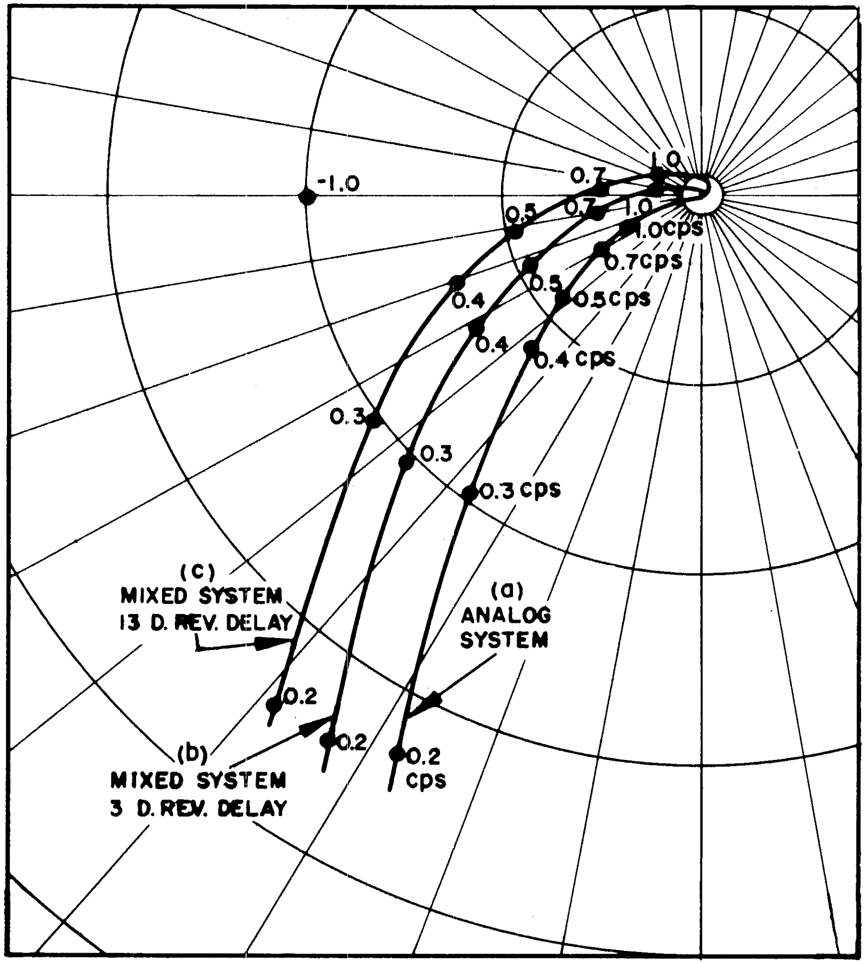


Figure 8 Relation of $G^*(s)$ Locus to $G(s)$ Locus

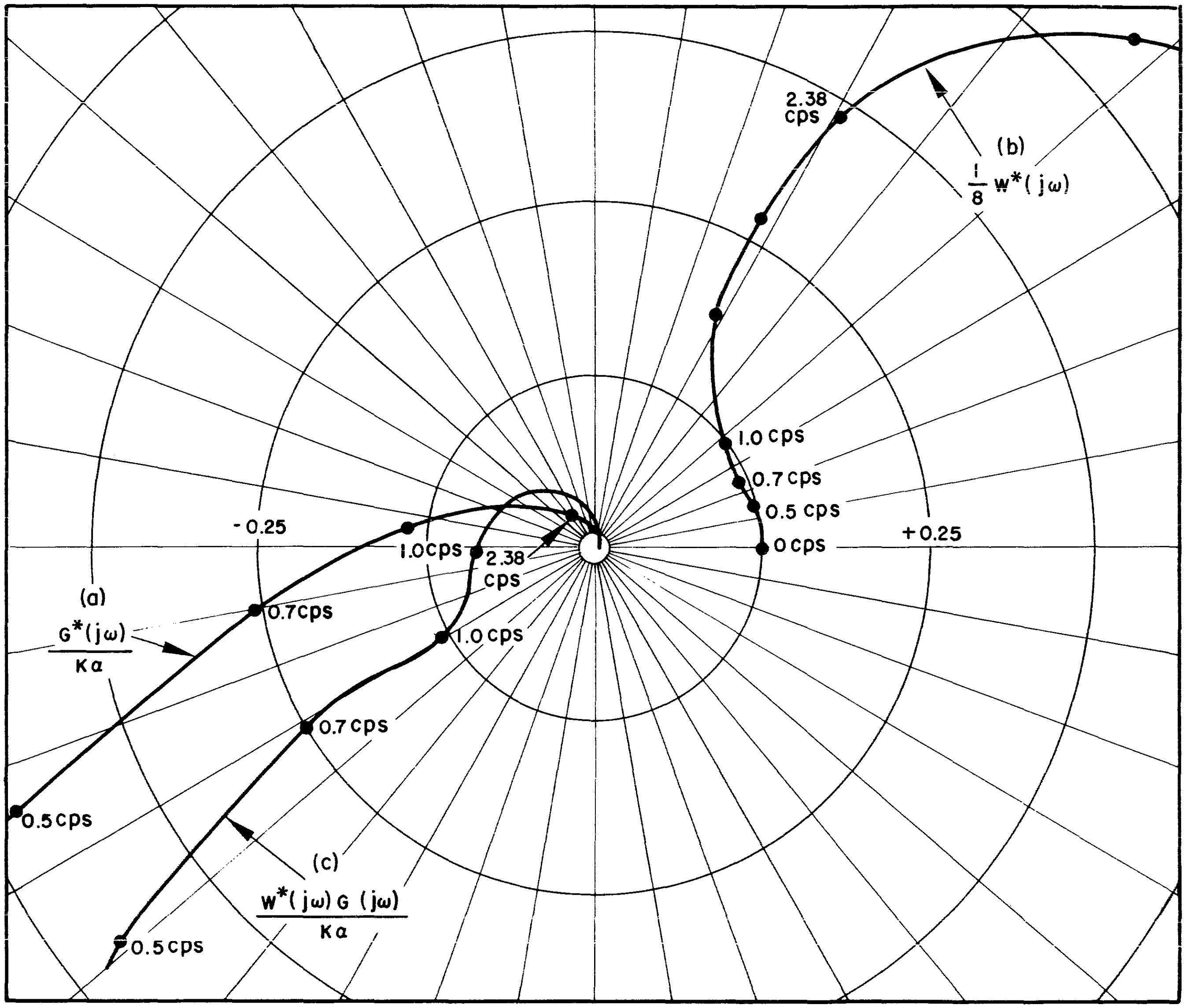


(a) $G(s)/K\alpha = G_2(s)/K\alpha = \frac{1/0.42}{s(0.42s+1)}$

(b) $G^*(s)/K\alpha \cong G(s)/K\alpha = e^{-\gamma Ts} \cdot \frac{1-e^{-Ts}}{s} \cdot \frac{1/0.42}{s(0.42s+1)}$; $\gamma = 3/14$, $T = 1.05$ SEC.

(c) $G^*(s)/K\alpha$ SAME AS (b) BUT $\gamma = 13/14 \cong 1$.

Figure 9 Nyquist Plots for Narrow-Band Case Without Compensation



(a) $G^*(s)/K\alpha \cong G(s)/K\alpha = e^{-3Ts/14} \cdot \frac{1-e^{-Ts}}{s} \cdot \frac{1/0.42}{s(0.42s+1)}$; $T = 0.105$ SEC.

(b) $\frac{1}{8}W^*(s) = \frac{1}{8}\left[2.5 - 2.5e^{-Ts} + e^{-2Ts}\right]$

(c) $W^*(s) \cdot G^*(s)/K\alpha \cong W^*(s)G(s)/K\alpha$

Figure 10 Nyquist Plots for Narrow-Band Case With Compensation

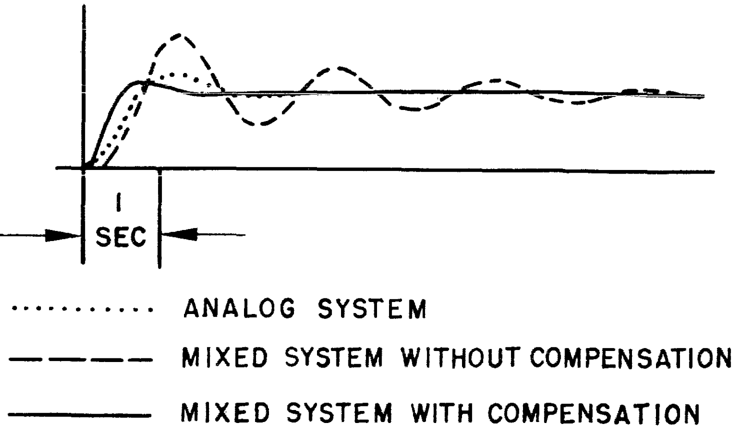
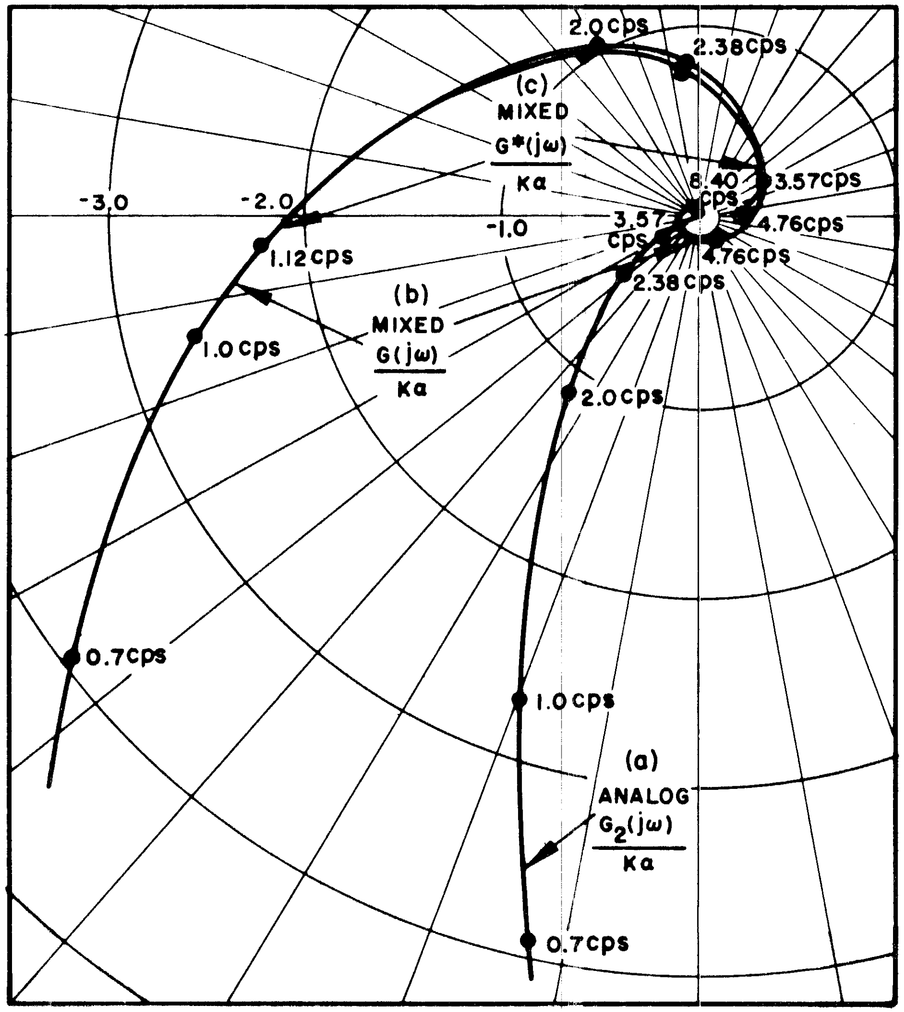


Fig. 11.
Step response of
narrow-band system

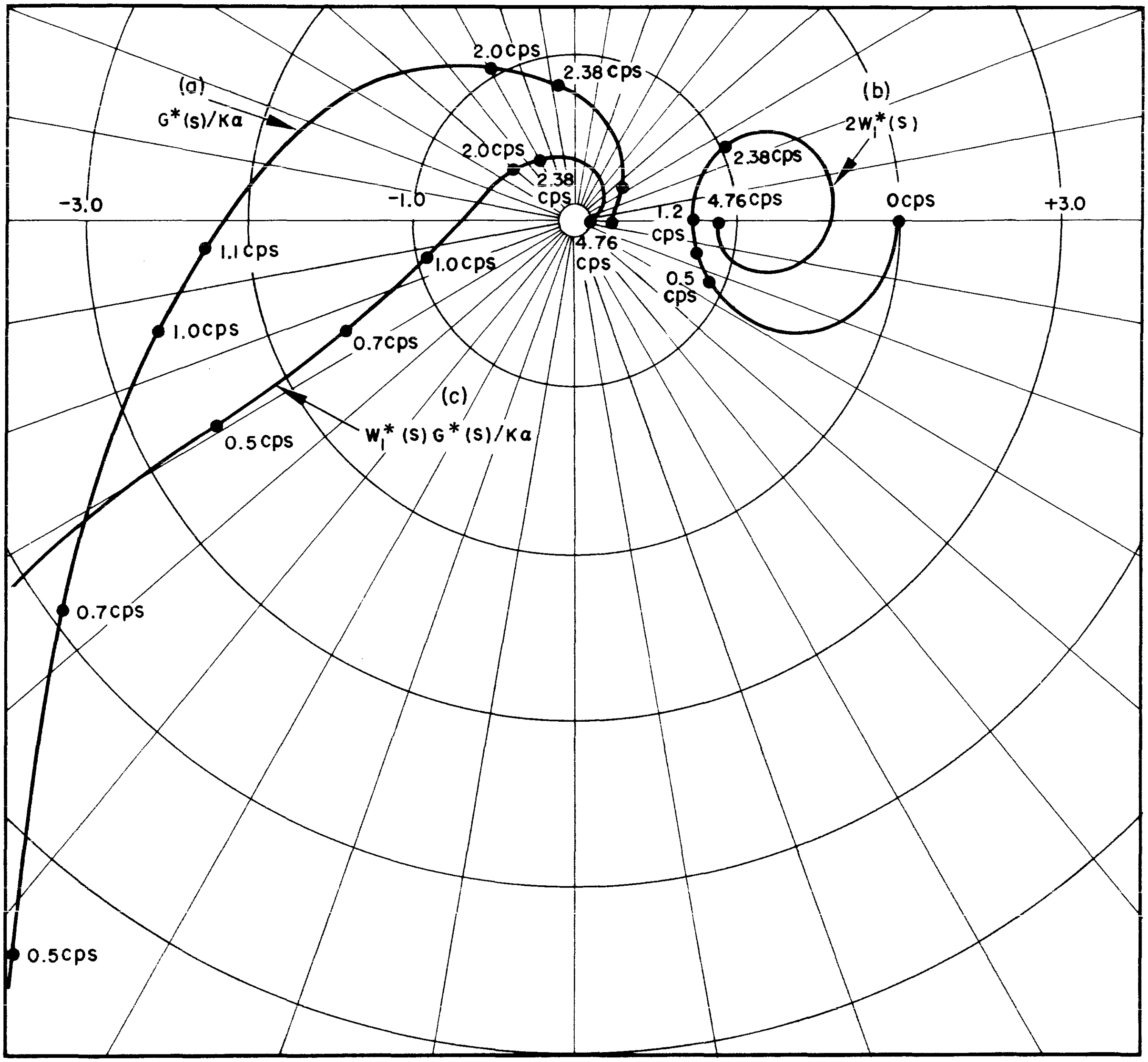


(a) $G(s)/K\alpha = G_2(s)/K\alpha = \dfrac{1/0.056}{s(0.056s+1)}$

(b) $G(s)/K\alpha \cong e^{-Ts} \cdot \dfrac{1-e^{-Ts}}{s} \cdot \dfrac{1/0.056}{s(0.056s+1)}$; $T = 0.105$ SEC.

(c) $G^*(s)/K\alpha \cong e^{-Ts} \cdot \left[3.67 + \dfrac{1.88}{1-e^{-Ts}} - \dfrac{5.55}{1-0.153e^{-Ts}}\right]$; $T = 0.105$ SEC.

Figure 12 Nyquist Plots for Wide-Band Case Without Compensation



(a) $G^*(s)/K\alpha \cong e^{-Ts}\left[3.67+\frac{1.88}{1-e^{-Ts}}-\frac{5.55}{1-0.153e^{-Ts}}\right]$; T = 0.105 SEC

(b) $2W_1^*(s)=2\left[\frac{0.075}{1-0.895e^{-Ts}}+\frac{0.452(1+0.33e^{-Ts})}{1+0.7e^{-Ts}+0.4e^{-2Ts}}\right]$; T = 0.105 SEC

(c) $W_1^*(s)\,G^*(s)/K\alpha$

Figure 13 Nyquist Plots for Wide-Band Case With Compensation

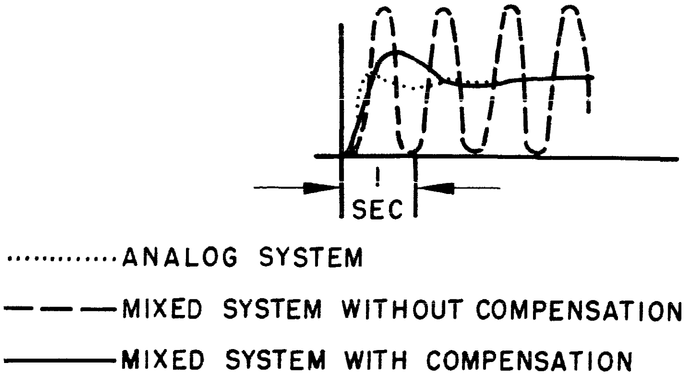


Figure 14 Step Response of Wide-Band System

THE AUTOMATIC HANDLING OF BUSINESS DATA

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Introduction

Probably the most impelling factor behind the desire of business to mechanize the handling of the data with which it is concerned is the astounding growth in the volume of these data in the last two decades. The productive capacity of every factory worker has increased greatly in this period, but it is doubtful whether or not that of the office worker has changed greatly. Many businesses, therefore, are now faced with office costs, the control of which spells the difference between profit and loss.

Obligatory reports to regulatory bodies have grown in number and the data demanded by these agencies is often so completely different from that needed to run a commercial enterprise that many businesses have essentially to maintain duplicate sets of records. The calculation of payroll has developed from a simple multiplication of rate times hours to an exceedingly complex one involving bonuses, overtime hours, and quite often ten or more deductions, many of which bear no relation to the pay. Further, as a business increases in size and geographical scope the reports which management must have become numerous.

Operations Where Mechanization Yields Greatest Returns

Where large volumes of business data are handled through routine operations with relatively few exceptional cases there is always a good possibility for the economic use of electronic equipment. While the mechanization of many existing operations of this sort can be handled by present day data processing equipment with great savings, still more economies may be expected when business operations are thought out anew from the machine point of view. This attack on the problem of mechanization results in what is coming to be known as the "consolidated functions approach."

Because the maximum rate at which human beings can process business data is relatively low, multiple files are often needed to allow access by a large numbers of clerks. The use of high speed electronic equipment permits hitherto separate files to be consolidated and, because the variable data or transactions can be manipulated entirely within the machine through several formerly disjointed operations, many transcriptions from paper to keyboard are completely done away with. A study of businesses dealing directly with the public soon brings to light the fact that a very large percentage of their total clerical effort is spent in checking processes. Many of the checks are designed to catch errors made during the very transcriptions which mechanization does much to eliminate.

The descriptive or index portions of business data often contain much redundancy which might be used to advantage by electronic computers with internal checking circuits, but unfortunately this redundancy is usually better adapted to the way in which human beings rather than machines catch errors and inconsistencies in the data. It is to be hoped that mathematicians and programmers will eventually make their voices heard in those circles where the category codes of insurance coverage and merchandise code numbers are generated.

Perhaps the least often mentioned yet the most far reaching gain to business will be the use of data handling equipment in analyzing sales trends and in helping to lay business strategy. Anyone who has read that fascinating volume entitled "Strategy in Business, Poker, and War" by John McDonald will feel that, once the specter of office costs eating up profit has been laid to rest by the adoption of machine methods, management will be able to conduct the business on the basis of up-to-the-minute facts, provided by these same machines. As more and more businesses follow the trend, operations based on out-of-date information about a business will become more and more costly in a competitive sense.

Outstanding Technical Problems

When the density of posting of items to a voluminous file is low or when a few items have to be interfiled in such a file a serious problem is posed to the computer designer today. If punched card techniques are compared with hand methods, machines fail to compete economically when fewer than ten percent of the records in the file is to be affected during a single pass. Electronic computers can hold their own against manual pulling from the file for much lower densities of posting, but they too fail on many very interesting problems. Until a random access memory of vast capacity with much lower latency than magnetic tapes provide is developed, clever indexing schemes and ingeniously devised operating schedules seem to be the only solutions possible in many cases of this nature. The problem of handling the records of Treasury bonds is a case in point.

Computer engineers who have received their training on machines for handling scientific problems are finding that in commercial applications the matter of making the input data available to the computer holds many more stumbling blocks than the design of the computer proper. The shibboleth for any input scheme is whether or not it puts the essential data into machine language at the earliest possible juncture in the operating procedure. Furthermore, no repetitious entries should be permitted except for checking purposes. Great gains can be made even with present day mechanical and punched card office equipment by adopting the so-called "common language" link between these machines. It is no secret that several office machine companies are working with punched paper tape toward this end for applications too small for large scale electronic machines. It should be noted, however, that devices to transcribe the basic input data into machine language often have to pass most stringent economic tests. The "mark-sense" card used to record public utility meter readings succeeds where printing devices attached to the meter are bound to fail, simply because the cost is only about one dollar a year to read the meter by eye.

It must be conceded that much of the demand for high speed printing with which we are faced is illusory. Many of the listings and output printings which the potential users of data processing equipment call for are not logically necessary. However, because auditors believe little magnetized spots on tape much as they would spots before their eyes, perhaps with justification for the time being, these lists must be produced. It is to be hoped that the demand will lessen. Nevertheless, every insurance policy holder wants a premium notice so we must concede a real need here, the answering of which raises real problems. One of these is that the cost of the printer system is too high. There is too much electronic gear associated with the printing head. A costlier head that would lower the overall expense of the system is the boon being sought, particularly by the makers and users of machines priced at under a quarter of a million dollars.

Types of Applications

In view of these difficulties, both administrative and technical, what are the sort of business applications to which data handling computers are being put? In large industrial companies it is often possible to find a single operation, such as payroll, the routine of which is well understood because it is now being handled by punched card equipment. Such an operation can be put lock, stock, and barrel onto a computer. The file problem is not acute, the arithmetic calculations are relatively simple, and "on-line" operation is not required. This application has, therefore, offered an excellent opening wedge for computers in several companies.

The development of actuarial data in the process of writing and servicing insurance policies is important to all insurance companies. However, the work is not as sensitive from the point of view of the insured as is the accountancy. Further, the actuarial tasks are usually handled centrally in contradistinction to jobs involving the insured more directly. In addition, the similarity of the actuarial studies to scientific calculations makes this field a good point at which some companies are choosing to initiate their automatic data handling programs. An additional and immediate bonus to be gained from such piecemeal applications is the operational experience which can be come by in no other way.

The matter of keeping up-to-date information on inventory and psuedo-inventory problems is of vital concern to those companies whose businesses involve mainly merchandise and not paper work like insurance companies. As a consequence, these companies have tended to lean toward small special purpose machines designed for inventory work rather than to large general purpose machines for their first installations.

Actual Installations for Business Work

If we confine ourselves to computer installations used in the processing of normal business data, we find the list headed by a number of UNIVAC machines: the Franklin Life Insurance Co. and the Metropolitan Life Insurance Co. are both reported to be about to use their machines first for actuarial calculations; and the General Electric Company in Louisville is to use its computer for payroll and cost accounting. In addition, some of the aircraft companies which have IBM 701 installations, primarily for aerodynamic computations, are undoubtedly finding them of service in cost accounting work.

In what is essentially the inventory field there are now operating some very interesting machines. The "Reservisor" of American Airlines, known now to most people, while not a true inventory machine, is doing yeoman service for that company in helping to fill their airplanes. Another most ingenious magnetic drum machine is the one which now stores bid and asked figures for stocks traded on the Toronto Stock Exchange. The drum may be remotely addressed for quick reference to any of these data.

There are three special purpose electronic drum computers at present being used in the retail merchandizing field for unit inventory control. The J. L. Hudson Co. of Detroit and B. Altman's of New York are using Magnafile machines made by W. S. MacDonald Co. for keeping track of their furniture inventory. In Chicago the John Plain Company is using a larger machine called the Speed Tally or Distributon manufactured by Engineering Research Associates, for inventory purposes in a mail order business.

The Position of Unit Inventory Control in Department Store Accounting

Because the following four papers will deal with the details of maintaining unit inventory control for a department store with an electronic system, a few remarks about the relationship of the inventory to the rest of the accounting system might not be out of place.

The flow diagram of Figure No. 1 shows the movement of the main bodies of information in the over-all system. Consider first the information which must go from the point of sale to the rest of the system. To the customer billing section must go an identification of the customer and the amount of the sale; to the general store accounting must go a record of cash intake; and to the inventory section must go a full description of the item or items sold.

The customer billing section sends statements to the charge customers and receives payments in response to these. The functioning of this part of the system is more or less automatically controlled by the two inputs. This, however, is not true of the inventory section. From it originate orders to vendors and in response invoices are received, but the orders are actually instigated by the buyers following an examination of the condition of the inventory. The two paired inputs and outputs to customer billing and to inventory are in turn monitored as accounts receivable and accounts payable for the store's general accounting section.

There is a very important link from customer billing to the point of sale which has not yet been considered; that is the credit authorization which follows an examination of the state of the customer's credit inventory, so to speak. Finally, a very vital piece of information, usually totally missing, which should be fed to inventory from the point of sale, is that about any unfulfilled demands by the customer for goods.

Generally it may be said that unit inventory control is maintained on the more valuable items of inventory. If, however, the basic approach is to minimize the total dollar inventory while at the same time staying in business and achieving a reasonable degree of customer satisfaction (synonomous in the long run), unit inventory control should be applied in a more flexible fashion. It is felt that a recording of unfulfilled customer demand is the missing link in inventory control. If an electronic inventory control system can make this link a practical possibility such a single achievement may well be fully as important as automatic inventory control in reducing the cost of inventory in department stores.

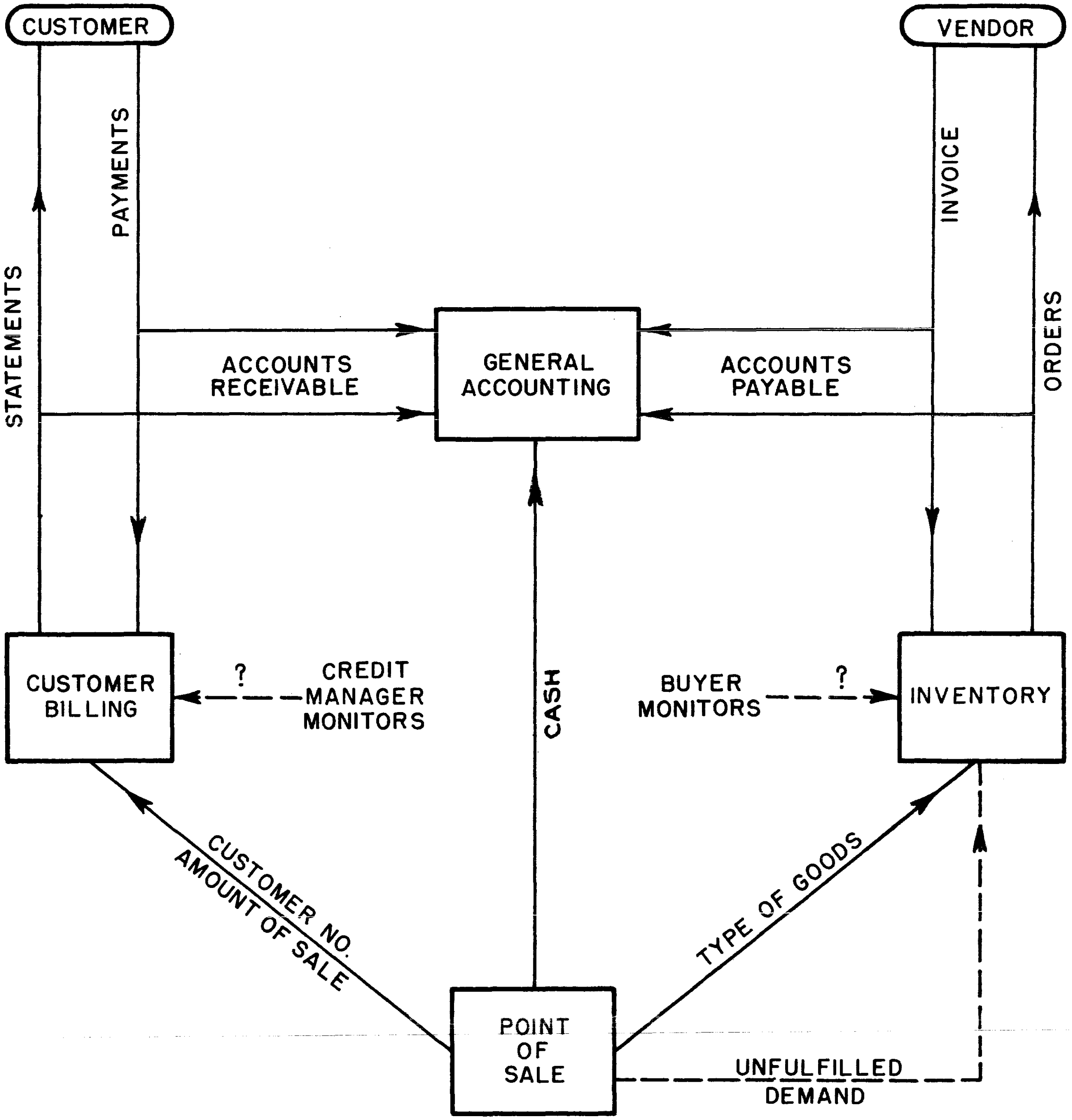


Fig. 1. The place of inventory in department store accounting

INTRODUCTION

BUSINESS DATA PROCESSING: A Case Study

Richard G. Canning

The advent of electronic data processing in business and industry will require the joint efforts of business management and equipment manufacturers. The following case study, conducted specifically for this Conference, is illustrative of a possible approach to one important business problem--unit inventory control in the ready-to-wear departments of a large department store. The participants in the study include representatives from business management and equipment manufacturing, as well as an important government computing agency.

Of the many data processing functions to be found in any large department store, only the one function of unit control was selected for this case study. In the type of approach represented in this session, all of the functions, such as credit billing, sales slip auditing, etc., are normally considered and merged into one processing system. A detailed analysis of so many functions could not be covered in one session, but the method of approach would be the same for each function.

The approach represented in this study might be termed "central records" or "delayed central processing." It is based on the idea of recording the data on all of the transactions within the store, at the point of the transaction and with as little manual effort as possible. The data is recorded on some medium that can be processed by the central machine; the use of magnetic tape for this purpose appears to have a number of attractive features, for example. These transaction tapes are then collected at periodic intervals, and brought to the central machine for processing--posting to the master files, detection of "exceptions" for management action, summarizing for management reports, and so on.

For an efficient operation, the "raw" transaction tapes are not in suitable condition for processing when received at the central machine. Rather, they must be sorted into the same sequence as the master file tapes to which they are to be posted. If several different master file tapes are affected by the transactions, then a separate sorting operation will be needed prior to the processing of each master tape. The type of sorting referred to here is completely electronic, and does not require physical items to be sorted, such as punched cards. One exception to this principle might apply to the central machines using primarily a punched card input, rather than magnetic tape input; in this case, the sorting may logically be done on punched card sorters, before the transactions are read into the electronic machine.

A major problem involved in designing any data processing system is the selection of methods of input for the various functions to be handled by the system. In the present case study, for example, the systems engineer has looked beyond the requirements of the one function being considered, and has selected a novel input device which not only applies to the unit control function but also has a fine potential for other important functions such as sales slip auditing, figuring commissions, etc. It is by the handling of these varied functions that the economies of the central records system become apparent.

Another point of view, not represented in this case study, might be called the "specialized machine" approach. Under this system, a separate (usually a small) machine is installed in each department, and is normally designed for handling one data processing function. This approach is especially appealing to the business management which is attempting to solve one major "crisis" problem through the use of electronics. A majority of the first few types of business data processing equipments already on the market have followed this philosophy.

Another approach, also not represented in this session, lies somewhere between the central records and specialized machine approaches. This method might be termed "real time processing." Where a certain type of transaction is occuring at a high rate, and the firm cannot tolerate a delay in the processing of these transactions, a central specialized machine is used to process this one type of transaction. "Exception" items, summaries for management reports, etc. are then brought out from the specialized machine, for the delayed type of processing illustrated in this session.

In the following case study, the problem of unit control is presented by the Controller of a large Los Angeles department store, which has three suburban branches. Next, the systems engineer shows the problem in flow chart form, and indicates the equipment requirements and selections. The operating characteristics of an electronic data processing machine, suitable for application to this problem, are presented. Finally, the systems operation will be discussed from the programmer's point of view, and the importance of machine characteristics as constraints upon the programmer are discussed.

Since the session was designed primarily for its educational value, different points of view among the participants were not discouraged, but rather were encouraged. Two different formats of the daily selling report are presented, for example.

Although Dr. Huskey was most active in the case study, an unforeseen press of other duties prevented the completion of the final draft of his paper in time for publication. However, a brief summary of the paper is presented from transcription; any errors or omissions are the responsibility of the Technical Program Committee.

The Technical Program Committee of the 1954 Western Computer Conference is most appreciative of the fine cooperative efforts made by all participants in this planned session, and the generosity of their organizations in allowing time to do the original work involved.

READY-TO-WEAR UNIT CONTROL PROCEDURE

S. J. Shaffer
The May Co.
Los Angeles, California

Scope of this Report

The procedures outlined herein apply to seventeen women's ready-to-wear departments, four women's accessories departments and one men's clothing department, all for four Los Angeles stores, and to six ready-to-wear and three accessory departments in the basement section of the Downtown store, a total of thirty-one departments.

The unit control work for these thirty-one departments is all performed on a centralized basis in two Downtown offices, one covering the work for the seventeen four-store ready-to-wear departments, the other covering the work for the remaining fourteen accessory and basement departments.

The procedures commence with the preparation and attachment of price tickets to the merchandise as it is received, and conclude with the preparation of the various daily, monthly and seasonal records and reports furnished by the unit control offices.

Receiving and Ticketing the Merchandise

Some ready-to-wear and accessory merchandise is received direct at each of the four stores, but a great deal of it comes first into the Downtown store, followed by the transfer of appropriate quantities to the other three stores.

At whatever store the goods are originally received, the buyer or one of his assistants indicates the proper retail prices on the vendor's invoice, and price tickets are prepared accordingly.

Price tickets for ready-to-wear and accessory items are mainly of two styles:

1. Dial-set tickets, with strings attached, for use with the larger types of garments. These tickets are two-part, three-part or four-part, with perforations. The two- and three-part tickets are used on single-piece garments; the four-part used when an extra portion of the ticket is to be attached to a separate skirt.

2. Pin tickets, for use with the smaller items of merchandise. These tickets are always two-part, with a single perforation down the center.

The dial-set string tickets are imprinted for the most part in a centralized ticket-making section of the Receiving Department, then accompany the invoice to the marking section where the garments are hanging on rods awaiting the tickets.

The pin tickets are imprinted from set type as they are attached to the merchandise by a standard pin-ticket machine.

Information imprinted on each part of either type of price ticket generally includes the following:

1.	Dept. No.	(2-3 characters)
2.	Season	(2-3 ")
3.	Classification	(1-3 ")
4.	Mfr. No.	(3 ")
5.	Style No.	(1-6 ")
6.	Color	(1-2 ")
7.	Size	(1-3 ")
8.	Price	(2-5 ")
		28 Maximum

Every piece of merchandise must have a fully imprinted price ticket attached to it before it leaves the Receiving Department.

Transfer Between Stores

When stocks are transferred between stores, the original price tickets remain attached. Store designation on tickets is not important.

Changes in Retail Prices

The Receiving Departments effect all price changes, small lots right on the selling floor, larger lots in the Marking Room.

For all changes upward, new tickets are substituted for the former tickets.

For changes downward, the former price is either clipped off or crossed off, depending upon the circumstances, and the new, lower price inserted on the ticket. Most such price changes are accomplished by means of portable, hand-marking equipment, though the re-markers are authorized to effect such changes in green ink whenever the use of hand equipment is not feasible.

Second, third and fourth price changes are made on some price tickets, those having the required space available.

Merchandise Returned from Customers

If an item of returned merchandise still has attached to it a price ticket of at least two parts, the former ticket is left attached. If the item has attached to it a price ticket of but one part, a new two- or three-part ticket, either machine- or hand-made, is substituted, bearing all the same data as before.

If the item has no ticket attached, the buyer or one of his assistants fills out a "Request for Re-Ticketing", noting as much of the original ticket data as can be readily ascertained. The Marking Room accepts such a Request as an authorization to prepare and attach a new ticket. Data indicated on Requests for Re-Ticketing is often incomplete as to Mfr. No. and Style No.

Procedure at Time of Sale

In order that there will be one portion of the price ticket from each item sold available for the Unit Control Office, one portion of the ticket (called a stub) is detached at the perforation at the time of sale. In some cases, the stubs are detached by the salesperson, in others by the wrapping desk.

At some central point in each selling department or at the wrapping desk there is a small, slotted box into which the detached stubs are dropped.

In the Downtown store, a clerical from the Unit Control office goes around to each department at or near store-closing time, or next morning before the store re-opens, and collects the various groups of stubs. They are inserted in small envelopes bearing Dept. No. and date of sale.

In the outlying stores, the Selling Department Managers remove the stubs from the boxes at the close of each day and mail them (store's own mail system) to the Downtown Unit Control Office in special envelopes which indicate Dept. No. and date. These mailed stubs reach the Unit Control Office by about 9:30 the following morning.

Unit Control Responsibility

The Unit Control Office is responsible for preparing and issuing Daily Selling Reports, showing separately for each selling department at each store a complete listing of what was sold the previous day.

It is responsible for maintaining Price Line Sales Records for each department, showing the number of pieces sold in each price line for each classification.

It is responsible for preparing and issuing twice yearly a set of Six-Month Price Line Selling Reports, showing for each department the number of pieces sold in each of the six months in each price line for each classification.

And, finally, it is responsible for posting, in number of units, each day's receipts, sales and returns and inter-store transfers, to detail style record books, usually called "Black Books".

Each of these procedures is explained briefly below.

Daily Selling Reports

Each morning clericals in the Unit Control office sort each department's stubs and list them in pencil on Selling Reports. A separate report is made for each department and for each store.

Stubs are sorted and quantities sold are listed according to the following arrangement:

Classification
Price
Mfr. No.
Style No.
Color (applies to many but not to all departments)
Size (applies only to a few departments)

Sub-totals of quantities are inserted at each change in price and at each change in classification.

Reports for upstairs departments are prepared in quintuplicate. The Unit Control office retains the original for its further uses. One copy is dispatched to the Downtown buyer. Copies are also sent to the various outlying store selling department managers. Since a separate report is prepared for each store, the buyer and each of the outlying store selling department managers receive daily copies of four separate reports of the previous day's selling, one for each store.

Reports for Basement departments are prepared generally in triplicate, one for the Unit Control office, one for the buyer, and one for the Basement Merchandise Office.

Price Line Sales Records - (Separate Record for Each Month)

From the Daily Selling Reports, the Unit Control office posts to a set of Price Line Sales Records for each department the quantities of items sold at each price in each classification. There is a separate sheet for each classification. Prices are inserted in order from low to high in the left-hand column. The remaining columns are headed with the days of the month, except for the extreme right-hand column which is reserved for monthly totals.

Each horizontal price section of the form used for this record is divided into four lines, providing separate spaces for posting each store's sales.

This record is at all times available to the buyer for reference, though its main purpose is as a basis from which to prepare a Six-Month Price Line Sales Record, as explained below.

Six-Month Price Line Sales Report

As a guide for buyers in planning their purchases the following year, a Six-Month Price Line Sales Report is prepared for each department and issued two to three months following the close of each half year.

This report, whose form is quite similar to that of the Price Line Sales Record, lists for each classification for each store the quantities sold during each of the six months, six monthly columns on this report replacing the 31 daily columns on the Price Line Sales Record.

Only one copy of this report is prepared, but translucent paper is used, permitting its reproduction in an Ozalid machine. Two Ozalid copies are made, one for the buyer and one for the Merchandise Manager. The Unit Control

Office retains the original for use in accumulating comparative sales data for other reports not covered in this study.

Black Books

The Unit Control office maintains for each upstairs department a loose-leaf binder in which there is a separate record sheet for each style handled.

The form now in general use provides space at the top for name of resource, description of item, classification, Mfr. No. and Style No. The form is divided into nine horizontal sections, one for each month during which the average style may be handled. Each horizontal section is divided, in turn, into four lines, one for each of the four stores.

Across the top are headings providing for the recording of dates and quantities received or transferred, and 1 to 31 for daily postings of quantities sold.

The Unit Control posts sales to these records daily, using as media the daily selling reports. As goods are received or transferred, the selling departments clear copies of the various documents through the Unit Control office for black-book posting.

The reverse side of the Black Book form provides spaces for recording receipts and sales by color and/or size, according to the particular requirements of each selling department.

Black-books are generally kept in the buyer's office except during such period each day as they are needed for posting in the Unit Control Office.

Approximate Volume of Stubs Handled

Sales in the thirty-one departments for which centralized unit control records are maintained account for a daily average of about twenty thousand stubs.

Unit Control Personnel

To process this volume of stubs and to prepare and maintain the various records and reports mentioned above requires approximately 25 people, including 2 supervisors. The weekly payroll of this particular group runs around $890.00; annually this amounts to $46,280.

Samples of Price Tickets and Forms

Appended hereto are exhibits including samples of the price tickets now in use, and samples of the Unit Control forms which are described above.

Objectives

The Company is keenly interested in the development and progress of mechanical (or electrical or electronic) procedures which would satisfactorily and economically replace some or all of the clerical work now performed.

Chief advantages of a mechanical system might be listed as follows:

1. A combined four-store daily selling report, showing by some columnar arrangement the number of units sold at each store for each different style. At present, in order to obtain a picture of the previous day's sales at the four stores, the buyer must spread out the four separate-by-store reports and attempt to correlate the mass of figures provided.

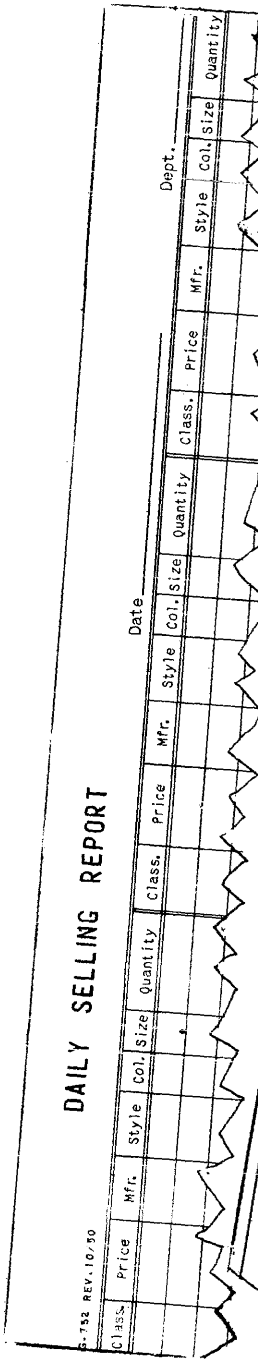
2. Selling reports issued and in buyer's offices earlier the following day. Earlier receipt of the daily selling reports would permit transfers between stores that same day to provide a continuance of the stock of those items then in demand. Earlier receipt of reports would also permit the saving of a few hours in re-ordering best sellers, with the result that replenishments might reach the selling floors sooner.

3. Greater accuracy in unit control records. Almost the entire present operation is dependent upon the human element. That portion which might be accomplished mechanically would be free from the high percentage of error attributable to the particular type of individuals necessarily assigned to this work to keep it within certain cost limitations.

4. The probability that the Price Line Sales Record and Six-Month Price Line Sales Report might be produced as a by-product of the Daily Selling Report. This would eliminate the clerical cost of preparing these Price Line records.

5. If a mechanical system were to be extended to include the maintenance of the black-books, still further reductions in clerical help could be effected and greater accuracy would be reflected in such records. At present, the black-book shows receipts and sales, but does not show stock on hand, due to the clerical cost of entering this figure. Under an electronic system, stock on hand could be shown, at perhaps small additional cost.

This store's prime aim is to substitute for part or all of the present manual operation some mechanical, electrical or electronic system which, in a reasonable time, will pay for itself, with possibly some overall expense saving, and will at the same time show some or all of the other potential advantages mentioned.



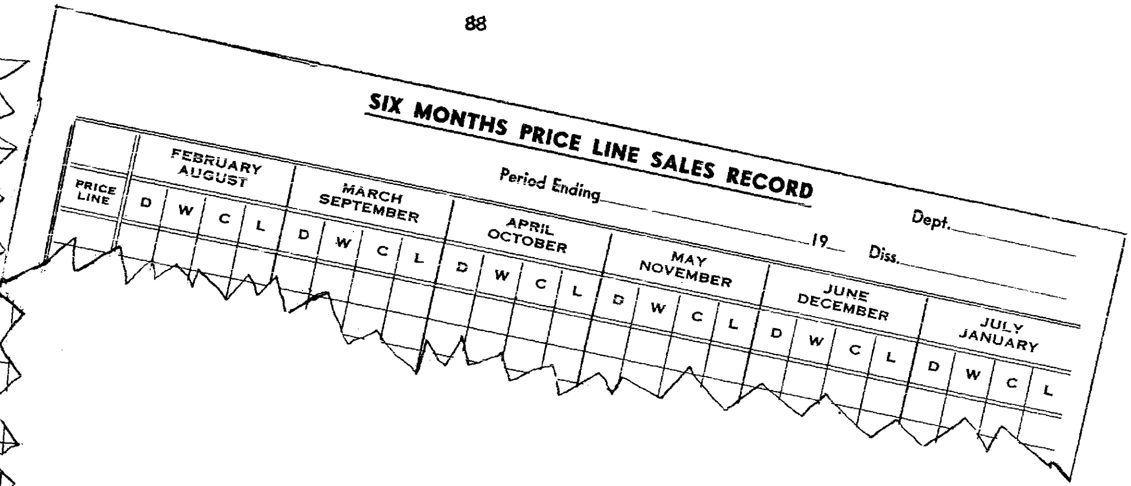
DAILY SELLING REPORT

Dept.______

Date______

G-752 REV.10/50

Class.	Price	Mfr.	Style	Col.	Size	Quantity	Class.	Price	Mfr.	Style	Col.	Size	Quantity	Class.	Price	Mfr.	Style	Col.	Size	Quantity



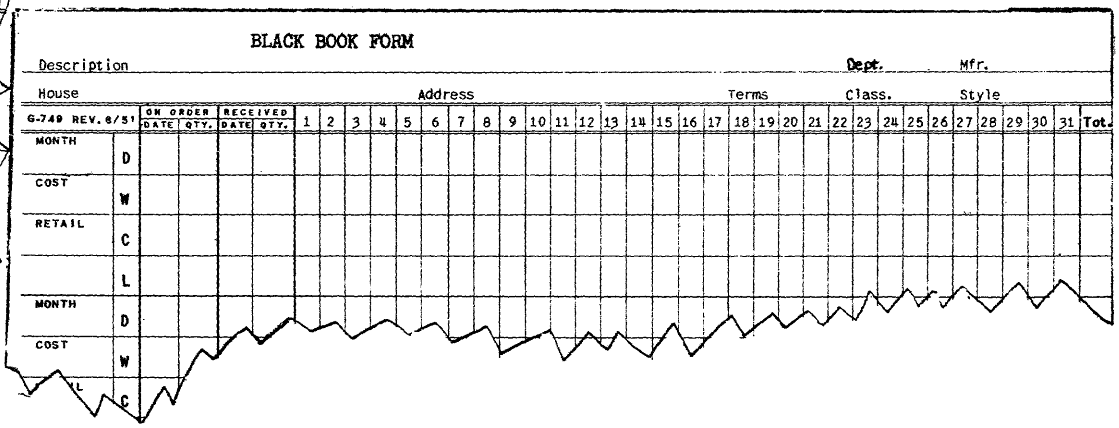
SIX MONTHS PRICE LINE SALES RECORD

Period Ending__________19__

Dept.______

Diss.______

PRICE LINE	FEBRUARY AUGUST				MARCH SEPTEMBER				APRIL OCTOBER				MAY NOVEMBER				JUNE DECEMBER				JULY JANUARY			
	D	W	C	L	D	W	C	L	D	W	C	L	D	W	C	L	D	W	C	L	D	W	C	L

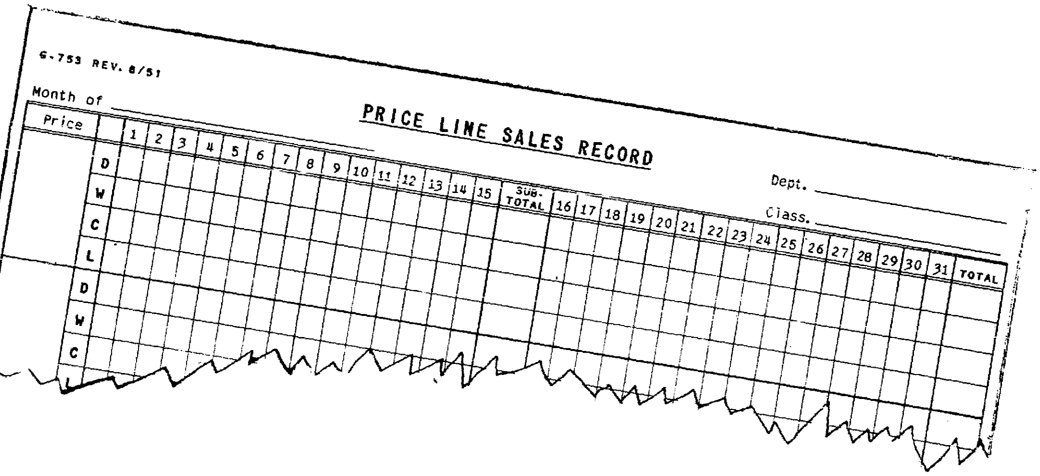


BLACK BOOK FORM

Description______ Dept.____ Mfr.____

House______ Address______ Terms____ Class.____ Style____

G-749 REV. 8/51		ON ORDER		RECEIVED																																
		DATE	QTY.	DATE	QTY.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Tot.
MONTH	D																																				
COST	W																																				
RETAIL	C																																				
	L																																				
MONTH	D																																				
COST	W																																				
L	C																																				



G-753 REV. 8/51

Month of __________

PRICE LINE SALES RECORD

Dept. ______

Class. ______

Price		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	SUB-TOTAL	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	TOTAL
	D																																	
	W																																	
	C																																	
	L																																	
	D																																	
	W																																	
	C																																	
	L																																	

UNIT CONTROL SYSTEMS ENGINEERING

Raymond Davis
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There are many areas in retailing in which electronic information processing systems may be applied. The areas of application given consideration for this discussion were the following: accounts receivable, including credit authorization; accounts payable; and unit control. To coordinate all of these functions into one system would have been an ambitious undertaking for this session. Accounts receivable and accounts payable are mechanized to a degree at the present time with electromechanical machines. Unit control, on the other hand, in this store is performed entirely by hand. The volume of data to be processed in the 31 departments is large enough so that one can expect an electronic system to produce a more efficient, reliable, and economical operation.

Before we discuss the proposed unit control system, let us briefly review some of the early work in department store record mechanization. One of the earliest attempts to mechanize department store records was the Central Records System. This system was installed at Kaufmann's Department Store, in Pittsburgh, Pennsylvania, in 1929. It was designed to coordinate the paper work in the major departments of the store in one central records system. A point of sale recorder was employed at the cash station to transmit sales data directly from a punched garment tag to a central recorder. The central recorder punched the data into a standard tabulating card. In addition, as a check feature, the information was listed on an adding machine paper tape. The punched cards were run through standard sorting and tabulating machines in order to prepare the various reports. The main areas covered by the system were unit control, sales statistics, and accounts receivable. Thus, we see that Babbage's Calculating Engine has its counterpart in the Central Records System for the retail field. It was withdrawn from Kaufmann's after a few years of difficult operation. It has been stated that the main reason for failure was that the system was 25 years ahead of its time. With this brief introduction, we are now ready to describe a proposed system.

It is generally agreed by people working on department store mechanization that sales data should be captured at the point of sale. At this point, all of the necessary factors for making the sale are together: the customer, the merchandise, and the sales clerk. This philosophy is subscribed to, and the proposed unit control system will include a point of sale recorder. The input media that has been selected for the system is magnetic. Therefore, the point of sales recorder will record the sales data on magnetic tape. From Mr. Shaffer's statement of the problem, it is evident that sorting and tabulating are the major operations to be performed. The system will include an electronic sorter with magnetic tape inputs and outputs. In addition to the four tape drive mechanisms associated with this type of sorter, a fifth tape unit will be included. The reason for this will be cleared up later on. Sorters of this general type should be available in the near future from a number of manufacturers. The data will be tabulated by an electronic computer which is flexible enough so that many other operations can be performed. The computer will have a magnetic tape input-output system. In addition to the magnetic tape output, it will be tied to a summary punch for punched card output. The additional punched card output was included to take economic advantage of present tabulating equipment for use as an output printer. A keyboard-to-magnetic-tape recorder is included in the system for the preparation of special tapes. The time schedule requires that all daily sales activity reports be delivered to the buyers the next morning following the date of sale. The volume of sales, 20,000 per day on the average, to be processed is such that a punched card printer capable of printing 150 lines per minute is adequate. As the volume of sales increases, and the system is expanded to perform additional operations, one of the high-speed printers could be used without the necessity of a complete system overhaul. Obviously at this time, the punched cards would be replaced by a magnetic tape output for all listing requirements.

The present cost of unit control, at this store, indicates that the cost target to shoot at is in the neighborhood of a quarter of a million dollars for an electronic system. If this can be depreciated over a five-year period, the cost would be $50,000 per year plus operator and maintenance costs. It is felt that a system of this size could be produced (not necessarily developed) for this order of magnitude of price. The task of estimating the savings a store may achieve by obtaining faster and more reliable unit control data is well beyond the scope of this paper. Certainly there is no historical data to serve as a guide in making such an analysis. The systems engineer must be cautious in accepting general statements by controllers that this will be considerable until these statements can be supported with factual data. Thus, the systems engineer must use as a guide to determine economic feasibility known present-day operating costs and not rely on conjecture. It was on this basis that the quarter of a million figure was arrived at as our cost target.

The first problem to be solved is the input problem. The systems engineer is inevitably faced with a difficult input problem when he seeks the solution to a business procedure. The difficulty arises, strange as it seems, because the data which must be utilized is recorded on a document in digital form. Our colleagues in the control session generally obtain their input data from instruments. It may be in voltage or shaft position form, which of course is not digital. However, a great deal of progress has been made in converting analog data into a useful digital form for data processing. The way in which this analog to digital transformation is accomplished is not biased by tradition or legal reasons. Tradition and legality are important factors which must be kept in mind in selecting an input media for a business system.

It was decided to use a tag similar to the one now in use. The present string tag is a three-part tag, while the pin tag is a two-part tag. When the merchandise is sold, one part of the tag is detached. If it should be returned, it is not necessary to retag the garment, in the case of a string tag. Thus, when it is sold again the second detachment is made. In case of a second return, the item must be retagged. These garment tags are generally printed either with a Dennison or Kimball Tag Machine in the marking department of the store. The tag proposed for this system is a single tag. That is to say, no section of the tag can be detached. The same tag will serve as a string or pin tag. In addition to the Arabic numerals printed on the tag by these machines, it is proposed that the marking machines be modified to print a binary coded decimal representation of the data. Thus, the tag is divided in half; one part has the figures printed on it, while the other part contains the binary coded decimal information. The coded portion will be printed with an ink containing a magnetic oxide. This portion of the tag is capable of being magnetized when placed in a magnetic field. In the case of a returned item, the tag may be re-used provided it is in good condition. The tag contains all of the necessary information for sales and receiving records. Figure 1 shows the proposed tag. It is realized that a tag of this type does not lend itself to a hand-marking machine. Mr. Shaffer is agreeable to the issuing of a new tag for marked-down items.

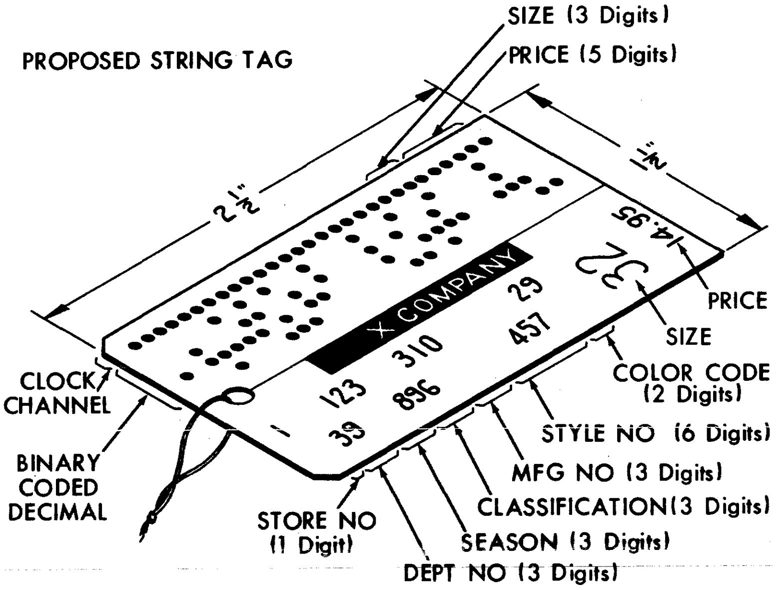
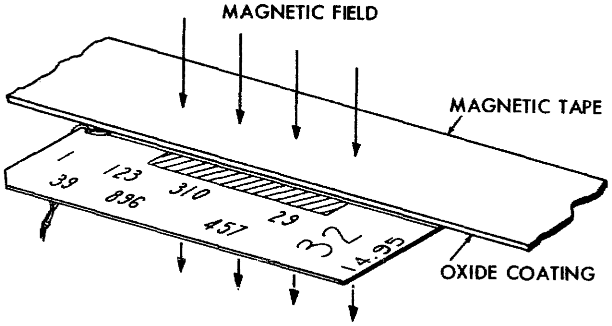


Figure 1

When the garment is sold, the transaction will be recorded by a point of sale recorder. The recorder will be placed adjacent to the cash register. No attempt is made to replace the cash register or its function. The recorder will contain a magnetic tape on which the sales data will be recorded. This tape is called the Sales Activity Tape. The tag is placed in a holder and inserted in the recorder. As it enters the recorder, the coded portion of the tag is magnetized. When it is fully inserted, the coded portion is under the magnetic tape. A lever is depressed which places the tag and tape in contact. An alternating magnetic field is applied perpendicular to the tag and the tape, and the contact printing is made. When the lever is released, the magnetic field is withdrawn, the tag holder is retracted, and the tape is indexed for the next recording. It would be desirable to use a magnetic ink of a higher remanence than the oxide used on the tape. The so-called 3M "Green oxide" should be a desirable material for this purpose when it is available in dispersion form. Interlocks would be designed in the recorder to insure foolproof operation. If we wish to record the sales clerk's number, another tag with the sales clerk's number in coded form would be required. Each clerk would be issued a clerk's tag, and both tags would be used in the point of sale recorder. In this case, if only one tag was in its holder an interlock would prevent a recording. This method of duplicating magnetically recorded information by contact printing was described in 1949 by Camras and Hess. It is felt that this method will give a reliable and economical sales recording. To my knowledge, recorders of this type are not being manufactured at the present time.



DUPLICATING INFORMATION ON TAG
BY CONTACT PRINTING

Figure 2

Figure 2 shows a tag in contact with a section of the magnetic tape.

Figure 3 is an artist's conception of a point of sale recorder.

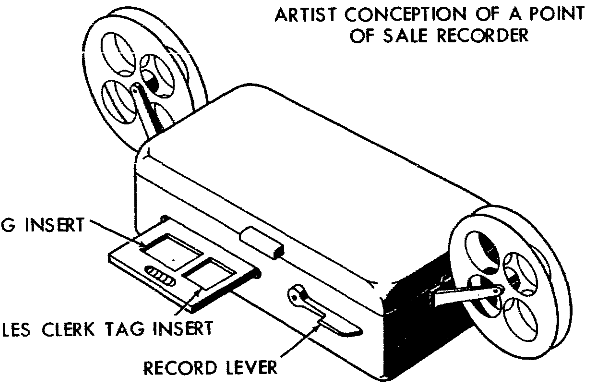


Figure 3

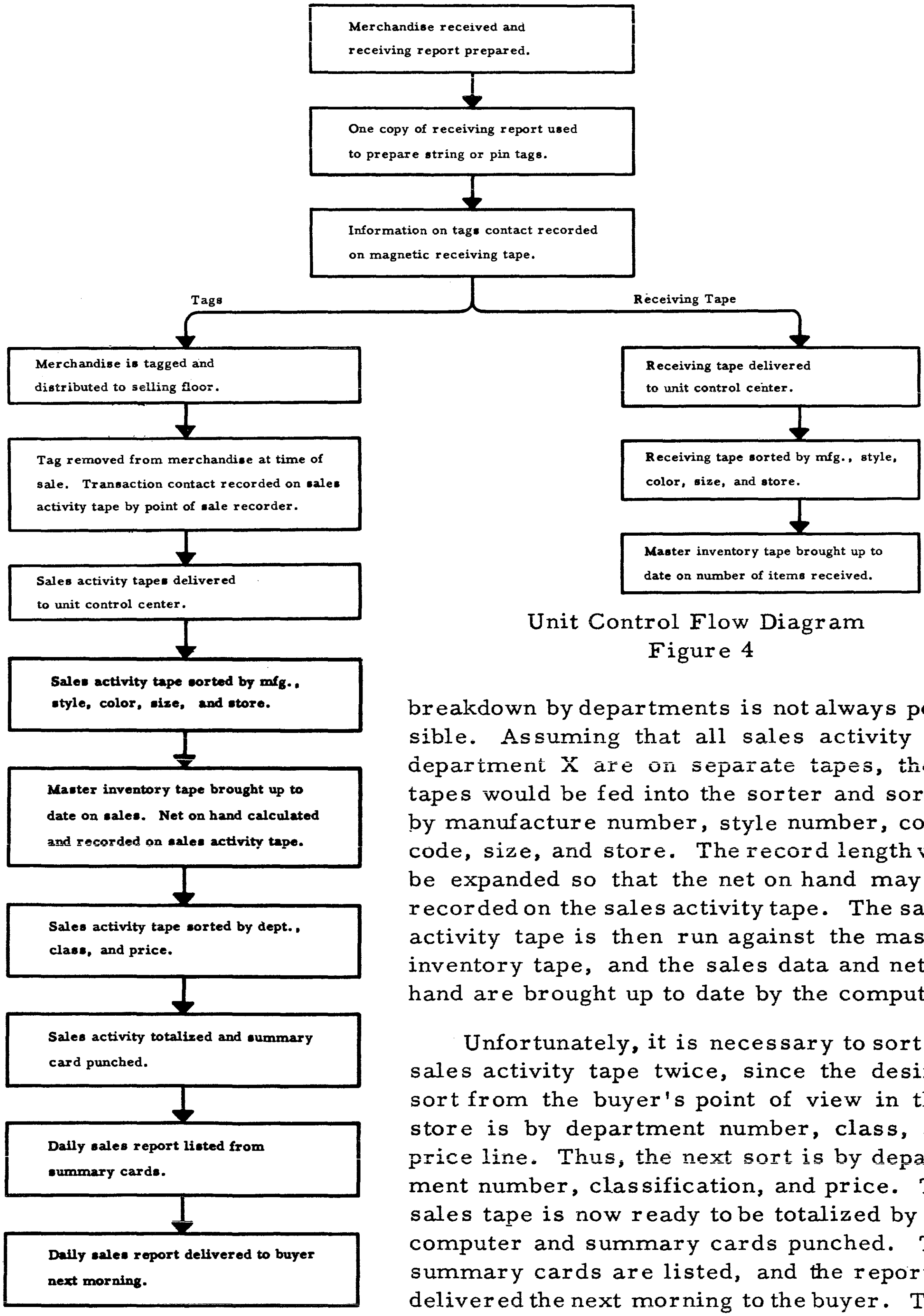
At an increase in the cost of the point of sale recorder, a keyboard could be added. The keyboard would be used to add additional information to the sales record. The linear density of digits with this type of recording is extremely low. However, this eases the mechanical registration of the tags in the recorder and allows a practical tolerance on the size of the tags. One-inch magnetic tape is proposed for the point of sale recorder. The amount of tape required for each recorder would, of course, vary with the volume of sales. Two hundred feet of tape would handle approximately six hundred sales per cash register. This should be adequate by a factor of 3 to 1 for most cash register stations in the stores used for this case study.

The linear density of recording by the contact recording method is too low to use for extensive data processing. In the interest of saving tape, it is necessary to compress this recording. Rather than construct a special tape compressor, the electronic sorter has a special input designed for these tapes. This tape drive is in addition to the four associated with the sorting process. All contact recorded tapes will be placed on this tape drive. The first pass in the sorting process will receive input data from this unit. As the data is recorded on the sorter tapes, it is compressed to 100 bits per inch. From this point on, all tapes have a density of 100 bits per inch. Clearly, the order of fields to be sorted must be capable of being programmed into the sorter. This could be accomplished by setting a group of switches or by having a plug board for this purpose.

We are now ready to follow the flow of information for the preparation of the daily selling report. The merchandise is received by the receiving department, and a receiving report is prepared. A copy of the report is sent to the buyer. He sets the retail price and sends the report to the marker. The required number of tags for each report is run off with the modified tag machine. The tags are first used to prepare the Receiving Tape. This is accomplished with a recorder similar to the point of sale recorder. However, this recorder is provided with an automatic feed mechanism. Thus, the tags are fed automatically, and the information is contact recorded on the receiving tape. After the tags have been recorded on the receiving tape, they are placed on the merchandise and delivered to the selling floor.

The receiving tape is sent to the Unit Control Center. It is sorted by manufacture number, style number, color code, size, and store number. On completion of the sort, the Master Inventory Tape must be brought up to date. It is assumed that the master inventory tape has been initially prepared on the keyboard-to-magnetic-tape recorder. The master inventory will be required to store approximately 200,000 items. In addition to the information that is sorted on the receiving tape, the master inventory tape will contain the current price of the item, the number on hand at the beginning of the month, the number received during the month, the number sold, and the net number on hand. These last four fields will contain three digits each. The total digits per master record is 32. The receiving tape is run against the master tape in the computer. Each item is totaled and added to the number received. The net balance is calculated and brought up to date on the master tape. This completes the receiving operation.

When the merchandise is sold, the tag is removed and the transaction is recorded by the point of sale recorder. At the end of the day, the sales activity tapes are collected and delivered to the Unit Control Center. It is proposed to process these tapes by department number wherever possible. Since some cash registers are shared by more than one department, a physical



Unit Control Flow Diagram
Figure 4

breakdown by departments is not always possible. Assuming that all sales activity for department X are on separate tapes, these tapes would be fed into the sorter and sorted by manufacture number, style number, color code, size, and store. The record length will be expanded so that the net on hand may be recorded on the sales activity tape. The sales activity tape is then run against the master inventory tape, and the sales data and net on hand are brought up to date by the computer.

Unfortunately, it is necessary to sort the sales activity tape twice, since the desired sort from the buyer's point of view in this store is by department number, class, and price line. Thus, the next sort is by department number, classification, and price. The sales tape is now ready to be totalized by the computer and summary cards punched. The summary cards are listed, and the report is delivered the next morning to the buyer. This process is outlined in Figure 4.

The daily selling report contains information which is not available in the present system. Size has been incorporated in this report, and the net on-hand for each store has been included, as well as the total on hand for all stores. This figure should be of value to the buyer, particularly when an item is moving in one store and not in the others. A glance at the report will tell him from what store to transfer stock without requiring a physical inventory of the stock in all stores. This additional information is obtained at relatively low cost by an electronic system of this type. The format of the daily sales report is illustrated in Figure 5.

DAILY SALES REPORT

							Store									
							1		2		3		4			
Dept.	Class	Price	Mfg.	Style	Color	Size	Sales	On Hand	Sales	On Hand	Sales	On Hand	Sales	On Hand	Total Sales	On Hand
39	11	295	310	2484	5	32		10		10		10	2	8	2	38
													2*		2*	
		299	64	3911	1	36.5	1	25	2	20		15		20	3	80
					3	34	1	10		10		14		15	1	49
			310	2476	1	38	1	18	3	16	2	20	1	19	7	73
							3*		5*		2*		1*		11*	
		399	74	118	10	32	1	12		13		13		14	1	52
							1*								1*	
							4**		5**		2**		3**		14**	

* Subtotal ** Total

Figure 5

There are several other required reports to be prepared. The monthly price line sales report will be prepared from the daily sales activity tapes. A monthly sales activity tape would be generated in this process and these would be used for the six months' price line report. The master inventory tape replaces the so-called "Black Books" at this store.

Time has not permitted a detailed analysis of the department store problem. Certainly there is much rethinking to be done on present methods in terms of new concepts and possible systems. The department store controllers and store operations managers must join forces with the digital computer systems engineers if electronics is to be successfully applied in this field.

Bibliographical Reference

Marvin Camras and Robert Herr, "Duplicating Magnetic Tape by Contact Recording," Electronics, Vol. 22, No. 12, pp. 78-83, December 1949.

A SOLUTION FOR AUTOMATIC UNIT CONTROL

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Summary

Sales activity tapes, as well as receiving tapes produced in the receiving departments of the several stores, are to be processed against an inventory tape, and a daily selling report produced. These tapes are to be sorted into order; in this particular case, they will be sorted according to store, department, class, manufacturer, style, color, size, etc. Since it has been indicated that the inventory consists of some 200,000 items, several tapes actually would be required for the master files, perhaps organized on the basis of stores and departments.

A significant point is that the information on these tapes is primarily an identification code; where 30 decimal digits are used to identify the item, perhaps only 2 digits of actual information has to be processed by the computer. Of these two digits of information, one may designate the type of transaction, such as a sale, return of goods, or other, while the other digit designates the quantity of items involved.

In general, the purpose of the computer is to identify the item from the transaction tape and to find the matching record or block of information from the inventory tape; after finding the proper master inventory record, the computer corrects the values of the inventory, and posts the transaction to the sales record. The arithmetic required is primarily simple addition and subtraction; there is no multiplication to be done in this part of the process, for example.

In the type of machine proposed, buffer registers will almost certainly be required to accept information from the tapes and feed information to the tapes. The buffer registers serve a synchronizing purpose, between the internal clock frequency of the computer and the different clock rate from the magnetic tape. Also, while one record is being read into one buffer, a second record may be already in the machine undergoing processing, while a third is being fed out of another buffer onto tape.

The types of commands that might be provided in this computer could include instructions to: read next item from sales activity tape, read next item from inventory tape, compare identifying portion of the code, if these are in agreement then the machine carries out the certain mathematical process, if these are not in agreement then the machine advances the inventory tape until such agreement is found.

Other commands would spell out which mathematical process are to be followed: correcting the number of items sold, the number of items on hand, and the number of items that have been received. A self-checking feature might involve comparing a net balance computed from the transaction tape with a net balance computed from the inventory tape. Another type of command would be editorial in nature, for arranging the output information in a form suitable for printing.

For the mathematical processes themselves, probably an extraction-add command would be used, plus the block make-up of the record being processed. Within the block of information from the inventory tape, perhaps three digits designate the number of items on hand. From these particular three digits, it is desired to subtract the quantity sold. In another part of the inventory block, this same quantity is added to perhaps three other digits representing sales for this month, or similar information. Since the same quantity information is to be added to one part of the block and subtracted from another, it is desirable to consider special purpose addition and subtraction commands. In contrast, general purpose computers normally add one complete number to another complete number. Other special purpose commands might post daily cash sales separately from daily credit sales. In general, the computer would be designed with a list of commands to carry out precisely the operations involved in the inventory process.

In another case, the receiving tape might store the quantity information on the number of items received at a different location within the transactions block from where it is stored in the sales transaction block. This quantity information may have to be added to the On Hand item and subtracted from the On Order item in the inventory block. In general, the sales activity tape will be processed in one way, the receivals a different way, and items that are returned still differently. But in all cases, it will be a matter of adding a two digit portion of one block to a three digit portion of another block, or a similar operation. Certainly these operations can be done with a general purpose computer, many of which are in existence in this country now. But to design an efficient machine, to compete in cost with the present system that has been described in an earlier paper, the machine will have to be built with the particular purpose in mind.

At the same time, the machine designer must guard against the possible change in the inventory system that would change the format of the block of information. The computer must not be too specialized, but must be capable of modification.

As a method of accomplishing the desired operations, and at the same time allowing for future modifications, the use of a special recirculating code register is suggested. Assuming that a binary coded decimal system is used, the six unused codes (not representing decimal digits) might be used to designate add, subtract, etc. These operation codes would now be inserted in the code register; when sensed, they would cause the following three digits in the transaction block to be added (or subtracted) to the following three digits in the inventory block. If the transaction quantity and inventory quantity are not "in phase," a three digit recirculation register may be added for delaying the transaction quantity a certain number of cycles. This might require that the division points between different types of information occur at multiples of three digit positions. It will be seen that this method is essentially a "no address" type of operation.

THE SYSTEM IN OPERATION

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The gentlemen who have preceded me here today have all represented what might be titled the "heroes" of the computer world; the business men of vision who can foresee the coming revolution in business data processing which the modern computer portends, the system engineer who molds this tool into usable and workable forms, and the computer designer who extends the developments of the day to meet the demands set forth by those who would use his equipment. I represent the "low man on the totem pole," the little guy on the end of the chain to whom, when all is said and done, they turn and say, "Well, this is what we want and this is the tool with which you must work. Now make it do something useful. Determine the commands which we must insert in order to put the system into operation." I am speaking of the programmer, the unsung hero of it all; the fellow who makes the whole works go and generally receives no credit for having done so. Possibly it is because the heroes speak in terms of microseconds and the programmer speaks in terms of months, but it seems that fate has surely destined him to become the buck private of the computer world. My purpose, therefore, in presenting this paper is two fold. First, it is intended to indicate how the proposed system might be specialized by instructions to carry out the task of producing desired results. Second, it will serve to demonstrate how the proposed system affects the programmer in the methods which he may use to attain these results.

Having philosophized about the programmer's role, let us examine the task which lies before him as he attempts to put the system into operation. The systems engineer has studied the problem, has proposed a general method of attack, and has defined the requirements for the basic equipment. The computer designer has met these specifications with data processing devices which he feels have the requisite inherent capabilities to produce the desired results. If past performance is any indication, neither of them has consulted the programmer on what he feels that the system needs in terms of detailed data processing capabilities. So, it is now up to the programmer to make the best of what he has been given. He must break down the task at hand to its minutest detail and determine the best method by which the equipment may be given instructions to specialize it to accomplish the required job. Let us consider the particular task of preparing the daily selling report and maintaining an up-to-date inventory record. The method by which these two groups of information are to be presented goes a long way towards defining the data processes required for their generation, for the key to most business problems of this type lies in a consideration of the order in which information is gathered for the system and stored in the system together with the order in which it must be presented outside the system. In this case the company requires a daily summary of its transactions broken down by department, class, price line, manufacturer, style, color, and size for each of its four stores. It would also be of value if the store could maintain a running record of its inventory and publish these figures in its daily report, for then this report would reflect a complete picture of the store's status for its buyers. (See Figure 1a.)

Now, if the inventory file could be maintained so that information in it were broken down into the same categories as those required for the daily report, the programmer's job would be extremely simple. Unfortunately, the inventory file cannot be so maintained for several reasons. It is not too desirable to have information concerning each manufacturer distributed all over the inventory record, nor is it reasonable to have price as an element of inventory control since this factor is so subject to change. Therefore, the inventory is ordered by manufacturer, style, color, size, and store. (See Figure 1b.) The incompatibility of these two orderings, as required by the store, forces on the programmer a situation which hampers the most efficient utilization of his equipment. This will be brought out more fully in what follows, but is interjected here in order to point out one instance among many where existing systems will have to be modified in order to provide for the best use of automatic equipment. Where manual, decentralized methods are used such compatibility factors are of little weight; where automatic integrated systems are used they become of extreme importance.

With the general problem blocked out and the limitations it imposes on the system described, we now consider one possible method for preparing the daily report and maintaining a running inventory record. Figure 2 presents a flow chart of the data processing which will be described. The transaction tapes manufactured by the point-of-sale recorders are collected and brought to the central processing center where they are passed through the sorter which produces a new tape in which the day's transactions are ordered in the same sequence as the master inventory tape, that is, by manufacturer, style, color, size, and store. This ordering is necessary so that the master inventory tape may be brought up to date in an efficient fashion. That is, we do not wish to waste time scrambling around in the inventory file so we order the data that we may move efficiently down the file. We digress at this point in order to point out that this sort destroys an implicit ordering by department which existed in our system by virtue of the fact that the individual tapes from the point-of-sale recorders provided just such an ordering. Now, sorting time will represent a large portion of our processing time in any method which we may choose. In the proposed sorting method it requires up to N passes through the sorter to produce a sort of M items if 2^N is the smallest power of two greater than M. This has significance here since the daily report is to be summarized by department and the individual tapes practically supply just that breakdown. Hence, if we were interested only in the daily report we would be able to pass each individual transaction tape through the sorter followed by a simple summarizing program. These operations would be rapid since the number of items involved for each tape would be relatively small. The whole job including that of bringing the inventory up to date would, therefore, be easy if the inventory could be organized in the same way as the daily report, hence the statements made earlier in this paper. Now, at the same time that the day's transactions are taking place on the selling floor, other store activities are occurring which will have effects on the state of the inventory. As goods are received from the manufacturer and prepared for the selling floor a daily receiving tape is prepared. Other store activities such as interstore transfers of merchandise, those customer returns not handled at the point-of-sale, price changes, and the results of physical inventories are recorded on special activity tapes at appropriate points in the system. These tapes, too, are brought to the central processing center where they are sorted so as to be compatible with the master inventory file. Thus, we have four tapes to present to the central computer, the master inventory tape, the daily receiving tape, the daily transaction tape, and the special activities tape, all sorted according to the same criteria. With the data from these tapes the computer is able to revise the master inventory tape so that it reflects the changes which the others indicate.

Besides bringing the master inventory tape up-to-date the computer performs two other tasks. It records the status of the inventory on the daily transaction tape so that this information may be seen on the daily report. In addition, this is a convenient point to prepare any special reports on the status of the inventory which the store may desire. For example, a list might be prepared which shows those items which have been active, are on order and overdue in delivery. Or the master inventory might be scanned for those items which have not been active for a predetermined length of time and a list of "dead stock" prepared. These special reports are punched out on cards in a form suitable for listing in a card reading printer.

With the inventory now brought up-to-date and the daily transaction tape modified to include the current status of the inventory, the system is now in a position to prepare the daily report for the buyers. The daily transaction tape which has thus far, been sorted by manufacturer, style, color, size, and store is returned to the sorter where it is further sorted by department, class, and price. (It is assumed here that the sorter operates in a fashion so as to preserve any lower order sort which may have been previously made.) It is then brought back to the computer where it is summarized for the daily report which is punched out on cards ready for listing in the printer.

It would be appropriate at this point to examine in greater detail one area of the data processing flow and study the programmer's problem at the next level. Unfortunately, this is impossible in this paper. To this point only the gross characteristics of the equipment with which he has to work have been of concern to the programmer. The characteristics of the problem itself have dictated to a large extent the general flow of information. But, as the details of his process begin to require further refinement the precise characteristics of the equipment become of greater importance. We can push the analysis no further without the fine details of the system. Let us, therefore, pass to the realm of speculation. Perhaps the most interesting phase of this problem is that of bringing the inventory tape up-to-date. This particular point will serve admirably to indicate the complexities and possibilities of approach which various possible mechanizations might afford. We shall concentrate on some aspects of tape organization to illustrate our point.

Basically, the processing steps for the inventory maintenance problem are simple. The computer must read information from each of its input tapes. It must then determine which inventory affecting item is next in sequence in the master inventory file. Following this it finds the required item on the master inventory tape and reads it into the main memory. It now modifies the information read from the inventory tape according to the change required by the input tape, and records the new item status in place of the old. The degree of complexity of this task is for the most part determined by the organization of the tape units and the means by which the computer can communicate with and control them. This is particularly true in file maintenance problems of this type where it is necessary for the central computer to find a given item on a master tape.

The first problem facing the programmer is that of finding a given item on the inventory tape. If the tape units are organized so that they, of themselves, have no data processing ability, then it may be necessary that every piece of information which they contain must pass through the central machine for its inspection in order that it may find the next desired item. On the other hand, if the tape unit is organized so that the computer can cause it to index itself automatically to a desired position, then the information intermediate to its current position and its desired position need not pass through the central machine. The relative importance of this factor in terms of processing speed is a function of the internal machine speed, The degree to which the programmer must provide control of the tape units in his search for desired information, thus has a profound effect on his program.

Now, tapes are generally organized so that information is stored in fundamental record keeping units called blocks. These blocks may be of fixed or arbitrary length depending on the system used. If the programmer can only cause the tape to move past one block at a time he must maintain information in his main memory which tells him at what block the tape is currently positioned, and how far along the tape he must move to arrive at the block which contains the information he desires. In addition, he must maintain an index which correlates block numbers and file control numbers, and, if more than one inventory record is stored within a single block, he must be able to determine the precise location of the record he desires within the block. The alternative to this is to read in and inspect every block in his master inventory file.

If the tape is organized so that the programmer can cause it to move a specified number of blocks forward or backward from its present location, he must maintain the same type of information but his task of moving the tape is somewhat simplified since he needs not control its motion across each individual block.

If the individual blocks on the tape are identified by a permanently specified block address number and the tape units are organized so that they can position themselves at any requested block address, the programmer's task becomes somewhat more simple. He need no longer maintain a record of the tape's current position nor need he know the relative position of the desired block with respect to that current position. Part of his record keeping problem is thus eliminated. Now he need only maintain an index which correlates specified block address numbers and file control numbers.

Finally, if the individual blocks on the tape are identified by a block address number which the programmer can assign and record with the block, and the tape units are organized so that they can position themselves at any requested block address the programmer's task is further simplified. Now he can cause the tape to move to the desired position merely by specifying the item by its file record number and he need maintain no information in his main memory.

It may be seen then that the programming problem of controlling the tape units in their search for specified information is inescapably tied up with the particular organization of the tape units themselves.

Whether or not he can rerecord information in a particular block on a tape is another problem which will affect the programmer. Some tapes are organized so that information cannot be rerecorded on them. In this event the programmer is forced to pass every piece of information in the inventory file through the central computer so that it may be recorded on a new tape with suitable modifications inserted according to the input tapes. With a high speed machine this process can be combined with that of inspecting each block to see if it is one which requires modification. With a lower speed machine, it would be desirable that information pass directly from one tape to the other if it need not be modified. If the programmer can modify and rerecord information on the same tape then this tape need not have all of its information pass through the central computer and it is highly desirable that the programmer be able to move it rapidly to any specified location. Here, again, it may be seen that tape organization will have far reaching effects on the final program.

If the programmer is faced with a tape which he can modify in individual blocks he is faced with the problem of an expanding file. When a new item enters the inventory record and must be placed in some central position in his file, it poses a new problem. Shall the programmer provide blank spaces in his file for such eventualities? This is generally not economically feasible. He has two choices. He can provide an index in his file which will tell him that the item is located elsewhere in the file. This is not too practical because of the lack of tape speed in arriving at a new point. It becomes practical only when the computer can be carrying out some other task while the tape is moving. The alternative is to rebuild the master inventory file by passing it through the central computer and recording a new tape which will embody the required expansion in the proper position. If this can be accomplished during off hours as an independent task the block modifying scheme for file maintenance may be preserved. If it must be accomplished in parallel with other forms of file modification, the programmer is forced to use the scheme in which all information passes through the central computer for recording on a new tape. Once more the tape and its organization have affected the methods which the programmer may use in putting his system into operation.

We have pointed out some of the considerations which the programmer must make in determining how his system is to operate with respect to the tape units with which he has to work. In the same fashion he is faced with considerations of the characteristics of the central computer in determining just how it shall best be incorporated into the data processing flow. If this paper has served to indicate how a programmer goes about putting a system in operation, it will have accomplished its objective. In addition, it will more than serve its purpose if it succeeds in calling the attention of the system desginers and computer designers to the fact that what they sometimes believe are minor points in their design, can, and do have profound effects on the efficiency with which the programmer can use the system they create.

Fig. 1a

DAILY REPORT

							SALES					INVENTORY				
DEPT.	CLASS	PRICE	MFR.	STYLE	COLOR	SIZE	STORE 1	STORE 2	STORE 3	STORE 4	TOTAL SALES ALL STORES	STORE 1	STORE 2	STORE 3	STORE 4	TOTAL
39	WE	795	36	599	1	16	1				1	2	3	3	3	11
				5810	45	16		1			1	3	2	3	3	11
		895	36	613	45	14		1	1	2	4	3	2	2	1	8
	WJ	595	36	461	13	14			2		2	3	3	1	3	10
						16		1	1		2	3	2	2	3	10
					45	14		1			1	3	2	3	3	11
	WP	795	36	592	1	14		1			1	3	2	3	3	11
					26	16			1	1	2	3	3	2	2	10
					45	16	1		1		2	2	3	2	3	10
	222	495	36	561	26	16	1				1	2	3	3	3	11
		595	36	2140	1	16	1				1	2	3	3	3	11
41	WA	1895	36	1124	1	16	1		1	1	3	2	3	2	2	9
		2195	36	1127	1	16	1	1	1		3	2	2	2	3	9
	WN	1695	36	1121	45	14		1	1		2	3	2	2	3	10
	WR	2195	36	1128	1	14		1	1	1	3	3	2	2	2	9
		2500	36	1132	1	16	2	2	3	3	10	1	1	0	0	2
	YR	1895	36	1125	1	14	3	1	1		5	0	2	2	3	7

Fig. 1b

INVENTORY FILE

						MONTHLY	ACTIVITY
MFR.	STYLE	COLOR	SIZE	STORE	ON HAND	RECEIVED	SOLD
36	461	45	14	1	13	6	0
				2	12	6	1
				3	13	6	2
				4	13	6	0
		13	14	1	13	6	0
				2	13	6	2
				3	11	12	5
				4	13	6	0
			16	1	13	6	1
				2	12	6	2
				3	12	6	3
				4	13	6	1
	592	1	14	1	13	6	4
				2	12	6	1
				3	13	6	3
				4	13	6	1
		26	16	1	13	6	1
				2	13	6	2
				3	12	6	0
				4	12	6	0
		45	16	1	12	6	1
				2	13	6	1
				3	12	6	3
				4	13	6	2
	599	1	16	1	12	6	1
				2	13	6	0
				3	13	6	0
				4	13	6	0
	613	45	14	1	13	6	4
				2	12	6	1
				3	12	6	2
				4	11	12	6
	5810	45	16	1	13	6	5
				2	12	6	3
				3	13	6	0
				4	13	6	1

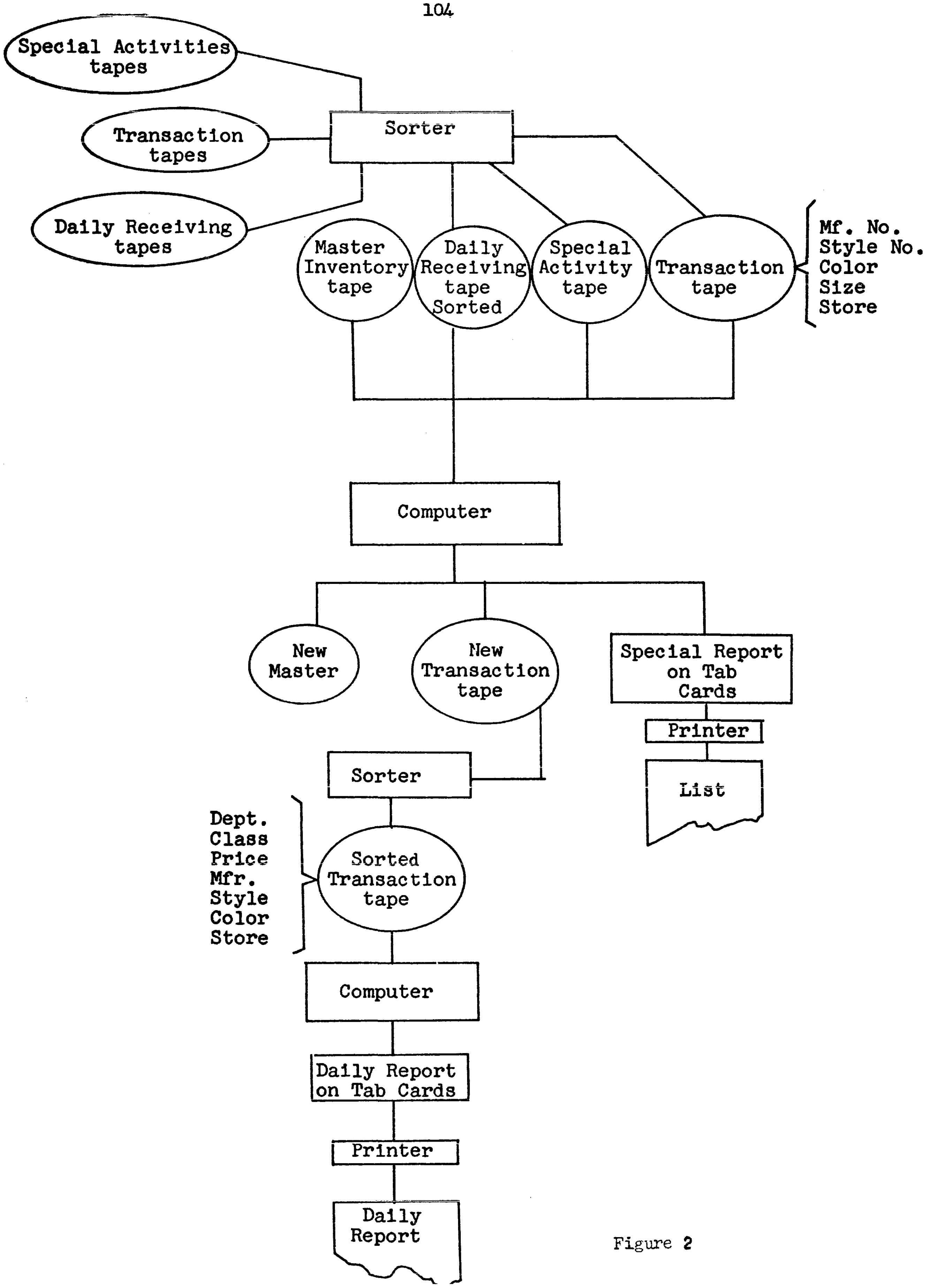
Special Activities tapes
Transaction tapes
Daily Receiving tapes
Sorter
Master Inventory tape
Daily Receiving tape Sorted
Special Activity tape
Transaction tape
Mf. No.
Style No.
Color
Size
Store
Computer
New Master
New Transaction tape
Special Report on Tab Cards
Printer
List
Sorter
Dept.
Class
Price
Mfr.
Style
Color
Store
Sorted Transaction tape
Computer
Daily Report on Tab Cards
Printer
Daily Report

Figure 2

APPROACHES TO DESIGN PROBLEMS IN CONVERSION EQUIPMENT

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The term conversion equipment is used here to denote devices which either express analog quantities in pulse-coded digital form or express pulse-coded digital data in analog form. These devices are called coders and decoders, respectively.

Conversion devices may handle a variety of variables which can represent such quantities as force, displacement and its time derivatives, angular rotation, pressure, pH, etc. Direct conversion between these quantities and their pulse-coded digital equivalents is frequently not feasible. By use of suitable transducers, all analog quantities are usually expressed either as a shaft rotation, a linear displacement, or a voltage. These are the only three forms of analog quantities to be considered here.

Problems in the design of conversion equipment arise from two areas. The first area consists of the usual over-all system requirements pertaining to reliability, size, environmental conditions, available power supplies, etc. The second area includes the following considerations which are peculiar to the conversion equipment: type of pulse coding, complexity of equipment, conversion time, accuracy of conversion, and holding ability. The discussion to follow will be restricted to the second area and will outline possible solutions to problems arising from it.

Type of Pulse Coding

The type of pulse coding used in a conversion device is either binary or decimal. Binary representation is more advantageous when the amount of equipment is to be kept to a minimum, but leads to more difficult interpretation when human observation is required. For example, when the problem is to design a converter which measures the ordinates of a curve and tabulates them through use of a typewriter, it is hardly practical to use binary representation. When, on the other hand, the problem consists of designing conversion equipment for a fully automatic control system, binary representation is indeed more practical.

In some cases, it is very helpful to use a modified binary code in which only one digit changes in the transition from one number to the adjacent number. For discussions of modified binary codes, also called cyclic or reflected, and translating circuits between modified and natural binary codes, the reader is referred to papers by members of the Bell Telephone Laboratories and the Moore School of Electrical Engineering.[1,2]

Regardless of the number base used, the pulse-code pattern may be of serial or parallel form. Which one of the two forms to select for design is not necessarily determined by whether a serial or parallel computer is used. Well-perfected shift registers are now available which can be inserted between the conversion equipment and the computer, so that serial-to-parallel translation can be reliably accomplished. The use of shift registers does, however, add to the system complexity and can be justified only if an overall improvement in performance results.

Complexity of Equipment

When many conversion devices are used in the same system, equipment complexity can be reduced by time-multiplexing techniques. The conversion process is then carried out in two steps, with the equipment necessary for one of the steps common to several of the conversion devices.

As an example of a multiplexed system, consider the shaft-to-digital converters shown in Figure 1 in block diagram form.[3] Only four inputs are drawn, but many others could be added.

The first step in the conversion consists of generating a pulse pair, the time interval between which is a linear measure of the shaft rotation. Consider Shaft 1, which is connected to Control Transformer 1 (CT1). Its stator is excited by three sinusoidal voltages displaced 120 degrees in phase. The resulting rotating flux field in the air gap induces a rotor voltage, E_R, the phase of which, with respect to one of the stator voltages, E_S, is linearly related to the shaft rotation. PG1 and PG5, which are pulse generators, give an output when positive-going zero crossings of E_R and E_S occur. Just as the interval between zero crossings is linearly related to the shaft rotation, so is the time interval between output pulses from PG1 and PG5. The desired pulse pair is thus obtained.

The second step in the conversion consists of measuring the time interval between the two pulses. This is done by counting clock pulses. Pulse Generator 5 starts the flow of clock pulses to the counter and whichever of the Pulse Generators 1, 2, 3, or 4 has been selected by the switch stops the counting action. The contents of the counter indicate the shaft rotation and are read by the computer. The equipment common to <u>all</u> the channels consists of the three-phase sinusoidal voltage generator, one pulse generator, the switch, and the counter and its associated flip-flop and gate.

The design of the switch poses no unusual problems since it handles only pulses. This would not be the case if the control-transformer voltages were to be switched and explains why it is considered preferable to use one pulse generator in each information channel.

Conversion Time

In a time-multiplexed system such as the one shown in Figure 1, the number of signal channels which can share the common equipment is limited by considerations of conversion time and required sampling rate. The conversion time, τ, is the time required to develop the equivalent of the quantity being coded or decoded. In the example of Figure 1, the conversion time may be as long as one period of the sinusoidal control-transformer excitation. (To simplify the discussion, it is assumed that the computer requests a shaft reading in synchronism with the zero crossing of the reference sinusoid.) If it is assumed that each shaft can be sampled at the same rate, r, it follows that the number of channels, n, which can share the common equipment is

$$n = \frac{1}{\tau r} = \frac{f}{r} \qquad (1)$$

A numerical example may be helpful here. Assume that it is required to resolve the shaft rotation in Figure 1 to one part in a thousand. A clock frequency of 2 MC is to be used. Hence it will take 0.5 millisecond to count to 1000, the largest required number. The period of the synchro excitation must then be 0.5 millisecond. Assume that the sampling rate is to be 25 per second. Equation (1) is then satisfied when n = 80. One may be tempted to increase the number of channels which can share the common equipment by increasing the synchro excitation frequency. But increasing the excitation frequency also requires increasing the clock frequency, if a given resolution of the shaft rotation is to be maintained. The maximum operating rate of practical counters does not permit clock rates much in excess of 2 MC.

Generally speaking, the conversion time required is a function of the elements used in the equipment and the basic conversion techniques employed in its operation. All-electronic converters achieve the lowest conversion time, which may range from microseconds to milliseconds. The upper part of this range is typical of devices in which a counting action is involved. The lower part of the range is typical of devices in which a parallel number is converted into a voltage amplitude. Converters in which electromechanical or mechanical elements are used will have conversion times ranging from tens of milliseconds to seconds.

Accuracy of Conversion

The achievement of high accuracy in the performance of conversion equipment poses the greatest problem to the designer. This is not surprising, since a part of any conversion device consists of analog equipment and is therefore subject to the usual accuracy limitations of analog equipment. These limitations are particularly severe when magnitudes of electrical voltages or currents denote the information. In analog equipment other than laboratory devices, accuracy of a voltage level to one part in 1000 is considered good. Hence conversion devices between voltages and pulse-coded numbers cannot, in practical cases, be expected to have accuracies much better than one part in 1000. Where the system is such that voltage levels represent the information at the input to a coder or voltage levels are required at the output of a decoder, this maximum possible accuracy does not pose a grave limitation, since whatever data processing precedes the coder or follows the decoder will have comparable accuracies.

However, if the system is such that the input to the coder is, for example, a shaft rotation, or the output of the decoder is required to be a similar mechanical displacement, the use of voltage levels in either conversion device may lead to unsatisfactory results. Mechanical displacements are frequently handled with an accuracy at least one order of magnitude better than electrical voltage levels. To achieve the full accuracy which the mechanical units in the system can exploit, properly designed conversion devices cannot involve parts which make use of electrical voltage levels, unless these parts are placed inside a closed loop. Such a loop is illustrated by the block diagram of Figure 2, which depicts a decoder having a shaft rotation as the output. In the feed-forward section of the loop, the error, expressed in digital form, is converted into a voltage amplitude by the decoder. The amplified output of the decoder energizes the motor which drives the output shaft. In the feedback section of the loop the shaft rotation is expressed in digital form by the coder. The loop is closed by the subtractor which compares the digital command with the digitally-coded response. In this block diagram, the entire burden of accuracy is placed on the coder, and the expected shortcoming of the digital-to-voltage decoder does not limit the accuracy to which the output shaft may be positioned.

Suitable coders for use in Figure 2 have been developed. One embodiment is the well-known coding wheel.[4] A recent design of a coding wheel with a diameter of about 10 inches has an accuracy of better than one part in 30,000. Still higher accuracy could be achieved if larger disc diameters were to be used, but the system would become more unwieldy.

At the present state of the art, coding wheels appear to be among the most accurate coders developed. Except for alignment difficulties in the reading equipment, their output is free from drift, and their accuracy is limited only by mechanical tolerances in establishing the code pattern. Through the use of closed-loop systems such as the one shown in Figure 2, coding wheels may be used in the design of decoders as well as coders, leading to devices comparable in accuracy to any but the very highest precision mechanical devices.

The high accuracy of conversion is achieved in a system of the type illustrated in Figure 2 at the expense of substantial complexity of equipment. If accuracy of one part in 30,000 is desired, a fifteen-digit reading system at the code wheel and a fifteen-digit subtractor must be supplied, in addition to the elements in the feed-forward section of the loop.

In some cases a saving in equipment can be achieved by using an incremental system, i.e., a system in which the command does not tell the shaft where to go with respect to an arbitrary reference point, but with respect to the point where the previous command has left it.

An illustration of an incremental system is given in Figure 3, which shows the decoding servomechanism used in the M.I.T. Numerically Controlled Milling Machine.[5] The input to the loop consists of a pulse train containing a number of pulses equal to the number of angular units through which the shaft shall turn. The unit of angular rotation chosen in this illustration is one degree, so that when, for example, the shaft is to turn 90° clockwise, 90 pulses are impressed on the upper command input to the reversible binary counter. Each command pulse is added to the contents of the reversible binary counter. An increase in the contents of the counter from normal, which is a number one-half the capacity of the counter, results in a positive voltage output from the coder and, through the amplifier and motor, in clockwise rotation of the output shaft. For each degree of rotation of the output shaft, a pulse originates from the coder on one of two lines, depending on the sense of the output rotation. For clockwise rotation, assumed in this example, the feedback pulses appear on the lower line from the coder and cause the contents of the counter to decrease. When the number of feedback pulses equals the number of command pulses, the reversible counter returns to normal, the decoder output is zero, and the output shaft comes to rest. When counter-clockwise rotation of the shaft is desired, the command pulses appear on the lower input line and the feedback pulses on the upper line from the coder. The coder consists of a wheel containing a commutator-like arrangement of alternate conducting and non-conducting segments which, in conjunction with interpreting circuitry, allow one synchronizing pulse to pass to one of the output lines for each degree of shaft rotation. The need for synchronizing pulses, which are arranged never to coincide with command pulses, arises from the fact that the reversible counter cannot add and subtract simultaneously and hence cannot handle command and feedback pulses at the same time.

When the long conversion time inherent in a system like that shown in Figure 3 is tolerable, the use of an incremental system of this type can give a very satisfactory design with moderate amounts of equipment. In the M.I.T. machine, 17-digit binary numbers can be handled, and yet a six-stage reversible counter and a six-stage decoder suffice. The amplifier and motor are of the usual instrument type. The code wheels used in the coders have mechanical pulse pickups, but photoelectric or magnetic pickups of equivalent functional performance can be developed and will probably lead to higher reliability. The interpreting circuitry associated with the code wheels consists of three flip-flops and six coincidence circuits.

A similar incremental system, the output of which is a linear motion, derives its feedback by counting the number of optical grating lines which pass a reference point.[6] Resolution to a fraction of a thousandth of an inch can be readily achieved in a practical system.

It should be noted that, unless special provisions are made, errors in an incremental system are cumulative. Thus if, in Figure 3, the coder fails to give an output pulse for every degree of shaft rotation, the missing feedback pulses will result in misalignment of the output shaft and this misalignment will perpetuate itself until the shaft is reset, either manually or by means of a supervisory circuit.

It has previously been emphasized that where high conversion accuracy is required, voltage levels must not be relied upon as a basic measure. The examples of high-accuracy converters cited have been shown to derive their high performance from optical gratings, coding discs, or wheels. Assuming properly designed and aligned reading circuits, the conversion accuracy depends only on the accuracy with which the lines or code patterns have been laid out. Mechanical tolerances thus determine the conversion accuracy. But while mechanical tolerances can be made to be small, equally small tolerances can be achieved electrically in the control of time or frequency, without recourse to specialized laboratory equipment. Thus designs of conversion devices which use an electrical measure of time as the accuracy-governing factor can be expected to result in high accuracy. No such devices appear to have been announced to date.

Holding Ability

Whenever a digital computer is used in a control system, a sampled data system results. With respect to the computer output, this means that the results of the computations are available not continuously in time, but at discrete values of time. In the interval between outputs from the computer, the decoder must be capable of remembering what the last output from the computer has been. We say that the decoder must have a holding ability.

One way to achieve holding ability in the design of a decoder is to incorporate a storage register into which the computer inserts its output. A storage register from which information can be read out continuously is required here. At the present time, such a register is still somewhat difficult to realize when operating speeds are too great for electromechanical devices, and the number of electron tubes must be limited.

Another way to achieve holding ability is to store the output of the decoder in analog form. Where voltage is the analog quantity, one might use a condenser for storage. Where shaft rotation is produced by the decoder, one might mechanically clamp the shaft. But very often storage in analog form is not satisfactory.

A third way to achieve holding ability involves storage in the time domain.[3] The number to be decoded is first converted into a linearly related time interval. This time interval is then remembered. Simultaneously, the time interval is continuously converted into a voltage amplitude.

The block diagram for a decoder in which holding ability is achieved in the time domain is outlined in Figure 4. The upper part of the figure shows how the number is converted into a pair of pulses, the time interval between which is proportional to the number. The computer presets the counter to the nines complement of the number to be decoded. The computer then starts the flow of clock pulses to the counter through the gate circuit marked G. When the counter has been filled, an end-carry pulse will appear at its output, which stops the further flow of clock pulses. The time interval, T, between the start pulse and the end-carry pulse is linearly related to the number to be decoded. Next, the pulse pair is held and converted into a voltage amplitude. The method involved there is shown in the lower part of Figure 4. The memory function is accomplished by the delay elements which are adjusted to have equal time delays, τ, and which are closed upon themselves. After the delay elements are cleared by the computer, a start pulse is generated. This pulse emerges τ seconds later from Delay 1, and every τ seconds thereafter. T seconds after the start pulse an end-carry pulse appears at the input to Delay Element 2, where it emerges τ seconds later and every τ seconds thereafter. Thus at time τ, 2τ, 3τ, ... $n\tau$ there is an output from Delay Element 1, and at time $T + \tau$, $T + 2\tau$, $T + 3\tau$, ... $T + n\tau$ there is an output from Delay Element 2. For every pulse on its upper input line the flip-flop is set to the 1 position and for every pulse on its lower input line, the flip-flop is set to the 0 position. Thus the flip-flop is in the 1 position for every T seconds out of τ. Since T is a linear measure of the number to be decoded, so is the duty-cycle of conduction of the 1 tube in the flip-flop. It only remains to remove the d-c component of the waveform at the plate of the 1 tube, which is accomplished by the low-pass filter. This completes the conversion process. It should be noted that the equipment in the upper part of Figure 4 may be shared by several channels. Each channel contains the equipment in the lower half of the figure and is connected to the common equipment by a switch.

Several devices may be used for the delay elements. In one application of this scheme, tracks on a magnetic storage drum are employed.[7] This is a particularly useful approach when the basic computer already contains a magnetic drum.

Summary

Some of the remarks made in the previous sections may be summarized as follows:

In designing conversion equipment for systems containing several signal channels, over-all equipment complexity can be reduced by time-sharing part of the converters between several channels. The number of channels which can share the common equipment is limited by the conversion time and the required sampling rate.

Accuracy is easiest to obtain by using time as a reference in an electrical system, or displacement or rotation in a mechanical system. An incremental system employing simple equipment can achieve high accuracy, but long conversion time results. Closed-loop techniques permit the use of a conversion device to its fullest accuracy as either a coder or a decoder.

In the interval between outputs from the digital equipment, decoders need to remember the previous output. This holding ability can be achieved conveniently in the time domain.

References

1. H. G. Follingstad, J. N. Shive, R. E. Yaeger, "An Optical Position Encoder and Digit Register," Proc. I.R.E., 40 (1952), 1573-1583.
2. H. J. Gray, Jr., P. V. Levonian, and M. Rubinoff, "An Analog-to-Digital Converter for Serial Computing Machines," Proc. I.R.E., 41 (1953), 1462-1465.
3. R. L. Sisson and A. K. Susskind, "Devices for Conversion between Analog Quantities and Binary Pulse-Coded Numbers," S. M. Thesis, M.I.T. (1950).
4. B. Lippel, "A High Precision Analog-to-Digital Converter," Proc. N.E.C. 7 (1951), 206-215.
5. J. O. McDonough and A. K. Susskind, "A Numerically Controlled Milling Machine," Joint AIEE-IRE-ACM Computer Conference, 1952, AIEE Special Publication S-53.
6. J. H. Brown, "Automatic Measurement of Lineal Motion Using Optical Gratings," Servomechanisms Laboratory, M.I.T., D.I.C. 6873 Engineering Report No. 3 (1951).
7. M. L. MacKnight and P. A. Adamson, "Multichannel Analog Input-Output Conversion System for Digital Computer," Convention Record of the I.R.E., 1953, Part 7, Electronic Computers, pp. 2-6.

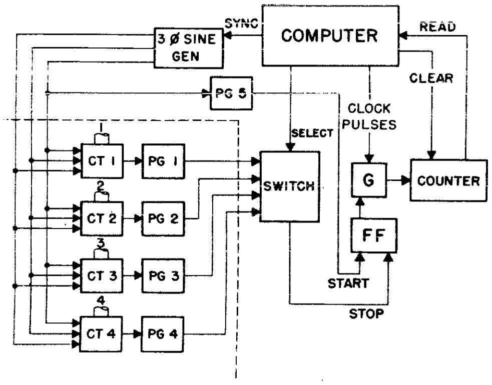

Fig. 1. Shaft-to-digital converters

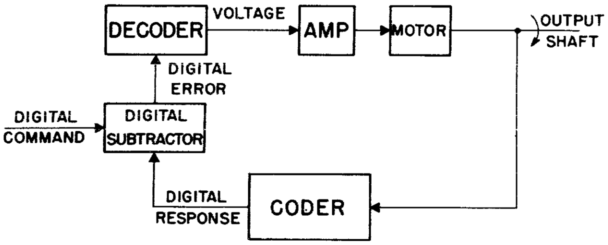

Fig. 2. Closed-loop decoder

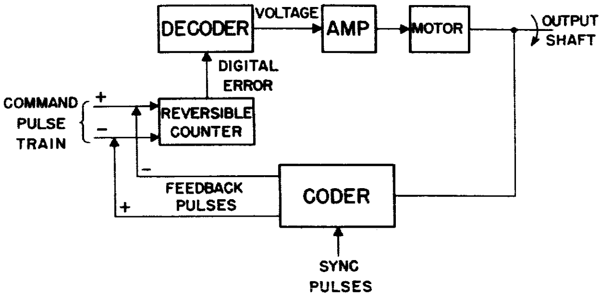

Fig. 3. Incremental decoder

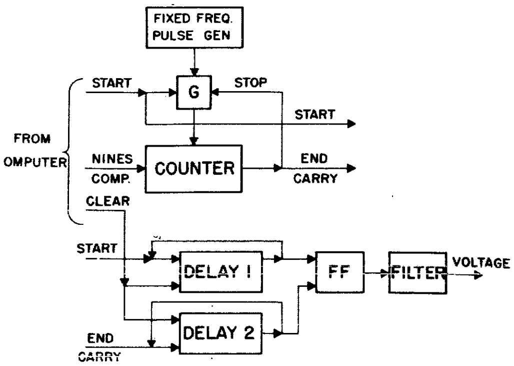

Fig. 4. Decoder with holding ability

MULTI-CHANNEL ANALOG-DIGITAL CONVERSION SYSTEM FOR D-C VOLTAGES

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This report is intended to cover a successive approximation type analog-digital converter which was designed for use in an airborne digital computer developed by Hughes Aircraft Company on an Air Force Contract. The unit which was developed was required to digitalize as many as 32 input voltages and derive the analog voltage from 32 digital output quantities in approximately 15 milliseconds. Critical requirements on space and weight of equipment, coupled with the large number of inputs and outputs, dictated the use of a common converter which could be multiplexed on a time basis among the various inputs and outputs.

Some of the more important specifications to be met were the following:

1. Inputs - 32; 0-100 volts dc; accuracy ± $\frac{1}{2}$% of full scale; sampling time, 200 μsec; sampling rate, 60 cycles; impedance of inputs, 200K min during sampling time.

2. Outputs - 32; 0-100 volts dc; accuracy ± $\frac{1}{2}$% of full scale; sampling time, 200 μsec; sampling rate, 60 cycles; maximum ramp, full scale in $\frac{1}{2}$ sec; load to be driven, 50K ohm min.

3. Digit rate - 160 kc.

4. The conversion needed to be done so that results were proportional to a system reference voltage.

5. The equipment was to be production designed to meet JAN specifications for airborne electronic equipment.

6. Critical limitations on size, weight, and power were to be considered.

7. Reliability requirements of a tactical military system had to be borne in mind.

Equipment designed to meet these specifications has been built and tested. A block diagram is shown in Figure 1. It consists of a decoder and inverter amplifier, which are used in common on all conversions, plus a control unit, a memory, individual power output stages, and electronic switches for connecting the desired input or output channel into the decoder.

The decoder consists of an 8-digit register, a binary current weighter, and a comparator amplifier. An analog input is converted to binary code by a series of comparisons of the input voltage to standard voltages supplied by the current weighter. The comparator amplifier, through the control unit, sets up the register according to the results of these comparisons. The binary-coded input is then shifted by the control unit into the computer memory for use as needed.

A binary-coded output is converted by shifting it from the computer memory to the register. Each flip-flop in the register controls a gate in the current-weighter which releases a current into the summing point proportional to the significance of the flip-flop. The output of the weighter, through the comparator amplifier, controls the charging of the output memory capacitor. This capacitor is necessary to act as analog memory between sampling intervals.

Figure 2 graphically illustrates the analog-to-digital conversion of an input quantity.

1. Assume that an input d-c voltage of 7/8 F_{FS} has just been selected by the control unit for conversion.
2. At T_0, which is the beginning of the 200-μsec sampling interval, the appropriate input selector switch is closed by control unit signals and the same unit shifts zeros into the register to clear it.
3. From T_0 until T_{100}, the circuit is permitted to stabilize so that the voltage at the output of the inverter amplifier is proportional to the selected input within ± 0.1%.
4. During the interval T_{100} to T_{200}, the following staircase sampling takes place, which involves the control unit, register, current weighter, and comparator amplifier:
   a. From T_{100} until T_{120}, the half-scale stage of the current weighter is energized by the appropriate register stage and this current is compared with the current from the input; I is proportional to 7/8 I_{FS}. Since the current from the register is not of sufficient magnitude to bring the summing node of the comparator amplifier to the ground reference, this stage of the weighter is permitted to remain "on" by the controlling output signals from the comparator amplifier.
   b. From T_{120} until T_{140}, the quarter-scale stage is closed in the weighter and the sum of this current and the half-scale current is compared in a similar fashion, this stage also being permitted to remain on at the end of the sampling interval.
   c. In a similar manner, the control unit closes eighth-scale and the comparator amplifier permits it to remain on; however, from T_{150} until T_{200}, as the control unit applies the remaining weighted currents, the comparator amplifier finds that its input has reversed, indicating that the current from the weighter is too great, so the comparator amplifier output signals return the remaining register stages and weighter to the zero state.

d. Consequently, at the conclusion of the sampling interval, the register is set as a binary representation of the input voltage. Since it is an 8-digit register, resolution is 1/256.

e. During the interval T_{200} until T_{300}, the register shifts the coded information into the memory and starts the conversion process on the next input voltage.

Since the decoder is fundamentally an output device, digital-to-analog, it could easily be used to derive an output d-c voltage by means of an operational summing amplifier. Such an amplifier would be required to deliver up to 100 volts into 50K-ohm load with a linearity of ± 0.1%. This was impractical with the limited supply voltages imposed by the use of subminiature tubes. To hurdle this problem, it was necessary to supply a feedback connection from the individual outputs to the input of the inverter amplifier. Because the decoder is time-shared by all the inputs and outputs, electronic switches are used to make this connection. With the incorporation of this feedback, the comparator needed to have only the requisite zero stability, about 10mv, and sensitivity, about 5mv; linearity was of little importance. The use of feedback on this circuit makes possible the use of an on-off type of servo. The power gates consist of two electronic switches, each of which connects a current source to the memory capacitor, one (+) and one (-). These switches are selected by the control unit and operated by the comparator amplifier output. A (-) output connects a (+) source to the capacitor and a (+) output connects a (-) source.

As indicated above, for an output conversion the computed result from the memory is shifted into the current-weighter register and the feedback switch for the associated output is closed. This is done in the first 100 μsec of the 200-μsec sampling interval (see Figure 3). The output from the binary weighter is permitted to stabilize during this interval, and the appropriate feedback selectro switch is closed, thereby applying the previously stored analog output voltage to the inverter amplifier for comparison with the new value from the current weighter. From T_{100} until T_{200}, the corresponding output power gate receives the proper signal from the comparator amplifier to raise or lower the voltage on the capacitor. If during this interval equilibrium is reached, alternate charging and discharging of the output condenser will result until the control unit disconnects the power gate at the end of the 200 μsec interval, T_{200}.

The loop which is involved in servoing of an output voltage consists of the power gate and the inverting and comparator amplifiers. The sensitivity of this loop, which is essentially the forward gain of the comparator amplifier, and the loop lags are the factors which determine the peak excursions in the servoing of an output voltage for any ramp driving function. It was not difficult to increase the forward gain of the loop so that it was no longer a determining factor and only the loop lags remained. For this design the lags amounted to about 2 μsec. For the specified ramps this results in hunting of ± 1/2 digit.

The limiting accuracy of this system is mainly determined by the resistors used in the current weighter. To maintain a weighter with an accuracy of ± 0.3%, it was necessary to use resistors with a tolerance of

± 0.1%. It was also necessary to control the shunt capacity of the units. As it turned out, this did not impose a problem because many commercially available wire-wound resistors would easily meet our requirement. Wire-wound units were used because there was no other available resistor with the necessary initial tolerance or temperature coefficient.

The zero stability of the system is limited by the electronic switches. To minimize the variation in this offset, dual diodes were paired in such a manner as to take advantage of the closer balance established by JAN controls for diodes in the same envelope. The JAN control imposed gives a spread of ± 250 mv. It may be of some interest that tests of a few hundred diodes from several lots indicated that this spread amounted to only ± 100 mv.

The linearity of these switches was better than ± 0.1%, operated in the circuit over the full range of input-output voltages. Zero stability within the inverting and comparator amplifiers was achieved by the use of chopper-stabilized amplifiers.

Parasitic or undesired capacities and leakage currents were effectively reduced by boot-strapping wherever possible. For example, heater-cathode leakage in the capacitor power gates was troublesome, but it was essentially eliminated by boot-strapping of the filament which was associated with the cathode tied to the memory capacitor.

Final checks on the system proved that the deviations from analog input voltage to binary code and from binary output to analog output voltage were within the basic tolerance of ± 0.5% of full scale. More meaningful information of statistical significance is presently being gathered by using the associated computer in special checking routines. It is hoped that the distribution of error for any possible number may be obtained by this method, which will take into consideration systematic errors due to component tolerance and errors due to all sorts of noise components, such as short- and long-term random component changes.

The size and weight requirements were met by using miniature and subminiature components and using advanced packaging techniques, such as etched circuitry. The final weight of the equipment was about 60 pounds and it occupied approximately 1.6 cubic feet. The power consumed by the units amounted to about 650 watts. The figures do not include the drum memory unit.

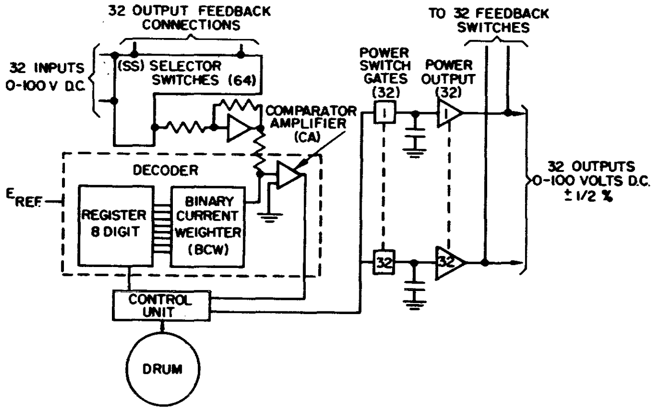

Fig. 1. Block diagram

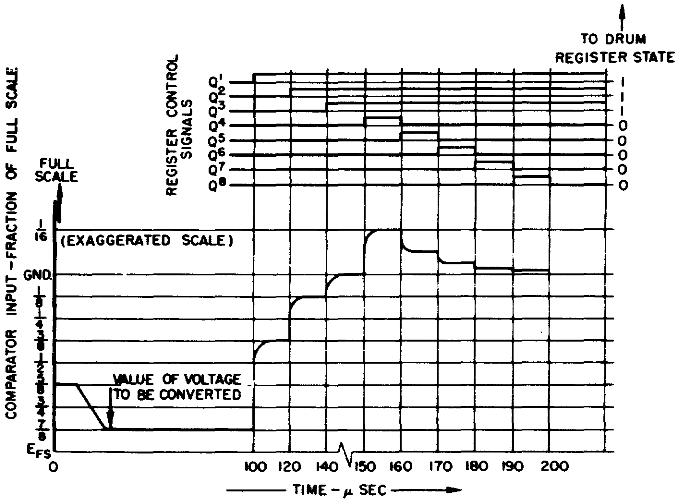

Fig. 2. Analog-digital input conversion

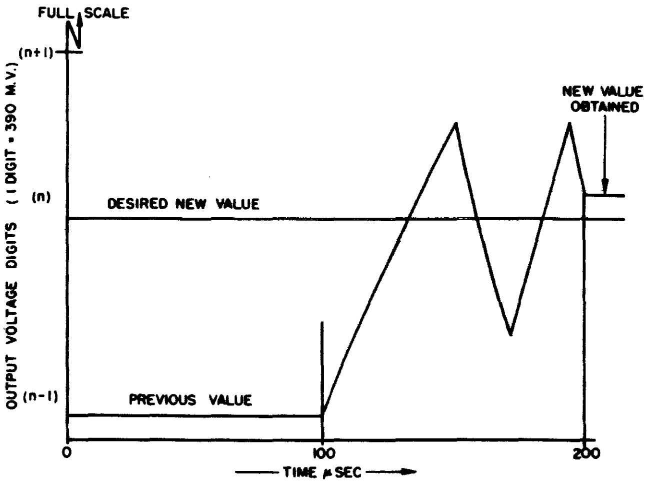

Fig. 3. Digital-analog conversion-output

A HIGH-SPEED MULTICHANNEL ANALOG-DIGITAL CONVERTER

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Introduction

The large-scale tests of aircraft, missiles, and components necessitate the recording of many parameters. These parameters are usually converted by transducers or pick-up devices to voltages proportional to the magnitude of the physical quantity being measured. The many resulting voltages may be recorded for later analysis, used immediately for performance calculations and for control, or they may be both recorded and used immediately. If the data is recorded, it is ideally done on a multi-channel recorder. The quantity of data taken on large-scale tests and the complexity of performance calculations make it desirable to obtain the data in a form suitable for digital computation. Since the final form of the data is frequently digital in nature whether it is recorded for future use or is used immediately for computation, a multi-channel high-speed analog-to-digital converter would greatly simplify the preparation of analog data for digital computation and tabulation. A high-speed multi-channel analog-to-digital converter and a complete data system of which it is a part will be discussed in this paper.

Description of the System

The system was designed for the specific needs of static structural load tests of airframes. The requirements of this system are, however, similar to those of other large-scale tests, differing only in the method of display and in the storage medium. Figure 1 is a block diagram of the entire data system. The inputs are 400 strain gages which must be read and recorded in less than two seconds. Since each strain gage can be in either tension or compression, it is necessary that the system be capable of measuring both positive and negative voltages. The strain gages are energized by a DC voltage giving a DC output in the low millivolt range. Since the system will measure these low voltages, it will work equally well for thermocouples, resistance thermometers, and other pickup devices producing a DC voltage and is not limited in the type of input. The 400 strain gages are sampled in sequence by the commutator which programs the entire recording operation. The actual switching of the inputs is done by 400 sets of mercury relays operating as the plate loads of 400 6L6 tubes. These relays were chosen for their low noise level, long service life, and fast operating characteristics. The relays selected are single-pole double-throw break-before make relays with a closing time of approximately .5 milliseconds. The drop-out time, however, is considerably longer and is not constant. The contacts in the relay consist of two sets of two contacts and a wiper. When the relay is not energized, the wiper connects one set of contacts; where energized it connects the other set. To compensate for the variable drop-out time of the relays, the input signal is connected through the normally closed contacts of a relay to the normally open contacts of the preceeding relay. Thus, the closing of a relay connects a gage to the converter and opens the connection of the previous gage, giving a constant period for each channel.

The converter, shown within the dotted lines, consists of a modulator and amplifier, the logical gates and summing networks, the write gates, and, in this system, a clock pulse shaper. The clock pulse is recorded on the magnetic drum and provides the basic frequency for the entire data system. The output of the converter is recorded on the magnetic drum for later recovery through the readout gates and output registers. This system will, in less than two seconds, convert and record the readings of 400 strain gages used in structural tests.

The tests for which this system was designed consist of taking a set of readings on 400 strain gages for each of 20 structural loads. To prevent creep or fatigue at the higher load levels, it is necessary to take the data rapidly and release the load immediately. After each load, the strain is plotted against per cent of full load. Thus, any non-linearity indicating that the elastic limit has been reached is found before structural damage occurs in the member under test.

Performance of the System

Programming

The programming of the recording system is shown in block diagram in Figure 2. For a recording cycle there are six binary counters and two selector switches required. The logical levels used throughout the converter system are a +20 for true and zero or ground for false. The clock pulse is a 120 KC negative pulse of .1 microsecond duration and a 20 volt amplitude, biased to +20 volts during the off period. The clock pulse originates from the magnetic drum turning 3600 r.p.m. In addition to this clock pulse, there is a single pulse on a separate drum channel for orientation on the drum and four quadrant pulses; the first coincident with the single pulse and a clock pulse, and three others separated by at least 508 clock pulses and coincident with a clock pulse. The negative clock pulse, applied to the grid of the conducting tube in a flip-flop, triggers it to the other stable state. In the block diagram, a square block designates a coincidence or a one to one correspondence between quantities; a circle designates an inverter where a false input results in a true output and vice versa; a triangle with the inputs extending within the triangle designates a sum gate where the output is true if any input is true; and a triangle with the inputs terminating at the side opposite the output designates a product gate and is true only if all the inputs are true.

The "C" and the "D" counters are five stage binary counters gated to count to 24 and 20 respectively and returning to zero with a quadrant pulse. Counter "C" returns to zero also with a 24 count and a clock pulse. K and L are 20 position selector switches which set five double-pole double-throw relays each to a binary representation of numbers between one and 20. When K is advanced one position to the next number, L advances to become the old value of K. The configuration of D, K and L are compared in two coincidence gates and the true signals from each gate are fed to a sum gate; the output of this gate being true whenever there is a coincidence between D and K or D and L. The output of the D and K coincidence gate is also fed to a product gate along with the 24 count of C counter, and the three count (fourth quadrant) of the Q counter. The output of this product gate, which is false at all times except at the 24 count of C counter when there is a coincidence of D and K in the fourth drum quadrant, is fed through an inverter to a product gate with the clock pulse. The output of this product gate, R_x, is fed along with the output of the D and K or D and L sum gate, to a product gate. The output of this product gate is a string of pulses, coincident with and similar to the clock pulse. In the first three quadrants of the drum this string of pulses will be 50 pulses long; 25 pulses during the coincidence of D and L, and 25 during the coincidence of D and K. In the fourth quadrant of the drum, however, there will be only 49 pulses; 25 during the coincidence of D and L and 24 during the coincidence of D and K. These pulses are counted by the R counter which counts zero to 24 and returns to zero. This counter originally is set at zero, and the zero count regresses 1 clock pulse each revolution of the drum. The zero count is used as the output of this counter and serves to program the entire recording cycle. It is fed to two product gates; one a product with the coincidence of D and K, the other a product with the coincidence of D and L. The product with D and L produces a pulse (P) which is used to initiate one conversion cycle in the converter. The second product, occurring 25 clock pulses later, is used to select the next input from the 16 x 25 matrix driven by counters Q, S, and G, and to record the value of the input just converted. Thus, during one revolution of the drum, four inputs are selected and recorded. A particular input is selected and 475 clock pulses later, conversion of its voltage to a digital output is started and 500 clock pulses later it is recorded. With each revolution of the drum, the information is stored displaced one clock pulse later in each quadrant because of the retrograding of the R counter. There are 36 write amplifiers on the drum, and 100 channels are recorded on nine drum tracks each 25 revolutions of the drum. The product gates shown are used for the write amplifier selection.

Since, during a test, it is necessary to examine the results of previous structural loads, the read gates are also shown. In the read programming, a four position (M) and a 25 (N) switch are added. A coincidence between the M switch and the Q counter selects the quadrant and a coincidence between the M switch and the C counter and a coincidence between the D counter and S counter selects the clock pulse address within the quadrant. For oscilloscope display, all readings (20) of a particular input channel are read in 20 revolutions of the drum or in 1/3 of a second. For printing the results, one reading is taken each 25 revolutions of the drum or every 25/60 of a second. There are only nine read amplifiers which are connected by a selector switch to one of the four groups of tracks formed by the write program. Thus, the input channels are divided into four groups 1-100, 101-200, 201-300, and 301-400 for reading depending on the connection of the read amplifiers. This completely programs the data system used for structural testing of airframes. Not shown on the diagram however, is the 16 x 25 matrix for input selection and the write gates for the write amplifiers.

Converter

The analog-to-digital converter is shown in Figure 3 by block diagrams. It consists of a pulse source, a modulator, an amplifier and filter, a phase discriminator, the summing network, and the logical circuits. The 120 KC pulse generator is driven by the clock pulse channel on the magnetic drum. The clock pulse is used for synchronizing a 480 KC oscillator and for the logical gates. The 480 KC oscillator is used for the bridge modulator excitation as shown. Two arms of the bridge are matched diodes, the other two arms are resistances. A balance potentiometer is connected as shown for compensation of any initial unbalance. Across the bridge there are a one ohm precision summing resistor, an input resistor, and an output transformer. The output of the modulator, a 480 KC sine wave equal in amplitude to the unbalance voltage across the modulator and of a phase determined by the sign of the unbalance voltage, is amplified and filtered for the input to the phase discriminator. The action of the phase detector will be explained in more detail in Figure 4, but it forms a Z signal which is true for one phase of the modulator output and false for the other. The true Z output indicates a positive voltage across the modulator and the false Z output indicates a negative voltage. This Z signal is used in the logical gates to determine the action of the converting cycle.

A conversion from an analog input to a digital output is accomplished in 16 time intervals defined by the four stage, B counter. The B counter rests in the one state until it receives a pulse P from the programming circuits. It then advances with each clock pulse through 15 configurations and returns to one until the pulse P. The configurations of the B counter are used, with the clock pulse, to trigger the nine A flip-flops. The final state of these nine flip-flops is recorded as the output of the conversion. Nine cathode followers are driven by these nine flip-flops. In the cathode circuit of each cathode follower there is a precision summing resistor clamped by a diode to a reference voltage and connected to the one ohm precision resistor in the modulator circuit. When each cathode follower is conducting, it adds current through the one ohm resistor and generates a voltage across the one ohm resistor. The current, voltage generated, and the digital value of each of the nine cathode followers is shown in Table I along with the time interval in which conduction is started.

Flip-Flop No.	Milliamps Current Thru 1r Resistor	Millivolt Voltage Across 1 ohm Resistor	Series Resistance	Digital Value	Time Interval
A_1	3.00	3.00 m.v.	5K	100	2
A_2	1.50	1.50 m.v.	10K	50	5
A_3	.60	.60	25K	20	7
A_4	.30	.30	50K	10	9
A_5	.30	.30	50K	10	10
A_6	.15	.15	100K	5	11
A_7	.06	.06	250K	2	12
A_8	.03	.03	500K	1	13
A_9	.03	.03	500K	1	14

TABLE I

Through the one ohm resistor there is also a current of 3 ma. from a precision negative supply generating a -3 mv. signal across it. A product of the two time interval and a clock pulse triggers the A_1 flip-flop true, causing a current of 3 ma. to flow through the one ohm resistor, generating a +3 mv. signal. This current continues until the 5 time interval when a comparison with the input voltage is made. If Z is true, the product of the clock, time 5, and Z triggers A_1 false, if Z is false, A_1 is left in the true state and the current continues to flow through the one ohm resistor. The sum of the A_1 current and the -3 ma. from the negative supply is zero and thus, the A_1 flip-flop determines the sign of the input voltage, remaining on if the input is positive and turning off if the input is negative. A_2, which along with A_3 through 9, was triggered false at time 2, is triggered true at time 5. The cathode follower for the A_2 true generates a current of 1.50 ma. in the one ohm resistor, representing a count of 50. At the 7 time, A_2 is left true if Z is false or is triggered false if Z is true. Also, at the 7 time, A_3 is triggered true. It results in a current of .6 ma. in the 1 ohm resistor and represents a count of 20. At the 9 time, A_3 is triggered false if Z is true and left true if Z is false. Similarly, A_4 is triggered true at time 9 and represents a count of 10 (.3 ma.); A_5 at time 10 representing a count of 10 (.3 ma.); A_6 at time 11 representing a count of 5 (.15 ma.); A_7 at time 12 representing a count of 2 (.06 ma.); A_8 at time 13 representing a count of 1 (.03 ma.); and, at time 14, A_9 is triggered true representing a count of 1 (.03 ma.). In each case, the flip-flop is triggered false if Z is true and remains true if Z is false. At the 16th time interval, if Z were false at time 5, A_1 and the 16 time interval cause A_2 through 9 to compliment. This is necessary since a -3 mv. is used as a reference and it is desirable to measure all voltages from ground. In this manner, a digital output proportional to the input voltage is generated in 16 time intervals. Since the clock frequency is 120 KC, the total time required for a conversion is 132 microseconds. The code 50, 20, 10, 10, 5, 2, 1, 1 was chosen in this application because it simplified the readout for display purposes. However, any code can be used by changing the values of the summing resistors. Also, the full scale output can be changed by changing the value of the 1 ohm resistor within the limit that the resistor must be small compared to the other resistors.

Phase Detection

The action of the modulator and phase detector will be made more clear by examining Figure 4. In this figure, the wave forms at the detectors are shown for three input voltages. The lower wave form is the clock pulse, a 120 KC, -20 volt, .1 microsecond pulse. Above it is the delayed clock pulse which is a +20 volt, .25 microsecond pulse delayed 5.67 microseconds after the clock pulse. The lower sine wave shows the wave form from the modulator after amplification and filtering for an input voltage of -1.39 mv. During the first and second time interval, a sine wave proportional to the input voltage is generated. It will be noted that the delayed clock pulse occurs at a negative peak of the sine wave. At the end of the 2 time, the +100 count is added to the one ohm resistor when A_1 is triggered true. The addition of the A_1 count causes a phase reversal and causes Z to become true when the delayed clock pulse and the positive peak coincide. Thus, at time 5, A_1 is triggered false and A_2 is triggered true, adding 1.5 mv. to the -3 mv.

across the one ohm resistor. The resultant -1.50 mv. across the one ohm resistor is less than the -1.39 mv. input and again we get a phase reversal. At the 7 time, A_2 is left on since the delayed clock pulse is coincident with the negative peak and Z is false. Also at the 7 time, A_3 is turned on, adding an additional .60 mv. or a count of 20 to the one ohm resistor. The resultant 2.10 mv. again causes a phase change and causes Z to be true, turning A_3 off at time 9. At time 9, .30 mv. or a count of 10 is added by A_4 to the 1.50 from A_2. The resultant 1.80 is again too great and A_4 is turned off and A_5 is turned on at time 10. A_5 likewise adds .30 mv. or a count of 10 to the 1.50, and is turned off at time 11. At time 11, A_6 adds .15 mv. or a count of 5 to the 1.50. The 1.65 mv. is again larger than the input voltage and A_6 is turned off at time 12. At time 12, A_7 is turned on, adding .06 mv. to the 1.50. Since the delayed clock pulse does not coincide with a positive peak, A_7 is left on at time 13 and A_8 is added. A_8 adds .03 mv. to the 1.56 and remains on at time 14. At time 14, A_9 adds a 1 count to the 1.59 mv. and is turned off at time 15. Then since A_1' is true, A_2 through A_9 are complimented at time 16. The resultant output is a count of 20 + 10 + 10 + 5 + 1 = 46 or, since each unit represents .03 mv., represents an input of 46 x .03 = -1.38 mv.

The sine wave in the center represents the wave form at the phase detector with a zero input. At time 2, as before, a count of 100 is added and at time 5 is left on since the delayed clock pulse does not coincide with a positive peak. At all other times, the flip-flop is turned false since the sum of A_1 and any other flip-flop is greater than zero. At time 16, the number does not compliment since A_1 is true and the resultant output count is zero.

In the upper curve, the sine wave represents an input of +1.39 mv. to the converter. Again, at time 2, a count of +100 is added to the -3 mv. reference and is left on at time 5. At time 5, a count of 50 or 1.50 mv. is added and is too great. Thus, at time 7, the 50 count is removed and a +20 count is added. This remains on at time 8 and a count of 10 is added. This remains on at time 9 and another count of 10 is added. At time 11, this 10 count also remains on and a count of 5 is added. This too remains on and, at time 12, a count of 2 is added. This is too large and is turned off at time 13 when a count of 1 is added. This count of one remains at time 14 when another count of 1 is added. This last count is too great and is removed at time 15, leaving an output count of 46 or +1.38 mv.

The phase detector is basically a coincidence circuit between the 480 KC sine wave and the delayed clock pulse. The 480 KC sine wave is clipped and shaped and, with the delayed clock pulse, is fed to the input grids of a 6AS6 gate tube. The output of the coincidence on the 6AS6 triggers the Z flip-flop true and each clock pulse triggers Z false. Thus, Z is false unless triggered true by the phase detector.

Conclusions

This converter has proven quite reliable. The code can be changed quite easily to fit any computer code and the number of significant digits can be increased by utilizing the time intervals not in use. When these circuits were designed, it was felt that these time intervals might be needed to allow transients to die out but this is not the case. Thus, using this same code, the number of significant digits, with a correspondingly higher input voltage, could be increased to 999 by adding a 100, 200, 500 and 1000 count. Also, the rate of conversion can be doubled by redesigning the gating circuits if more rapid conversions are necessary. Preliminary experiments have indicated that a clock frequency of 1/2 m.c. would not be too difficult to achieve if circuit techniques reducing distributive capacity were used.

Acknowledgments

The author is deeply indebted to Mr. A. Untrauer and Mr. L. Fisher for much of the circuit design and checkout of the circuits described here. Also, he is indebted to the International Research Corporation of Santa Monica for their cooperation in designing and building the magnetic drum and associated circuitry.

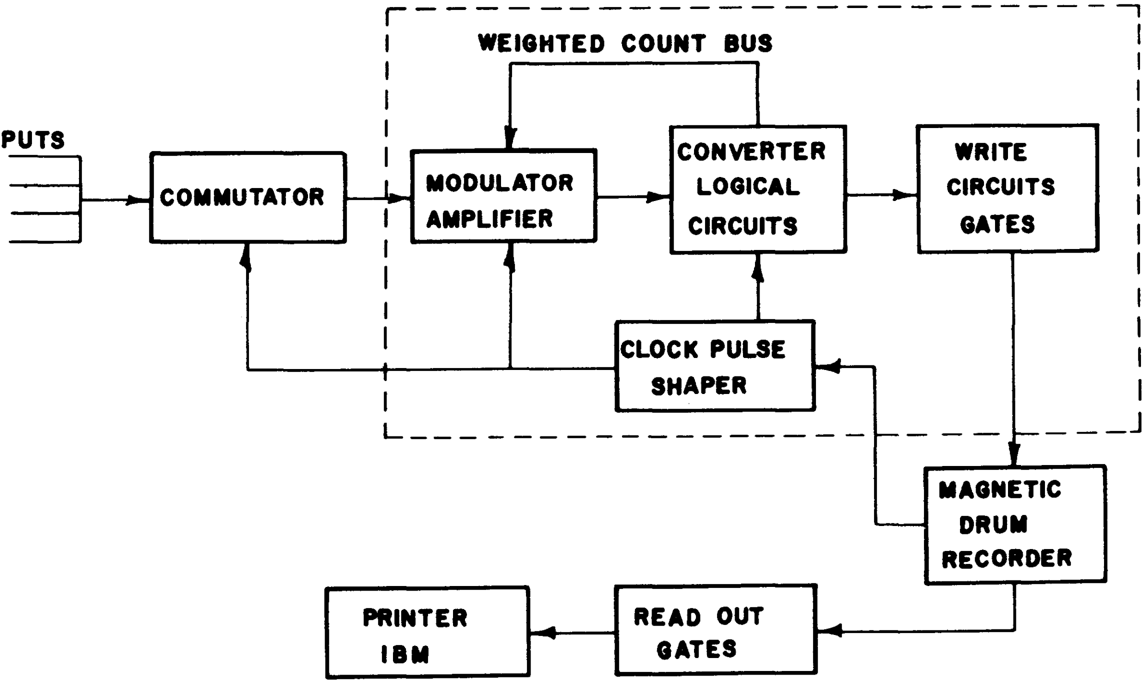

Fig. 1. Block diagram - converter system

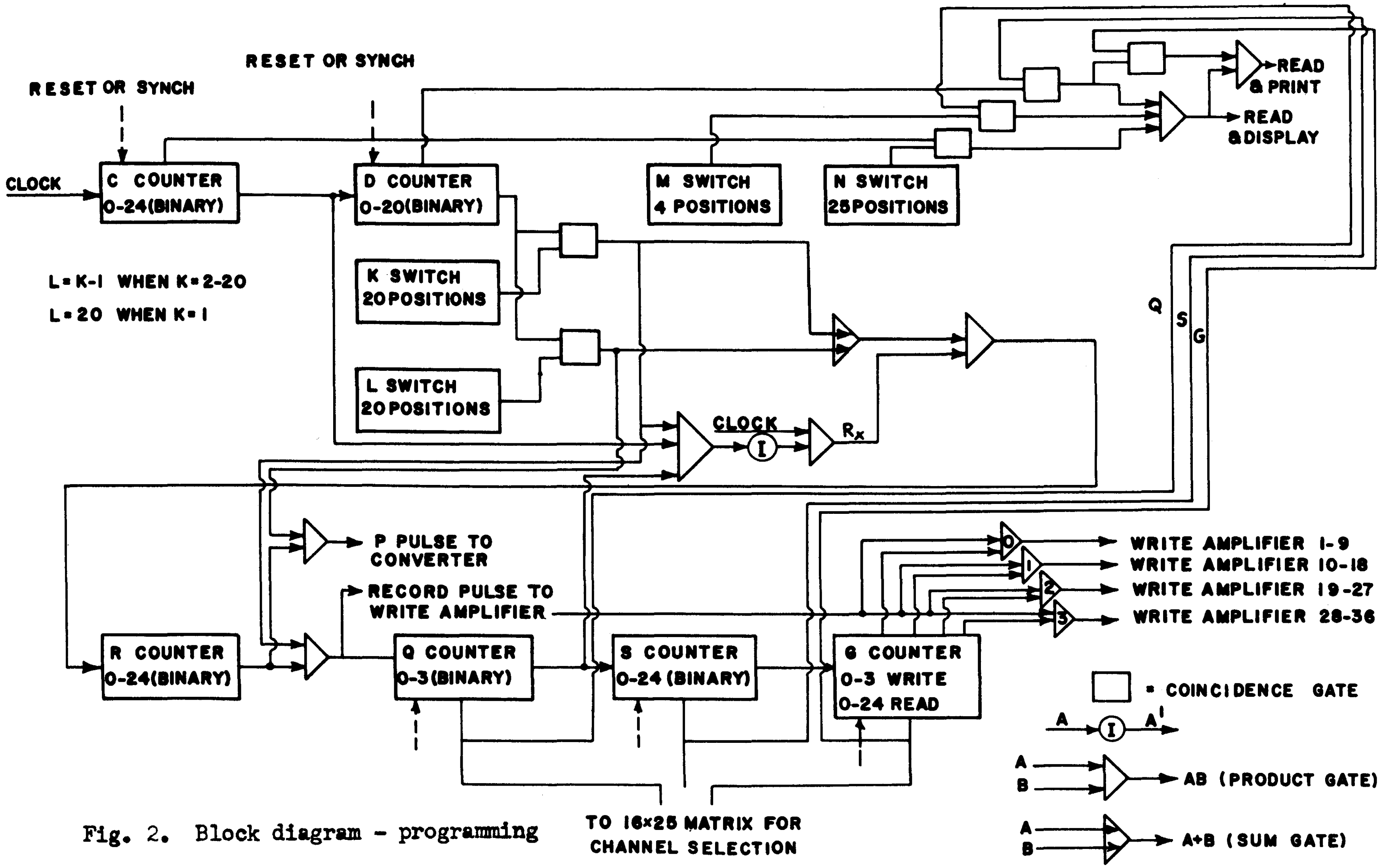

Fig. 2. Block diagram - programming

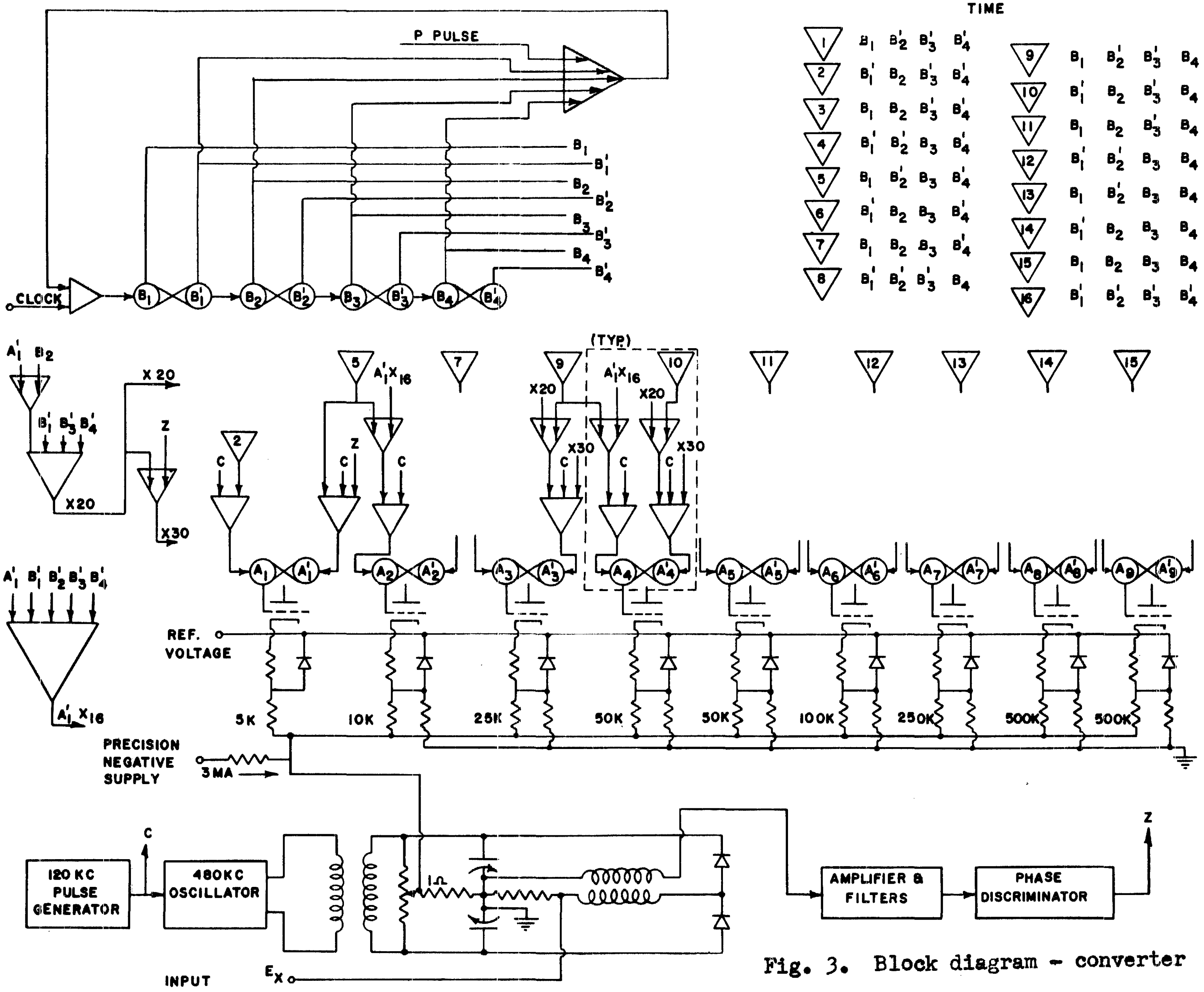

Fig. 3. Block diagram - converter

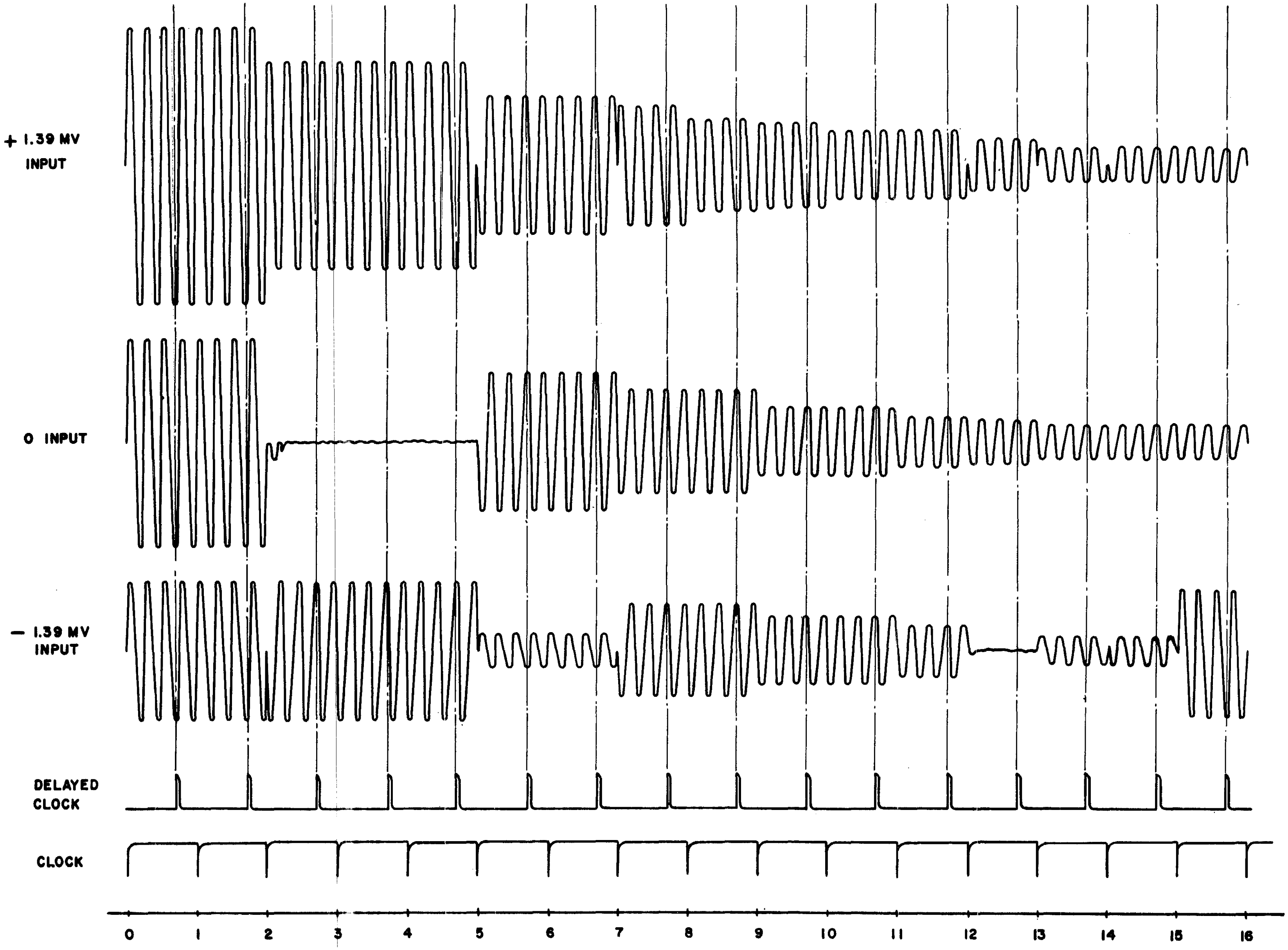

Fig. 4. Waveforms at phase detecter

A SHAFT-TO-DIGITAL ENCODER

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INTRODUCTION

The increasing application of digital techniques, particularly in control systems, has heightened the need for a device capable of translating shaft position into a digital representation. A survey of technical literature of the past several years indicates that many approaches to such a device have been made. This paper is presented to describe what is believed to be a unique approach to the problem of shaft-to-digital conversion.

Since shaft positions are commonly found as inputs in many digital control systems, these angular positions must be translated into digital form. The device to be described is capable of accepting a rotational input and yielding a parallel binary code which represents the angular position of the input member. Since digital techniques are often employed to maximize the system accuracy, the translation from shaft position to digital form must be at least as accurate as the input member. In some cases, where the shaft position involved is an element of a highly accurate closed-loop system, a relatively large number of binary digits may be needed to represent an angular position. In other cases, fewer digits may be required, in which case, the number of digits must be compatible with the accuracy of the input shaft position.

Since the shaft-to-digital encoder under discussion has immediate application in several different systems, a flexible unit was sought. Flexibility was achieved by repeated use of identical components which could be added or removed as demanded by the particular application. This type of construction minimized the number of different parts and, consequently, the over-all cost.

The important problem to be solved in this type of device was that of eliminating ambiguities. Very often, special codes are employed which change only one digit at each transition. The use of special codes often requires additional equipment to translate the special code into a form compatible with the system involved. The encoder discussed here, by its unique operation, has a straight binary code output with all ambiguities avoided.

CHARACTERISTICS

The encoder is characterized by light weight, small size, low torque, and long life. The output is in the form of parallel lines, each being at one or the other of two voltage levels representing the ones and zeroes of a binary number. The number represents the angular position of the input shaft. The actual character wheels are not merely alternately conducting and non-conducting segments, but are segments connected alternately to one or the other common bus. The two voltage levels involved can be set by the user since the common buses supplying them are made available.

A feature of this unit is the ability to accomodate a synchronized switching from one number to the next. Obviously this can only be done if timed pulses at a rate higher than the rate of change of the least significant digit of the converter are available. This is the prevalent case since, in general, shaft positions change slowly compared to electronic pulse rates available in the systems into which they work. Two important characteristics of the unit that result from this synchronized switching are; that the switching can be done at a time when no data pulses are present, and that the switching time can be a few microseconds since it is electronically derived.

The converter is also able to read out either the number or the complement of the number upon demand. This change from number to complement can also be accomplished at microsecond rates, thus allowing operations of addition and subtraction by complementing as is common in binary arithmetic.

The block diagram of Fig. 1 can be used to demonstrate the functional operation of this digital encoder. A shaft to be monitored is connected to shaft 1. This shaft is connected through a 1-to-256 gear ratio to shaft 2. Four identical gear stages are used. This particular gear ratio is chosen for encoding the input shaft into 512 (2^9) discrete numbers. The reason a particular gearing is required is that the least significant digit wheel has 16 segments on its circumference. For 9 binary digits this least significant digit must undergo 512 changes for a complete revolution of the input shaft. This means that shafts A and B must travel 32 revolutions for 360° of input rotation. Shafts A and B are geared to shafts 3 and 4 respectively through a 1-to-4 gear ratio whereby shafts 3 and 4 will make 128 revolutions for 32 revolutions of shafts A and B. Connected to shafts 3 and 4 are star wheels having four slots separated by 90°. These slots engage the pins of the spider connected to shaft 2. Since the spider has two pins engaging 4 slots of the star wheels, shaft 2 will travel twice as fast as shafts 3 and 4. Therefore, shaft 2 will make 256 revolutions for 32 revolutions of shafts A and B or 256 revolutions for 360° of input rotation. These conditions then satisfy the requirements for encoding the input shaft position into 512 discrete numbers.

The intermittent spider and star wheel drive is chosen so that by using two parallel banks, one of the two banks is stationary while the other is in motion. This is easily accomplished by mounting the pins on the spider so that they engage the two star wheels 90° out of phase. This alternate moving of banks permits reading out from a stationary set of digit wheels at all times.

To select the proper bank to be read, a timing wheel is mounted on shaft 2. This timer has four segments on its wheels and since it is geared up in speed by a factor of 8 from shafts A and B, it will experience 1024 changes for one input revolution. This permits two bank selections for each least significant digit of input rotation. A more detailed operation of this timing is indicated below.

The two banks consisting of three cylinders each are identical in construction. In turn the six cylinders are identical and consist of six wheels keyed together on a common shaft. The periphery of the outer two wheels of all cylinders is solid conducting material. These outer wheels serve as slip rings through which the two voltage levels are introduced into the particular cylinder. The inner four wheels consist of 16, 8, 4, and 2 segments making the character wheels for four binary digits. Alternate segments of each wheel are connected together and to one or the other of the slip rings.

The gearing between cylinders is accomplished by geneva transfers in which case the cylinder is locked in position at all times except when a carry is propogated. The effective gear ratio is 16-to-1 thus propogating a carry for the four binary digits of the previous cylinder.

Since the requirements for this unit were originally for eleven binary digits, a choice of the number of cylinders and gear ratios to meet these requirements had to be made. Since small size was necessary, it seemed hopeless to try to use one cylinder in which case the least significant digit would have to have 2048 segments, since the minimum number on any wheel is 2 segments. The converter as it stands then, is a compromise between a large number of segments on any one wheel and a large gear ratio at the input.

A brush block of six brushes forms an integral unit serving as read out and voltage supply. Again the six required brush blocks are identical.

The size of this unit is extremely small and the fabrication was carried out essentially as a watch-making operation. The cylinders are one-quarter inch in diameter and mounted in the housing with the relative positions as in Fig. 1, the outer diameter is one and one half inches. The overall length is two and one half inches. The unit weighs approximately 8 ounces. The average input torque at shaft 2 is 1 inch-ounce. Most of this torque is used in overcoming friction in the spider and star wheel drive.

OPERATION

The operation of the converter can be shown from Fig. 2. The block diagram indicates the use of the converter in the system for which it was primarily developed. The switching is all done electronically in this case to comply with system requirements. All the functions to be described could be done equally well with relays, the logic of the diagram remaining unchanged.

Looking at Fig. 2, assume that the correct number to be read is on bank A. The timer actuates the appropriate gate and allows a synchronized pulse to set the bank selection flip-flop so that the gates on bank A are actuated while those of bank B are inhibited. In this case, the two cathode followers associated with bank B are held at the lower voltage. Therefore, all segments of all wheels on bank B are at the lower potential. At the same time the complementing flip flop introduces the upper potential on one of bank A's gates and the lower potential on the other. These gates drive cathode followers which supply the levels to the digit wheel segments through lines A_1 and A_0. Since the outputs from both banks are buffed together in a manner such that the output terminal will go to the most positive potential, the read-out is from A. If a signal to complement now arrives, the potential of line A_1 and A_0 are exchanged, and every segment in bank A reverses its potential. When the timer calls for a bank switch, the gates associated with A are inhibited and those of B are actuated. The complementing information is given to both A and B at all times so that bank switching does not effect the complementing.

To clarify the bank switching technique, a detailed timing sequence is presented. Assume an arbitrary starting point which, for simplicity, can be a reading of zero. At every position of the converter one bank is being read while the other is ready to be moved. Assume bank A is being read and then assume that an angular rotation is applied to the input shaft. The table below indicates the sequence of events for the four least significant digits.

Rotation in Number of Digits	READING	
	Bank A	Bank B
0	$\underline{0000}$	0001
1/2	0001	$\underline{0001}$
1	$\underline{0001}$	0010
1 1/2	0010	$\underline{0010}$
2	$\underline{0010}$	0011

NOTE: Underline indicates bank being read out.

These two banks are physically assembled to be one least significant digit out of phase. Since the timer traverses twice as many segments at the least significant digit wheel, it must change a segment for every half least significant digit. The phase of the timer is such that it signals for a bank switch just before the spider engages the star wheel as seen in Fig. 1. This signal causes the reading to be made from the stationary bank and causes all the segments on the moving bank to assume the lower of the two potentials. Since all segments on the moving bank are at the same potential, brushes need never interrupt current, a feature which avoids arcing and greatly prolongs brush life.

SINE AND COSINE GENERATOR

Frequently the need arises for the generation of the sine or cosine function of an input angular position. A componion unit has been developed in which a cam is used to convert linear input velocity into harmonic motion, which in turn drives the actual converter. The unit has two output shafts moving in quadrature to provide the sine and cosine functions of the input angle.

When assembled this sine-cosine unit has an outer diameter of five and one half inches and is one and one quarter inches long. The large diameter comes about due to the relatively large size of the oscillating member. Fig. 3 shows the configuration of the cam and oscillating member.

APPLICATIONS

This shaft-to-digital encoder has wide application in operational-digital techniques, many of which have been introduced at the Laboratory for Electronics. The original application was in an airborne digital computer. The encoder was employed in a variety of ways as input and output equipment for this computer.

A common and useful application of this device is in the solution of right triangles. Fig. 4 indicates in block diagram how this converter is used to produce the magnitude and direction of the resultant vector when the quadrature components are known.

ACKNOWLEDGEMENT

The mechanical design of this entire unit was carried out by Instrument Development Laboratories, Inc., Needham Heights, Massachusetts under contract from Laboratory for Electronics. The authors wish to extend their gratitude to Mr. George McNabb of I.D.L. for his cooperation throughout this project.

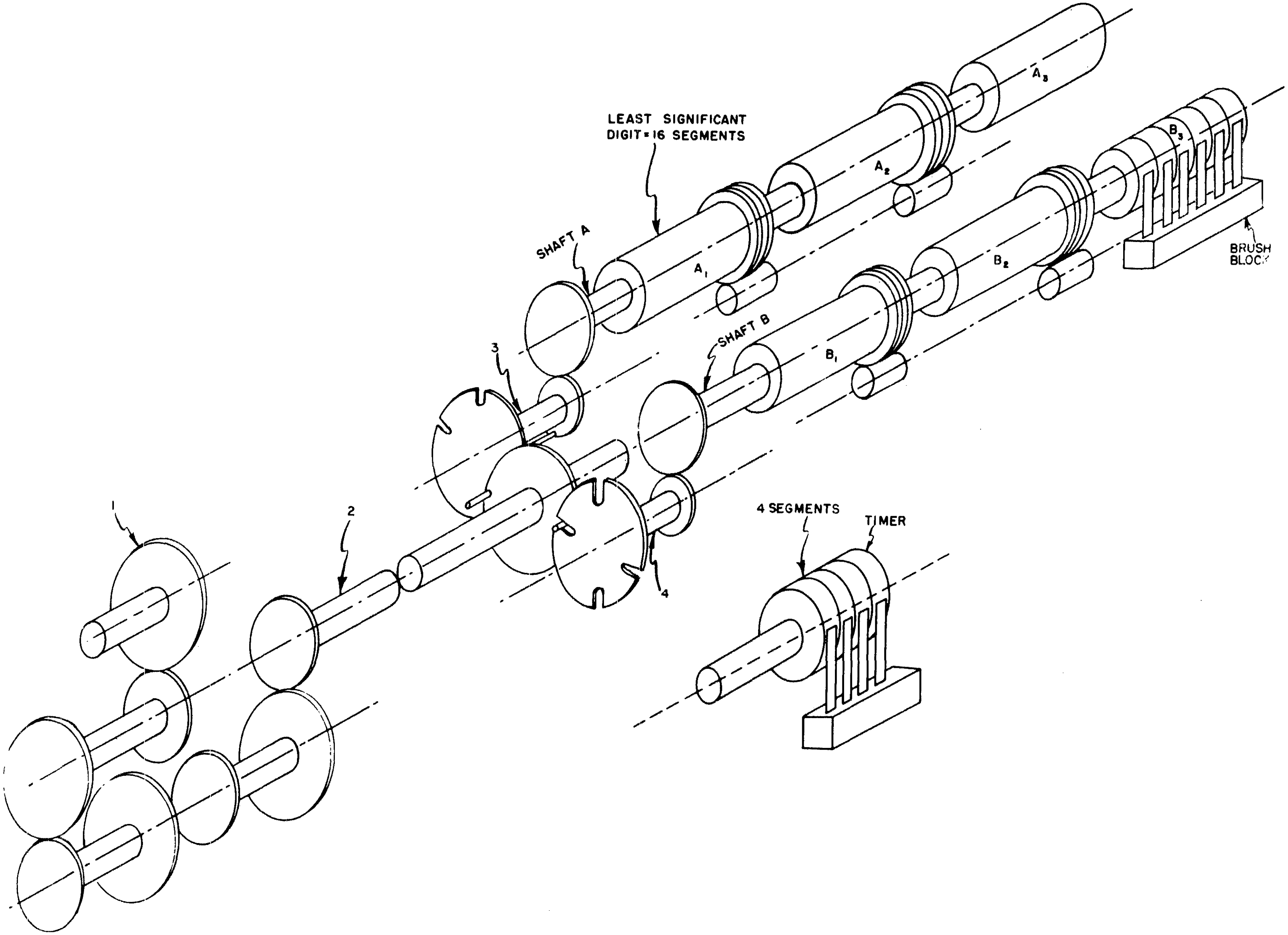

Fig. 1. Functional mechanical operation

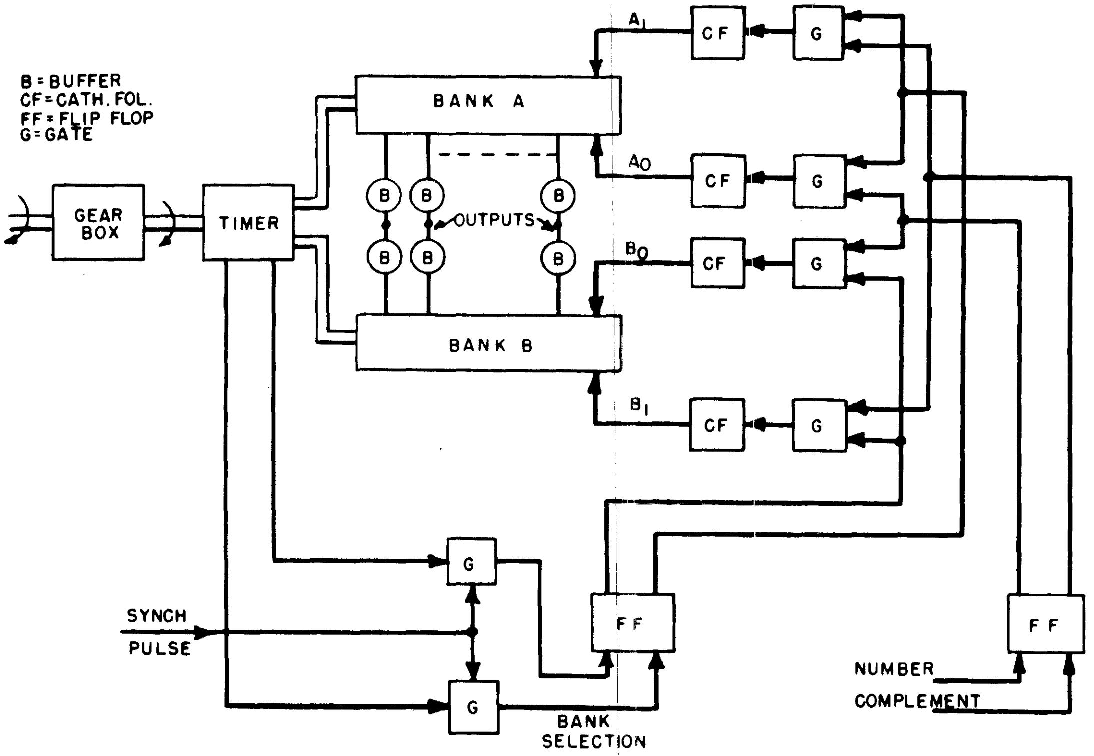

Fig. 2. Converter block diagram

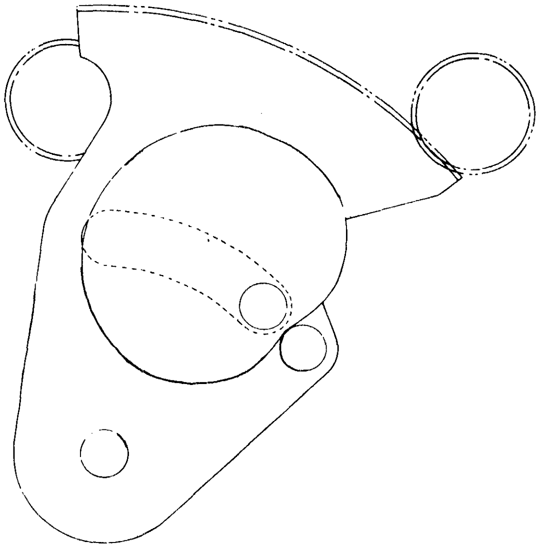

Fig. 3. Trigonometric converter

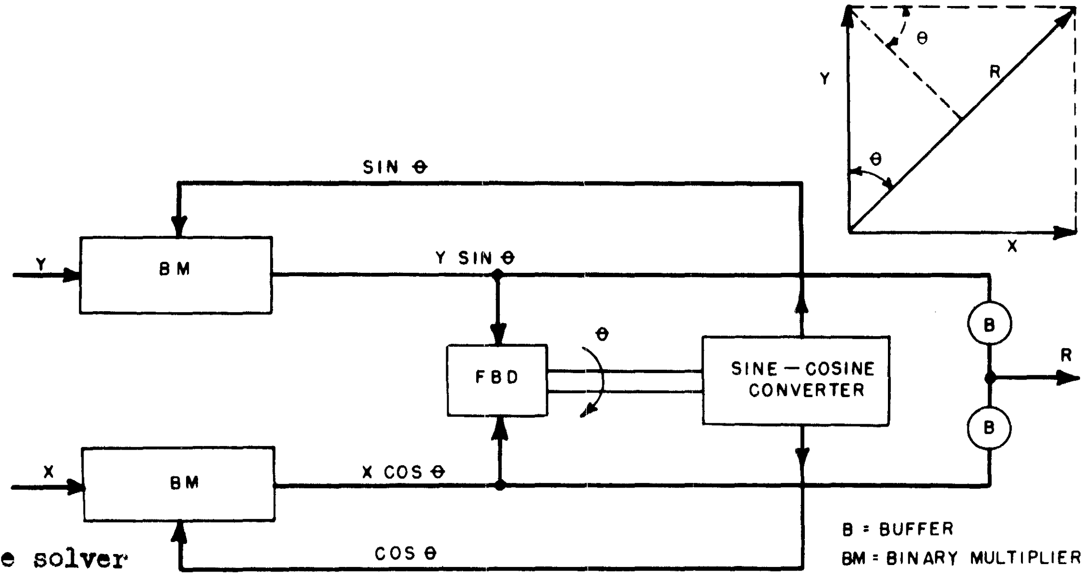

Fig. 4. Right triangle solver

REAL-TIME DIGITAL DIFFERENTIAL ANALYZER (DART)

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Introduction

The solution requirements of differential analysis problems are increasing to the point where solution speed requirements are often beyond the capabilities of present-day conventional digital computers, while analog computers will not provide sufficient accuracy. For many of the problems of this class, a computing system is needed which possesses the desirable characteristics of both analog and digital computers - that is, one which has the inherent speed of an analog computer and the basic accuracy of a digital computer. One approach to the problem of designing a computer having these characteristics is described in this paper. It involves the use of a system design based on the electronic analog computer, with components which are digital in nature.

Basic Concept

The concept on which the DART system design is based involves the combined use of pulse-train information (such as is used in digital differential analyzers like MADDIDA or the CRC-105) and of information in the form of sets of d-c gating voltages. The relation between these two kinds of information can be readily shown. If a train of pulses is fed into a binary counter, consisting for example of a row of flip-flops, a set of d-c voltages, constant between pulses, is available at the plates of the flip-flops. This set of voltages may be used to control logical gates or switches of various types; hence, they are referred to as "gating voltages."

A study is in progress at the Naval Ordnance Laboratory, Corona, to investigate the design of computing elements using both these kinds of information, and to investigate the incorporation of these separate computing elements into computing loops for the solution of systems of differential equations.

The pulse-train units under consideration in this project depend upon essentially the same logic as do other digital differential analyzers. No magnetic drum or other central memory is used, however, since a separate computing unit is provided for each operation. For example, if a problem requires three integrations, three separate integrators are used. These are plugged together in the same basic manner as the integrators of an analog computer.

By eliminating the memory, and thus eliminating the time-sharing feature of magnetic-drum computers, a much higher basic pulse rate is made possible, although at the expense of equipment.

Present designs are aimed at a 10-kilocycle basic pulse rate, but much higher rates are possible without requiring the use of any radically new circuit techniques.

Gating Matrices

Once a binary number is available as a set of gating voltages, other related sets of gating voltages can be produced by using gating matrices. For example, an adding matrix would give the sum of two numbers available in gating-voltage form; a multiplying matrix would give the product. Other functions which could be performed by using gating matrices would include the extraction of digits, limiting the value of a variable, and other logical operations.

Combined System

In combining pulse-train computing elements with gating matrices, to produce a computing system for the solution of differential equations, it is possible to take advantage of the fact that a pulse-train integrator contains a register, from which a set of gating voltages may be obtained. This is the register in which the dy pulses are counted to produce y (see Figure 1).

The set of gating voltages representing y may be combined with other sets in gating matrices, as required to solve the given system of differential equations. Figure 2 shows an example of the use of this method, to solve the system:

$$dy = pdt \tag{1}$$

$$-dp = (p + 1)\, ydt \tag{2}$$

In this example, a pulse train, dp, is fed into the Integrating Register to produce p as a set of gating voltage. This is combined with the pulse train, dt, in the Rate Scaler to give the pulse train, pdt.

Since, by equation (1), this is equal to dy, it is again integrated to give y. The two sets of gating voltages now available, y and p, are combined in the Multiplying Matrix to produce py. This is added to y in the Adding Matrix. At this point, py + y, or (p + 1)y, is available as a set of gating voltages. Another Rate Scaler is used to produce (p + 1)ydt. According to equation (2), this equals -dp which, except for a simple sign inversion, is the same pulse train used originally.

This example illustrates the combined use of pulse-train units and gating matrices for the solution of a simple system of differential equations.

Feasibility

It remains to be shown whether gating matrices can be produced which are simpler or faster than the elements which would be required to perform the corresponding operations with pulse trains. As yet, no specific detailed designs have been worked out for any of these gating matrices. Preliminary analyses indicate, however, that such units can be designed which would have desirable features as compared with pulse-train systems used alone.

Pulse-Train Operations

There are a number of possible choices involved in the detailed design of computing elements to perform pulse-train operations. There are a number of different ways of handling signs, both in the pulse trains and in the registers of pulse-train integrators. Also, at least two basically different methods of designing rate scalers (the "transfer" method and the "sieve" or "scaled-train" method) have been used.

In the design of pulse-train components for DART, these choices have been made in light of the fact that it must be possible to use these components along with gating matrices.

Integration

A pulse-train integrator consists of an Integrating Register and a Rate Scaler. The Register contains a row of flip-flops which count the incoming pulses to produce a set of gating voltages representing a binary number, y. The rate at which the number in the Register, y, is changing depends upon the pulse-train rate, dy.

The Scaler has as one of its inputs the number y, represented as set of gating voltages (which are constant between inputs to the Register). The other input to the Scaler is a pulse train, dx, which in many cases is a uniform train of pulses originating in the clock-pulse generator. This pulse train is scaled down by the factor y/k (where k is chosen so that y/k is always less than unity). The output of the Scaler is, then, a pulse train, (y/k)dx; that is, the number of pulses at the output of the Scaler is less, by the factor y/k, than the number of pulses at the input.

This is accomplished by feeding the input pulse train, dx, into a row of binary scalers to produce scaled trains $dx/2$, $dx/4$, ... , $dx/2^n$. Each of these scaled trains corresponds to one of the binary digits of the number y, with the most significant digit of y corresponding to the first scaled train, which has the largest number of pulses. The gating voltages representing "ones" in the binary number y allow their corresponding pulse trains to pass; those representing "zeros" do not. The scaled and gated pulse trains are then recombined to form the output pulse train, dz.

The number of pulses in the output pulse train, dz, is proportional to $dx \sum dy$. This is a numerical approximation (according to the Rectangular integration formula) to the integral, Kydx; K is a constant of proportionality which depends simply upon the number of binary digits in the number y.

The integrator, then, has two input pulse trains, dy and dx, and an output pulse train, dz = Kydx. In addition, it should be remembered that the number y exists as a set of d-c gating voltages (constant between dy inputs) at the output of the Register.

Signs

As shown in Figure 3, each of the inputs and outputs consists of a pair of pulse trains, one (labeled "Δ") carrying magnitude information, the other (labeled "—") carrying sign information. A pulse on the "Δ" line of the dy input represents an increment of y (a change in the lowest digit of the Register). If the "Δ" pulse is accompanied by a pulse on the "—" line of the dy input, the increment is negative; if it is accompanied by no pulse on the "—" line, the increment is positive. If there is no pulse on the "Δ" (magnitude) line, the Register is unchanged, whether or not there is a pulse on the "—" (sign) line.

Count Control

The number in the Register represents the absolute value of $\int dy$; a separate flip-flop is used for the sign of y. A positive increment must cause the absolute value, $|y|$, to increase if the Register sign is positive and to decrease if it is negative; a negative increment must cause $|y|$ to decrease if the Register sign is positive and to increase if it is negative. In other words, if the incoming increment has the same sign as the Register, the number in the Register must be made to increase in absolute value ("count up"). If the signs are opposite, the number in the Register must be made to decrease in absolute value ("count down"). The Count Control, shown in Figure 3, accomplishes this. The pulse on the "—" line is made available before the "Δ" pulse; a logical network is used to sense whether the Register and input signs are the same or opposite, and to produce a gating voltage on one of a pair of lines, ordering the Register to "count up" or "count down." When the "Δ" pulse arrives, the count order has been established, and the magnitude of the number in the Register increases or decreases as required.

Figure 4, showing in detail a single digit of the integrator, illustrates the manner in which the Register is made to count up or to count down. Essentially, the method simply requires that the pulse which causes a flip-flop to change state (the "carry pulse") come from either plate of the preceding flip-flop, depending upon whether it is desired to "count up" or "count down."

In the binary number system, "counting up" proceeds as follows: The lowest digit is changed (from 1 to 0 or from 0 to 1). If it is changed from 0 to 1, the process ends; if it is changed from 1 to 0, a "carry" occurs: i.e., the second digit is changed. If this digit is changed from 0 to 1, the process is finished; if from 1 to 0, the third digit is changed. This process continues until the first digit is reached which was initially 0. At this point, a change from 0 to 1 will occur, and nothing will happen to change any of the higher digits. Electronically, this is done by producing a "carry" pulse whenever a flip-flop changes from the "1" state to the "0" state; this carry pulse is used to flip the next higher flip-flop.

When "counting down," the process is exactly the same except that the roles of the 1's and 0's are reversed: a carry occurs from every digit until the first digit is reached which was initially 1. This requires a carry pulse whenever a flip-flop changes from "0" to "1". This simply means that the carry pulse must be derived from the opposite plate of the flip-flop when counting down. Outputs are available from both plates of every flip-flop; when counting up, carry pulses are taken from the "RO" plate of each flip-flop, and when counting down they are taken from the "RC" plate. The "RO" plate is the one which is down ("open") when the Register is reset to zero; the "RC" plate is up ("closed") when reset. The gating voltage is also taken from the "RC" plate, since this is the plate which is down ("open") when the flip-flop is in the "1" state.

Scaler

The Scaler consists simply of a row of flip-flops, with the number of pulses at the output of each flip-flop equal to half the number of pulses at its input. One somewhat unconventional feature, however, is that the pulses which are used to flip the next flip-flop are taken from one plate, and the pulses which are combined to form the dz output are taken from the other plate. This insures that no two flip-flops will feed pulses into the dz line on the same input pulse, and allows these pulses to feed directly into the output line from all the flip-flops without danger of coincidence.

Acknowledgment

The work described in this paper was sponsored in part under I.P.R. No. AF(33-038)-51-4345-E, between the U. S. Air Force and the National Bureau of Standards, Corona (now the U. S. Naval Ordnance Laboratory, Corona), and in part by Foundational Research Funds allocated to the Naval Ordnance Laboratory, Corona.

The electronic design of the components described is being developed by Mr. E. O. Codier, Naval Ordnance Laboratory.

Bibliography

"Fundamental Concepts of the Digital Differential Analyzer Method of Computation," by R. E. Sprague, Mathematical Tables and Other Aids to Computation, VI, 37, January 1952, p. 41, The National Research Council, Washington, D. C.

"Real-Time Digital Differential Analyzer (DART), Preliminary Analysis," by L. P. Meissner, National Bureau of Standards Report 1231, Corona, California, May 1953.

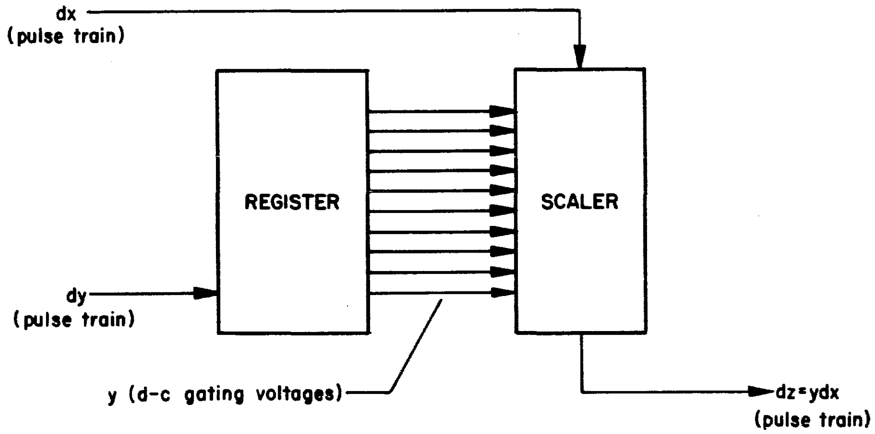

Figure 1. Pulse-Train Integrator (Simplified)

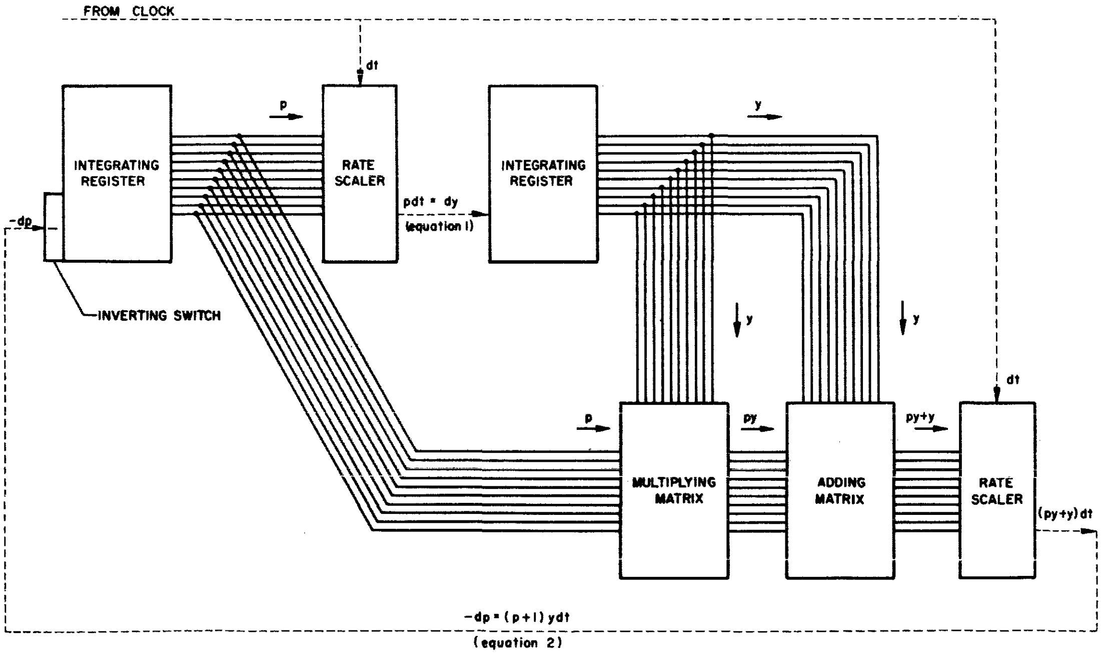

Figure 2. Use of Combined System

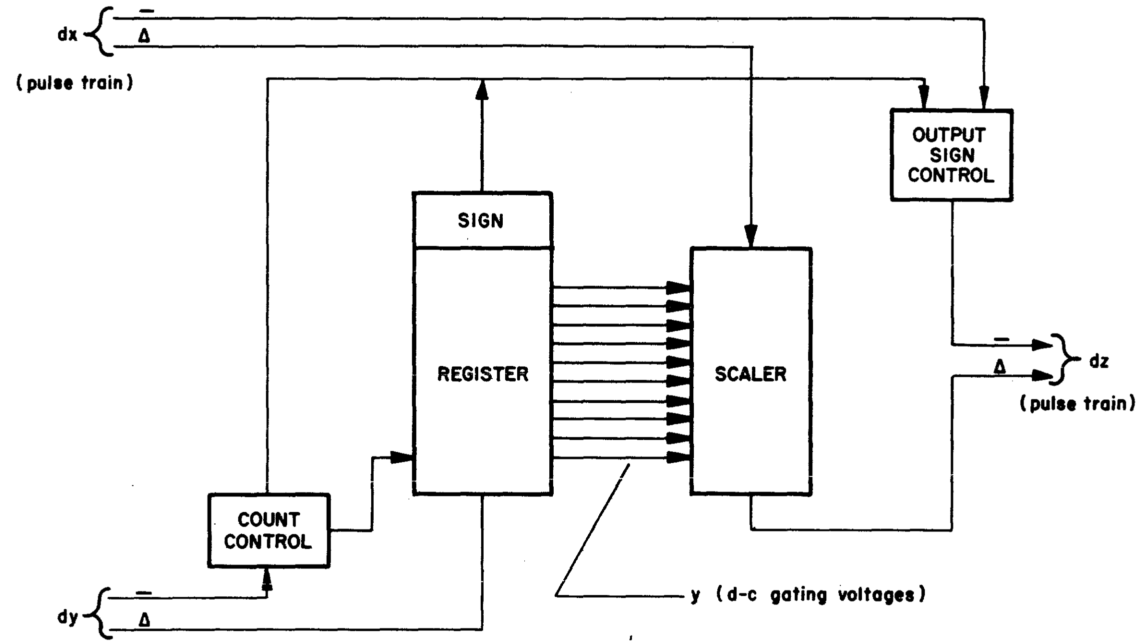

Figure 3. Pulse-Train Integrator, Showing Signs

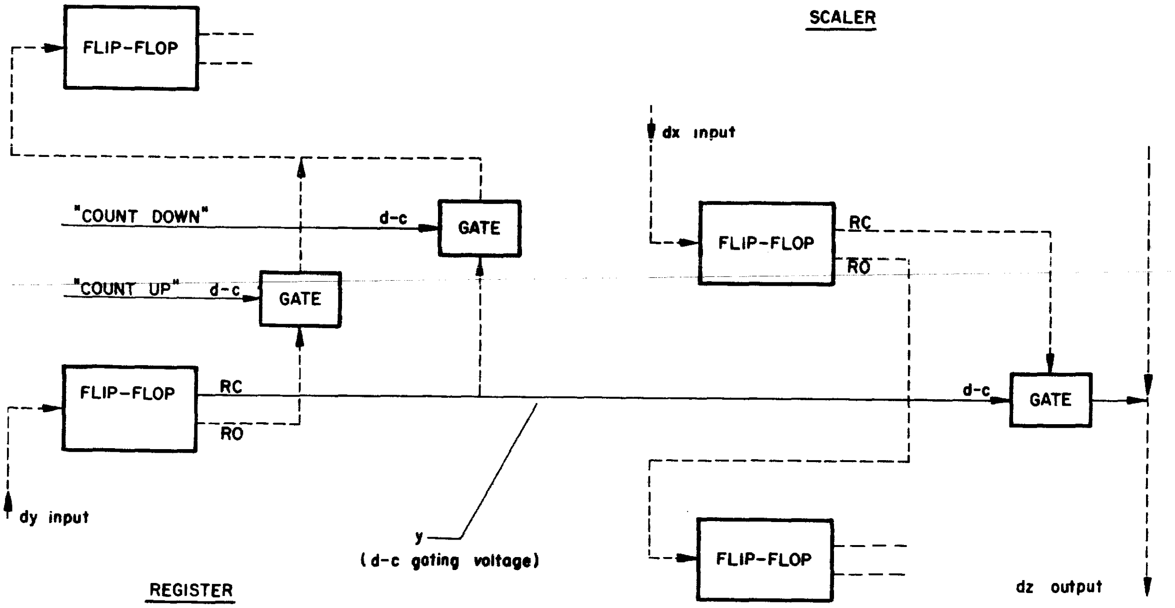

Figure 4. Single Digit of Integrator

THE IBM MAGNETIC DRUM CALCULATOR TYPE 650
ENGINEERING AND DESIGN CONSIDERATIONS

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Resume

This paper covers the engineering principles and design considerations given to the components that are used in the International Business Machines Corporation's Type 650 Calculator. The factors that led to the selection of the particular systems and components are discussed, rather than the way and manner in which the calculator functions.

The general topics that are covered include a review of the machine as a unit, self-checking features, and storage systems. Self-checking codes supplemented by control checks to form a self-checking system are covered in some detail.

The storage system is broken down into two types - main storage and buffer storage, with comments on their adaptability and flexibility in the complete system. Significant test data are presented.

The IBM Magnetic Drum Calculator Type 650 is a stored program, two address calculator, intermediate in speed, capacity, and cost. Its comprehensive order list, punched card input - output, memory capacity, and self-checking features give it the flexibility that is required in both the commercial and scientific field. Its moderate cost, ease of operation, and small size places it within the reach of many users.

Machine specifications and special features include:

1. Two thousand words of storage on the magnetic drum with an average access time of 2.4 milliseconds.
2. Input of 200 cards per minute with full 80 columns.
3. Output of 100 cards per minute with full 80 columns.
4. 10 X 10 multiplication to give 20 digit product. Average time is 11.6 milliseconds including access times.
5. Twenty digits divided by 10 digits to give 10 digit quotient. Average time is 14.5 milliseconds including access times.
6. Addition and subtraction of 10 digit words to give 20 digit sums. Average time 5.2 milliseconds including access times.
7. Consult storage for both reading and writing -- 5.2 milliseconds.
8. Instructions are stored on the drum as 10 digit numbers plus sign.

An instruction consists of two digits for operational codes, four digits for address of data or alternate instruction address (D Address), and four digits for address of the next instruction (I Address). See Order List, Figure 1.

A seven bit biquinary code is used for input, output, accumulator, and program control. Drum storage uses a condensed five bit code for economy. Information is stored parallel by bit, serial by digit, and word.

A table look-up (TLU) operation is performed automatically with one operation code. An equal or high search may be performed on arguments stored in an ascending order. Related functions may be located by normal programming procedures after a constant has been added to the storage location of the argument.

The built-in, self-checking features include a validity check for number transmission, read-in and punch-out checks, control checks on the program, and timing and synchronizing checks. Figure 2 shows the data flow paths and validity checks.

Figure 3 shows the operator's control console which serves as a comprehensive means for monitoring and manually controlling the operation of the machine.

The storage display lights show the contents of any memory location, or the contents of the program register, distributor, upper accumulator or lower accumulator. The display switch and the address selection switches select the proper location for display. The storage entry switches provide a means for entering information, either in the form of data or instructions, manually into the machine.

The order, address and operating lights indicate the operating condition of the machine. The checking lights indicate the source of a detected error, except for the error sense light which indicates that an error has been detected and a self-correcting routine has been employed. This error sense light can only be turned off manually, and it will remain off only if the error is not repetitive. The address selection switches provide a unique means for choosing key points in "de-bugging" a program. They allow a stop at any desired instruction in particular routine being "de-bugged" by merely setting the switches to the location of this instruction and setting the control switch to the address stop position.

The power requirements are as follows:

Either 208 volts or 230 volts with ± 10 per cent regulation
60 Cycles
Single Phase
100 ampere service
16.8 kilovolts-amperes power dissipation
45,500 BTU/hour heat dissipation

The direct current power is provided by selenium rectifiers with primary power regulated by saturable reactors thus avoiding the need for electronic regulation.

Figure 4 shows the three units that make up the complete calculator. The unit in the foreground is the Type 533 read-punch unit, the center unit houses the drum, program control, and computing circuits, and the rear unit provides the card scan, translating and power supply circuits.

A broad outline of the complete calculator has been given. With this in mind it is possible to review the calculator from an engineering evaluation of the logic and components used.

The general specifications are that the machine is intermediate in cost and speed, simple to operate, and self-checking.

The self-checking feature determined the selection of the biquinary code. The binary code is excellent for large, high-speed machines where the cost of conversion can be absorbed. The forms of binary coded decimals were eliminated in favor of the positive checking features, and ease of use of the biquinary code, since it closely resembles the decimal code.

Since the biquinary code requires seven bits per digit, there is a question as to its worth because of extra bits that must be stored. When serial - serial recording is used in drum storage, the extra bits of storage cost very little in terms of dollars. However, if the pulse repetition frequency (prf) and bit density remain the same, the drum circumference must be increased thus resulting in an increase in access time. In a parallel-by-bit, serial-by-digit system, the dollar cost increase is directly proportional to the bit increase but the access time remains the same.

The MDC is based on the parallel-by-bit, serial-by-digit system and the extra cost is partially nullified by other means. This is accomplished by taking advantage of the simplicity of the biquinary system as illustrated by a few examples.

In Figure 5 (Operation Code Matrix) it is shown how decoding is eliminated, a timed output is obtained, and grouped signals are automatically available.

In Figure 6 (Static Head Selection) the circuitry for the selection of the forty bands is shown. Since there are 50 words per band, selected on a dynamic basis, this will give a total of 2000 words. The outputs from the address registers energize the three dimensional matrix directly, eliminating the necessity for decoding or buffer amplifiers. This also gives the optimum load distribution since any one line drives a maximum of five intersections. These are only a few of the advantages that are realized due to the simplicity of the biquinary code. Others include simplification of the matrix adder, ease of reading on the display lights, and ease of interpretation by the service engineer.

The selection of a magnetic drum for storage is a natural choice since it offers a large volume of storage at medium access and cost. The details of resolving the size, configuration, frequency, surface speed, revolutions per minute, and bit density present a more complicated problem. It is necessary to determine the frequency early in the design stage since amplifiers and synchonrizing circuits are not readily redesigned for various frequency characteristics. When a reasonable bit density has been established, it, combined with the chosen operating frequency, will determine the surface speed. The remaining characteristics are merely determined by the access time that is desired. In the MDC design, an operating frequency of 125 kilocycles per second (8 microseconds bit spacing) and 50 bits per inch were chosen.

$$\text{Surface speed} = \frac{1{,}000{,}000\ \mu s}{8\ \mu s \times \text{bit/in.}} = 2500\ \text{in/sec.} \qquad (1)$$

The drum layout is shown in Figure 7. It is readily apparent that once the bit density and frequency (bit spacing) is determined, the remaining characteristics are fixed by access time and capacity.

The mechanical aspects of the drum must also be given special consideration since dynamic balance, concentricity, and long life is of prime importance. The drum assembly is shown in Figure 8. In the simplest sense it consists of a one inch steel tube placed inside a four inch steel tube with a set of precision ball bearings in between. A drive pulley is fastened to the outside tube and it rotates about the inside tube which is clamped to the mounting plate. The assembled drum is then turned in its own bearings which results in almost perfect concentricity. After the unit has been dynamically balanced and mounted in its final assembly (Figure 9), a run out of more than 0.0001 inch is not accepted.

A general requirement in many calculators is several one word buffer storage registers. The Type 650 uses four such registers with specifications illustrated in Figure 10. The scan pulse repetition frequency (prf) is 125 kilocycles per second and the delay varies between +2, and 0 cycles to give a right and left shift. The normal operation is to read out one digit early, delay one digit time, and then store on time. Several types of storage were considered for this application. Tube shifting registers and cathode ray tube storage were too expensive. Core storage, as either a shifting register or static single turn arrays, was compared in cost and operating characteristics to a form of condenser storage.

Both methods are comparable in cost, in an advanced stage of development, and known to operate reliably. After considerable investigation, condenser storage was chosen for the following reasons:

1. Basic components readily available.
2. Large output signals of 30 to 35 volts adaptable to the rest of the calculator units.
3. Matrix drive for condenser storage is less rigid than that required for core storage.
4. Assembly and manufacturing techniques same as those for other electronic components.

The basic circuit[1] and waveform is shown in Figure 11. A stored "1" is represented by no charge on the condenser, and a read-out signal at 1 will produce a differentiated

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[1] For other work done on condenser storage see A. W. Holt, "An Experimental Rapid Access Memory Using Diodes and Capacitors", National Bureau of Standards, Washington, D. C.

signal at point "3". If a "1" is to be regenerated a pedestal will appear at point "4" at the same time a clamp signal appears at point "2". As a result the condenser is left uncharged as shown by waveforms 3 and 5.

The circuit in Figure 11 is arranged in a 7 X 12 matrix as shown in Figure 12 to give a one word storage unit.

Self-Checking

The Type 650 has been designed with reliability as a paramount consideration. Conservative circuit design, and components chosen for their high reliability, are employed throughout. The Type 650 also employs built-in self-checking as a supplement which further improves this degree of reliability.

Self-checking within the machine is separated into two categories - validity check and control checks.

Validity Check

The validity check consists of checking all information in the distributor, the accumulator, and the program register for a valid biquinary code. Since all information used in a problem eventually passes through these units, any invalid codes will be detected.

In addition to the above, if any brushes in the card-read-unit are shorted together (touching each other) they will read in double digits and cause a validity check. If a brush has short strands, it will read the same hole twice and cause a validity check.

Control Checks

The control checks are dependent upon the proper combination of signals within the machine, the proper sequence of signals or double circuitry. Some of these are as follows:

1. Meaningless address and operation codes are detected and cause an error indication.
2. Checks are provided to insure that the signal to perform the operation was received and that the operation was completed.
3. The main timing circuits and their outputs to the machine are continuously checked. Any timing error is detected and an error is indicated.
4. The accumulator is designed to detect an accumulator overflow or a division error resulting from more than a ten digit quotient.

Address Selection Checking

Checks are provided to insure that information is read and recorded in the proper location.

Input Checking

Should incorrect reading occur as a result of misfeeding or open or shorted circuits, the error will be detected by a combination of the control and validity checks when the information is processed. In the event that misfeeding results in the card being exactly one hole early or late, too little or too much information will be read as a result of brushes reading the bare contact roll at 9 or 12 times. In this case, the error will again be detected by the validity check. To completely satisfy input checking, the signs, both plus and minus, must be punched in the card.

Output Checking

Punched results are checked by means of double punch and blank column detection. This is equivalent to a validity check. In addition, there are internal machine checks to make sure that the drum is reading out a digit corresponding to the correct punch timing for that digit.

Programming for Error Correction

When the machine detects an error by means of a validity check or a timing circuit check, it is very possible that this error is a random one which will not occur again, or at worst occur very infrequently. Hence, it is reasonable to assume that the machine will probably perform the problem correctly if given a second chance. Therefore, it will prove profitable in some applications to program the machine to repeat a problem in the case of errors detected by self-checking.

In practice, very large problems will be broken up into smaller segments, each segment representing a small part of the whole. In this way, it will not be necessary for the machine to repeat the whole problem, but to repeat only that segment in which the error occurred.

The use of a self-checking code alone is not sufficient to determine a satisfactory system check. Storage selection, translation, synchronizing of input-output, and program control in general are directly dependent upon the clocking system. In the 650 a complete check is applied to the clocking system and is illustrated in Figure 13. The start and completion of each ring is checked by a recorded pulse on the drum. As an example, the word ring would be started by sector pulse "0" and checked by sector pulse "1". Since they are open ended rings, it will be started again by sector pulse "1" and then checked by sector pulse "2". The process is continuous. This check determines that each ring cycle is correct, but in itself is not sufficient to say that each individual output is correct. This check is determined by a characteristic of the latch circuit which is used in the ring. A cathode follower output is used as a feedback on each individual stage, and it must be correct to insure the cycle completion at the prescribed time as dictated by the clock drum recording. This results in a complete check on all the output synchronizing signals that are distributed throughout the machine. Experience has shown that faulty components, located throughout other units of the machine that are associated with synchronizing signals, will usually indicate a timing error on a particular ring and timing output. This aids materially in quickly locating the faulty component.

A complete analysis of the checking system is not within the scope of this paper, nor can its effectiveness be fully revealed until considerable field experience has been realized. It can be stated however, that approximately one year's experience of useful work on an engineering prototype model has shown that no errors, to the operator's knowledge, have escaped the machine detecting circuits. The type of problems that have been applied to the machine do not include programmed checks, and are of such a nature that the results can be checked to a reasonable degree of accuracy.

A total of 2100 tubes and 3600 diodes are used in the production model. The tubes are mounted in a total of 1856 pluggable tube units which consist of 29 different standard types. The diodes are mounted in 516 pluggable diode units of which there is one standard type. The various combinations of logical "and" and "or" circuits are determined by the manner and position in which the individual diodes are clipped in the diode unit.

Tube operating experience on an engineering model during a period of controlled test from December, 1952 through September of 1953 (a total of 1848 operating hours) has shown the following results:

Table I

Tube Type	Number of Replacements	Total Used	Per Cent Replacements
5965	3	765	0.4
2D21	2	120	1.7
12AY7 [1]	7	113	6.1
6211	0	35	0.0
12BH7 (Type 6350 to be used in production model)	2	92	2.6

Diode operating experience during the same controlled test period:

Table II

Diode Type	Number of Replacements	Total Used	Per Cent Replacements
Germanium diodes of several manufacturers	19	2800	0.7

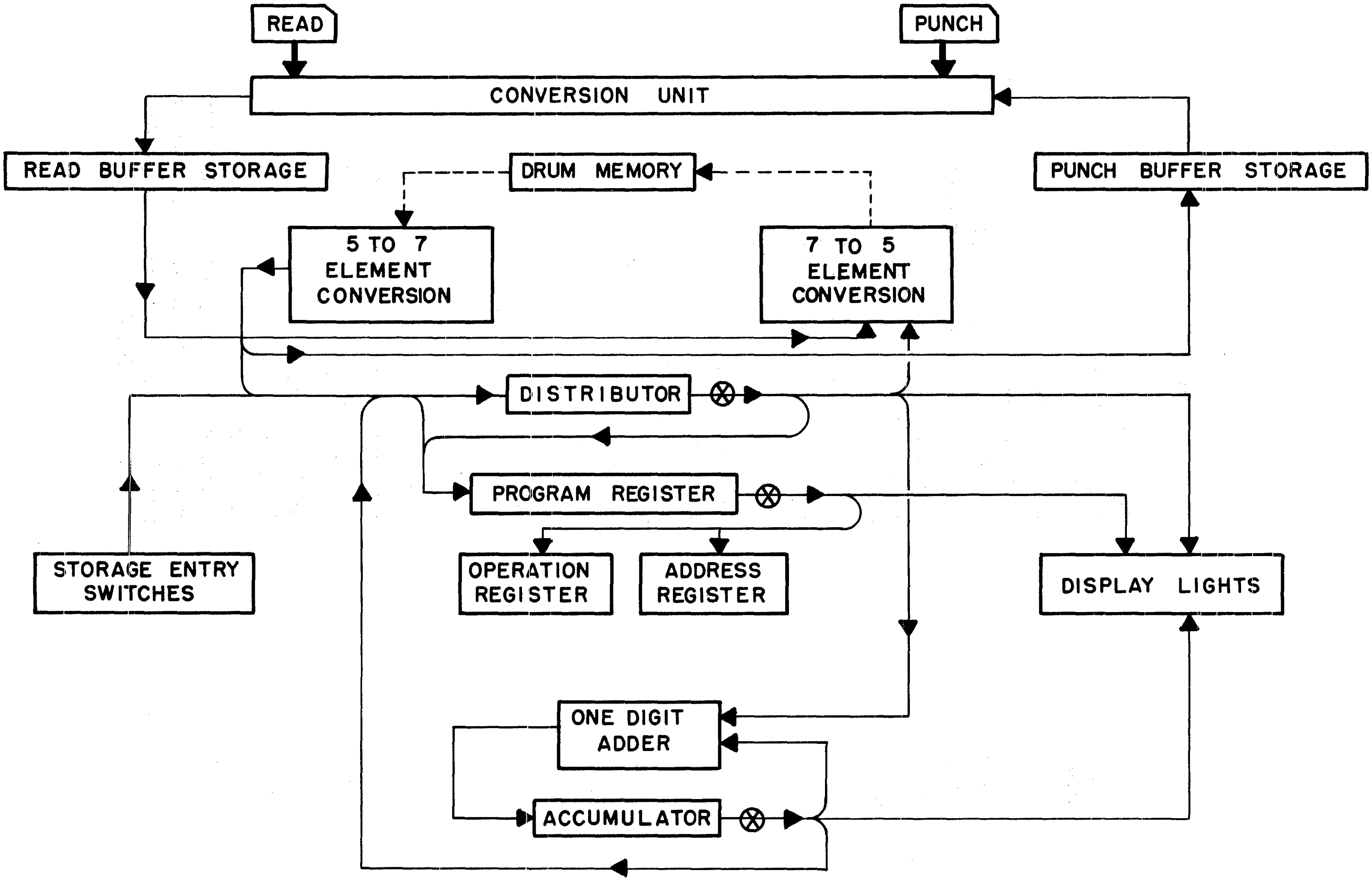
Additional tube types which will appear in the production model include the 5687, 6350, and the 6AL5.

[1] Eighteen Type 12AY7 tubes are used in the production model and may be replaced with the Type 6072.

Order List

Code	Abbreviation	Order
00	No OP	No operation
01	STOP	Stop
10	AU	Add to upper
11	SU	Subtract from upper
14	DIV	Divide
15	AL	Add to lower
16	SL	Subtract from lower
17	AABL	Add absolute value to lower
18	SABL	Subtract absolute value from lower
19	MULT	Multiply
20	STL	Store lower
21	STU	Store upper
22	STDA	Store lower data address
23	STIA	Store lower instruction address
24	STD	Store distributor
30	SRT	Shift right
31	SRD	Shift and round
35	SLT	Shift left
36	SLC	Shift left and count
44	BRNZU	Branch on non-zero in upper
45	BRNZ	Branch on non-zero
46	BR MIN	Branch on minus
47	BR OV	Branch on overflow
60	RAU	Reset-add to upper
61	RSU	Reset-subtract from upper
64	DIV-RU	Divide-reset remainder
65	RAL	Reset-add to lower
66	RSL	Reset-subtract from lower
67	RAABL	Reset-add absolute value to lower
68	RSABL	Reset-subtract absolute value from lower
69	LD	Load distributor
70	RD	Read one card
71	PCH	Punch one card
84	TLU	Table look-up
90	BR D10	Branch on 8 in 10th position of distributor
91	BR D1	Branch on 8 in 1st position of distributor
92-99	BRD2-BRD9	Branch on 8 in 2nd position through 9th position of distributor

Figure 1



NOTES :
1. ⊗ VALIDITY CHECK POINTS.
2. HEAVY LINES SHOW HOLLERITH CODE TRANSMISSION.
3. LIGHT LINES SHOW 7 ELEMENT CODE TRANSMISSION.
4. DASHED LINES SHOW 5 ELEMENT CODE TRANSMISSION.

Fig. 2. Basic 650 circuit

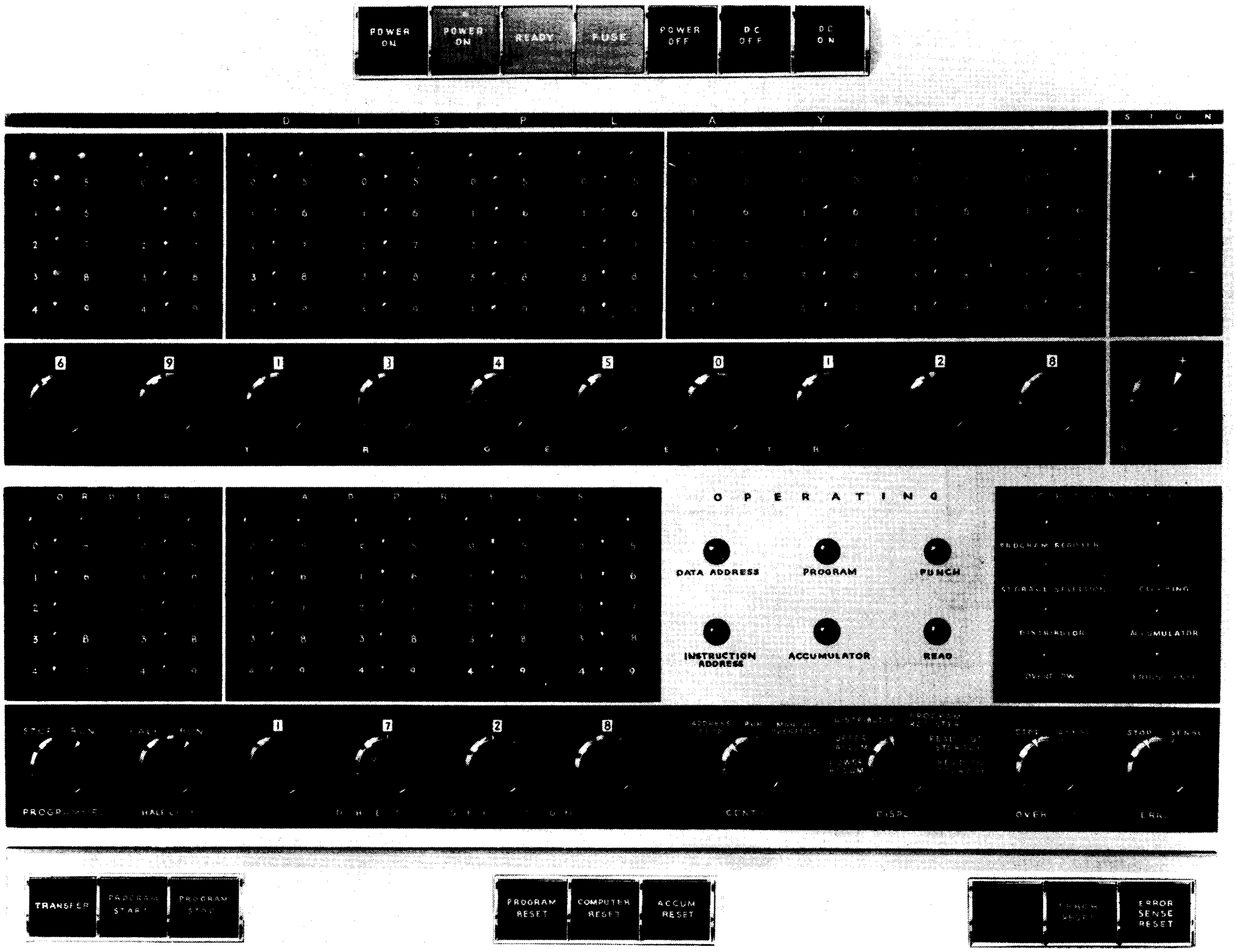


Fig. 3. Operators control console

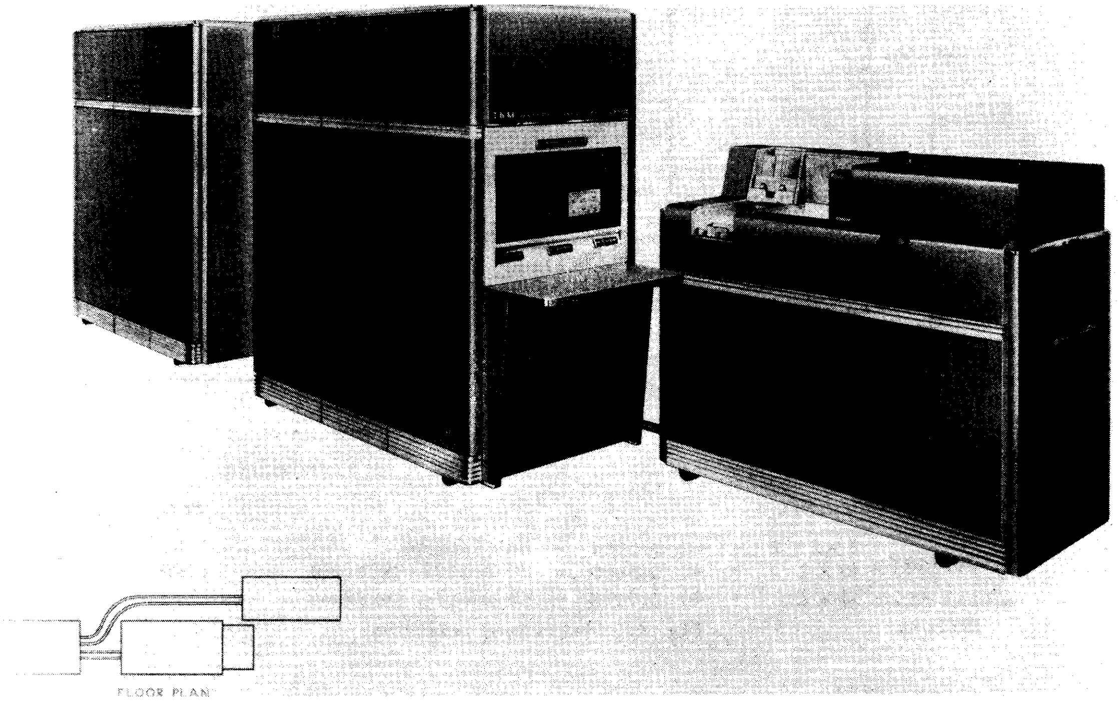


Fig. 4. Magnetic drum calculator type 650

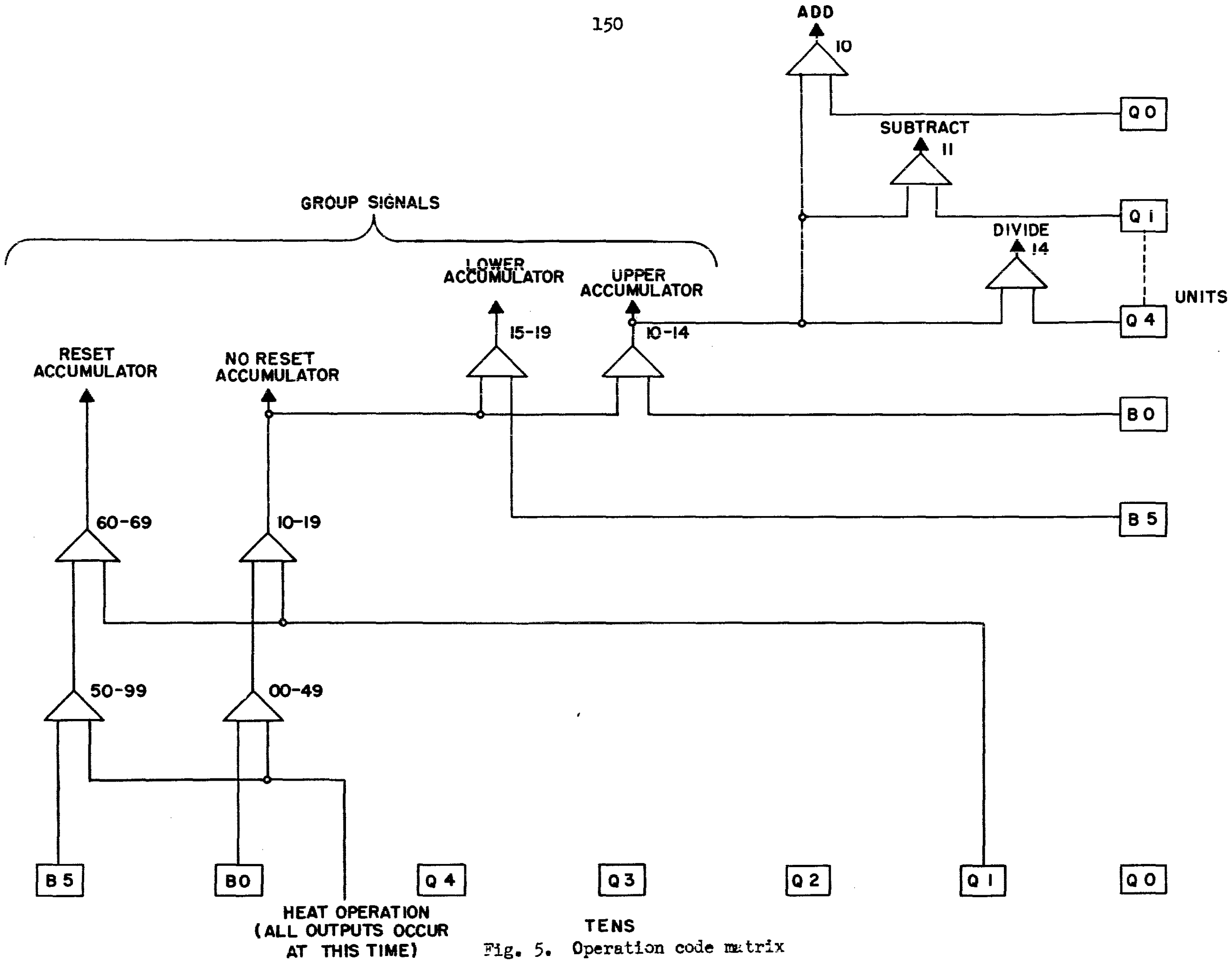
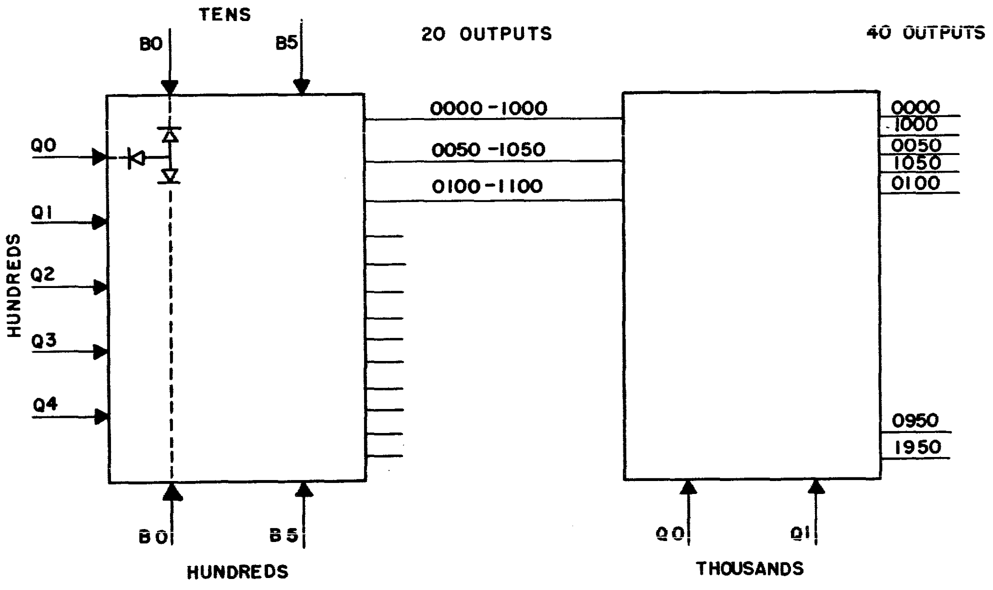
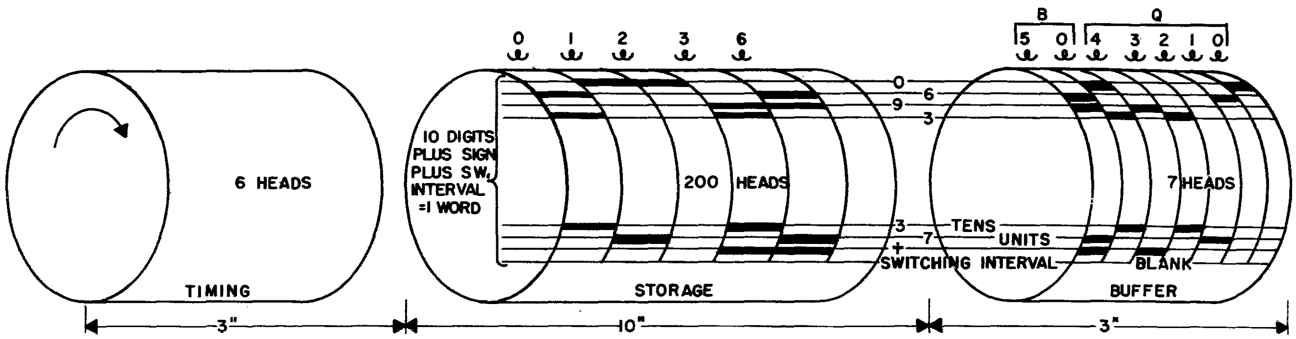


Fig. 5. Operation code matrix



	MATRIX				TOTAL
BI-QUINARY	5 X 2 X 2	-	60 DIODES	- NO DECODING	60
	10 X 2	-	40 DIODES	- 20 DIODES DECODING	60
BINARY CODED DECIMAL	10 X 2	-	40 DIODES	- 33 DIODES DECODING	73

Fig. 6. Static head selection



50 BITS PER INCH

8 MICROSECONDS BIT SPACING

12 BITS PER WORD

50 WORDS PER REVOLUTION

50 X 12 = 600 BITS PER REVOLUTION

600 X 0.008 MILLISECONDS = 4.8 MILLISECONDS PER REVOLUTION

$\frac{\text{600 BITS PER REVOLUTION}}{\text{50 BITS PER INCH}}$ = 12" CIRCUMFERENCE

$\frac{\text{60,000 MILLISECONDS}}{\text{4.8 MILLISECONDS PER REVOLUTION}}$ = 12,500 REVOLUTIONS PER MINUTE

$\frac{\text{2000 WORDS}}{\text{50 WORDS PER BAND}}$ = 40 BANDS

40 X 5 HEADS PER BAND = 200 HEADS

$\frac{\text{200}}{\text{20 HEADS PER INCH}}$ = 10 INCHES

Fig. 7. Drum layout

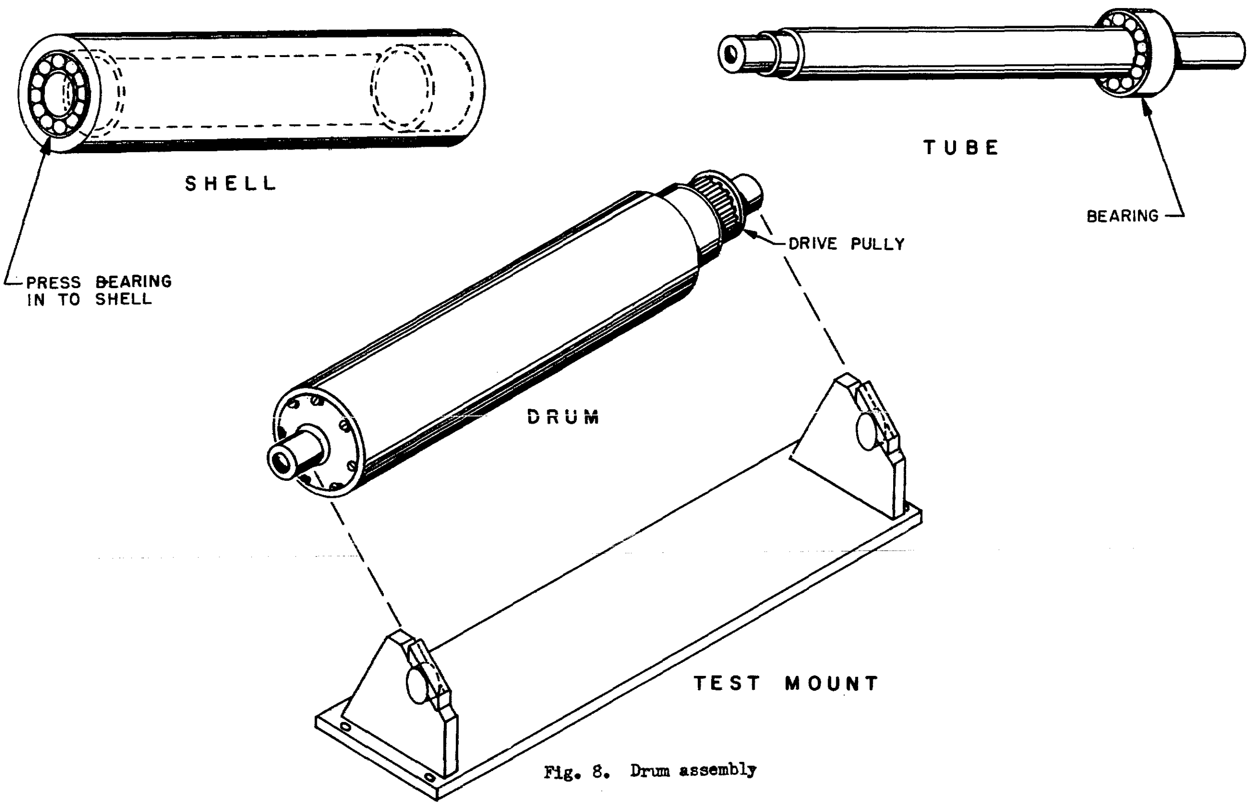


Fig. 8. Drum assembly

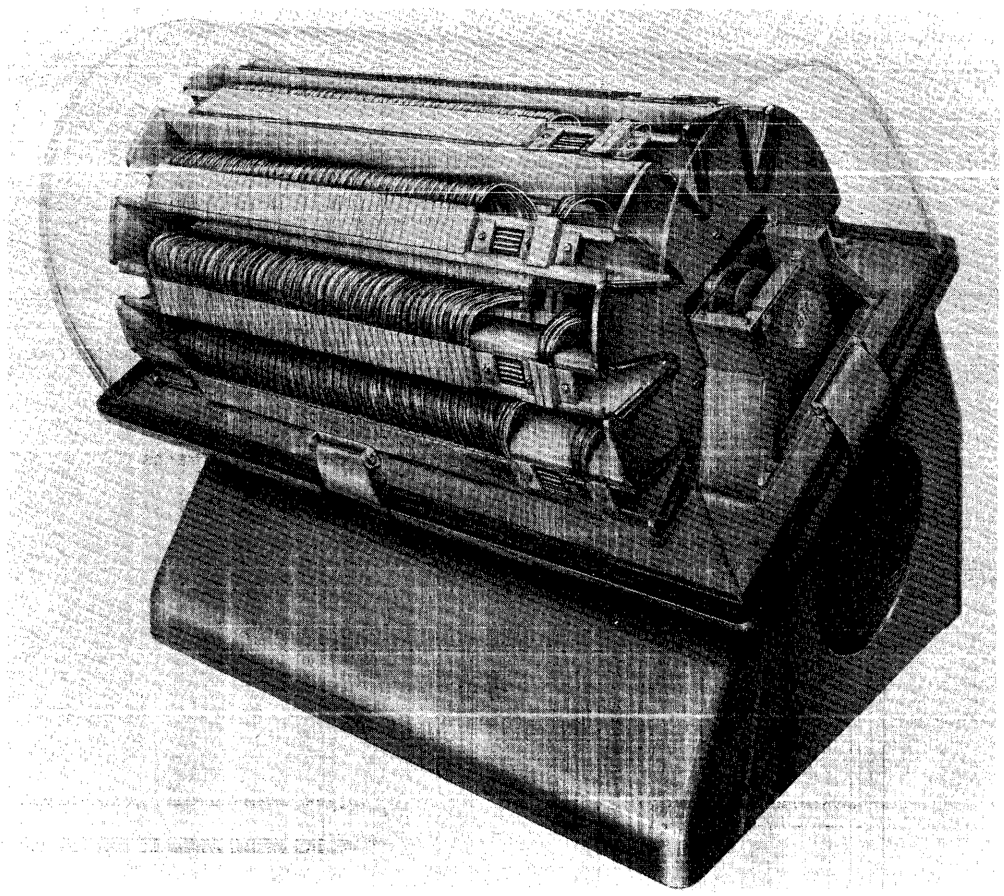


Fig. 9. Magnetic drum final assembly

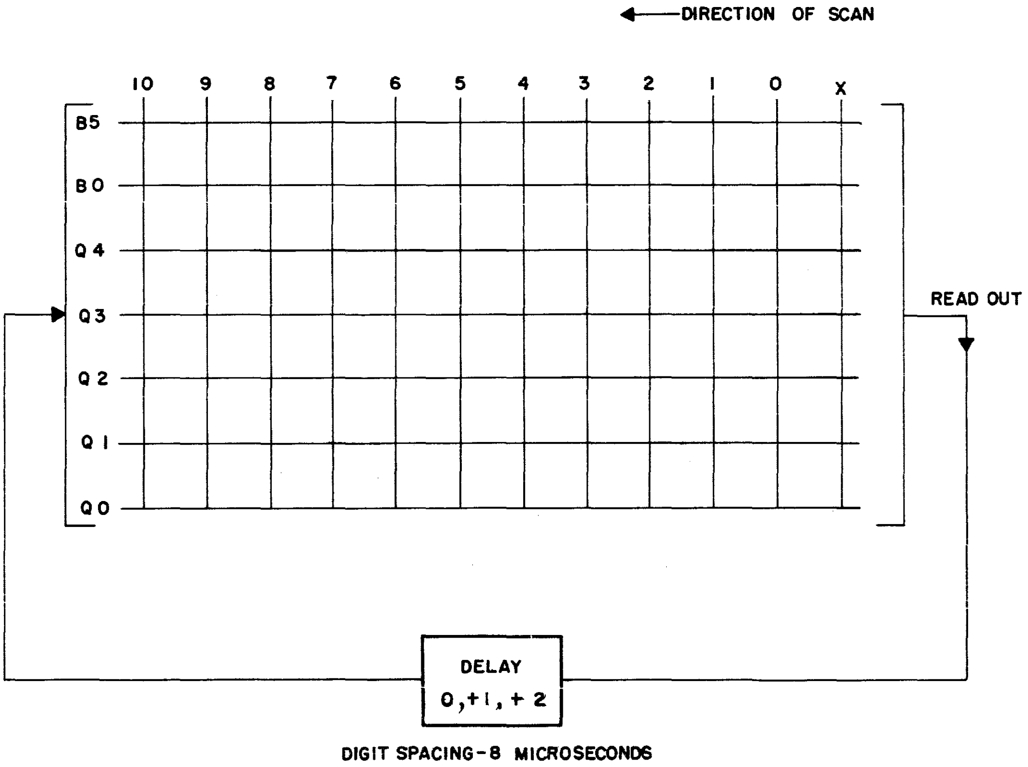


Fig. 10. Buffer storage specifications

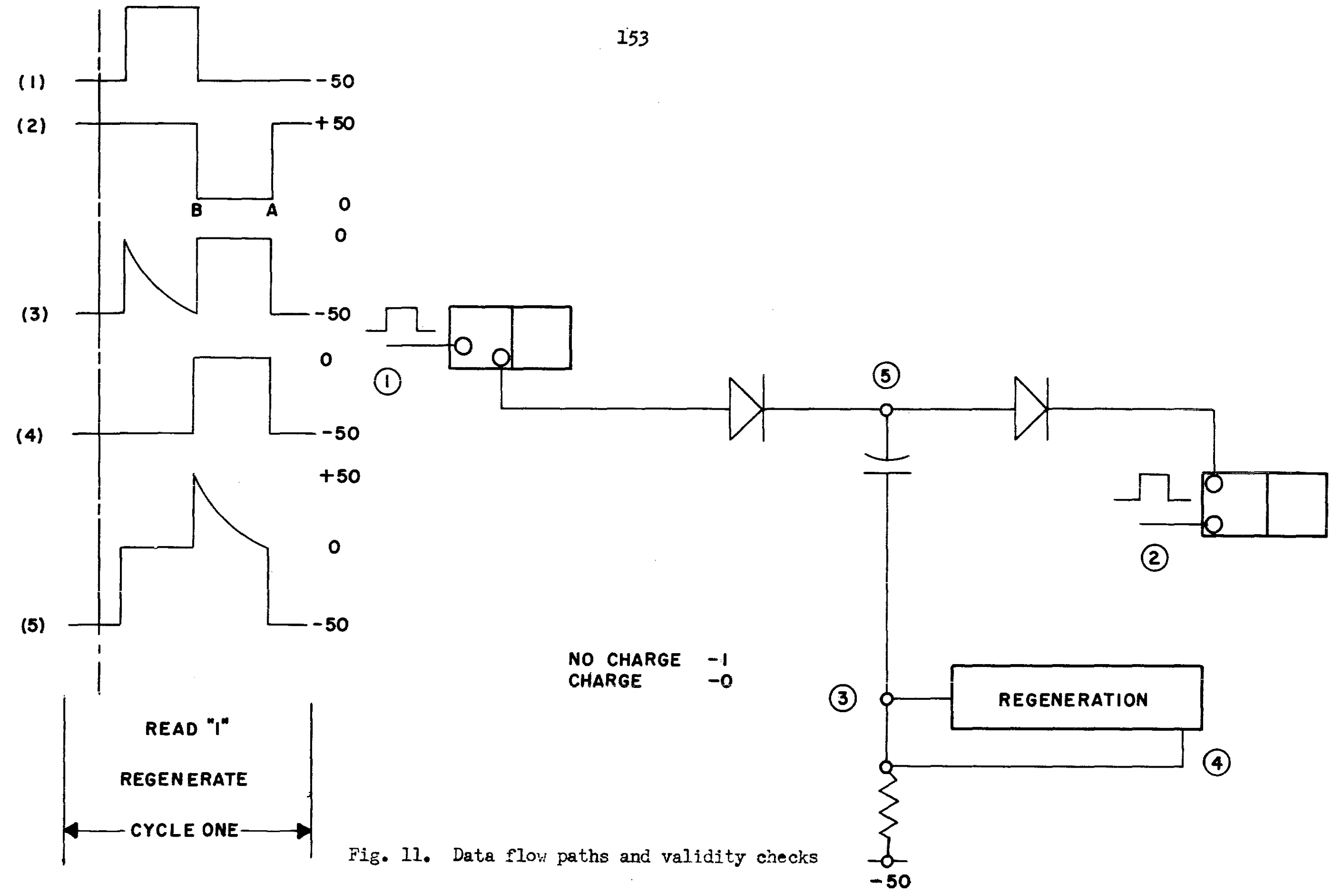


Fig. 11. Data flow paths and validity checks

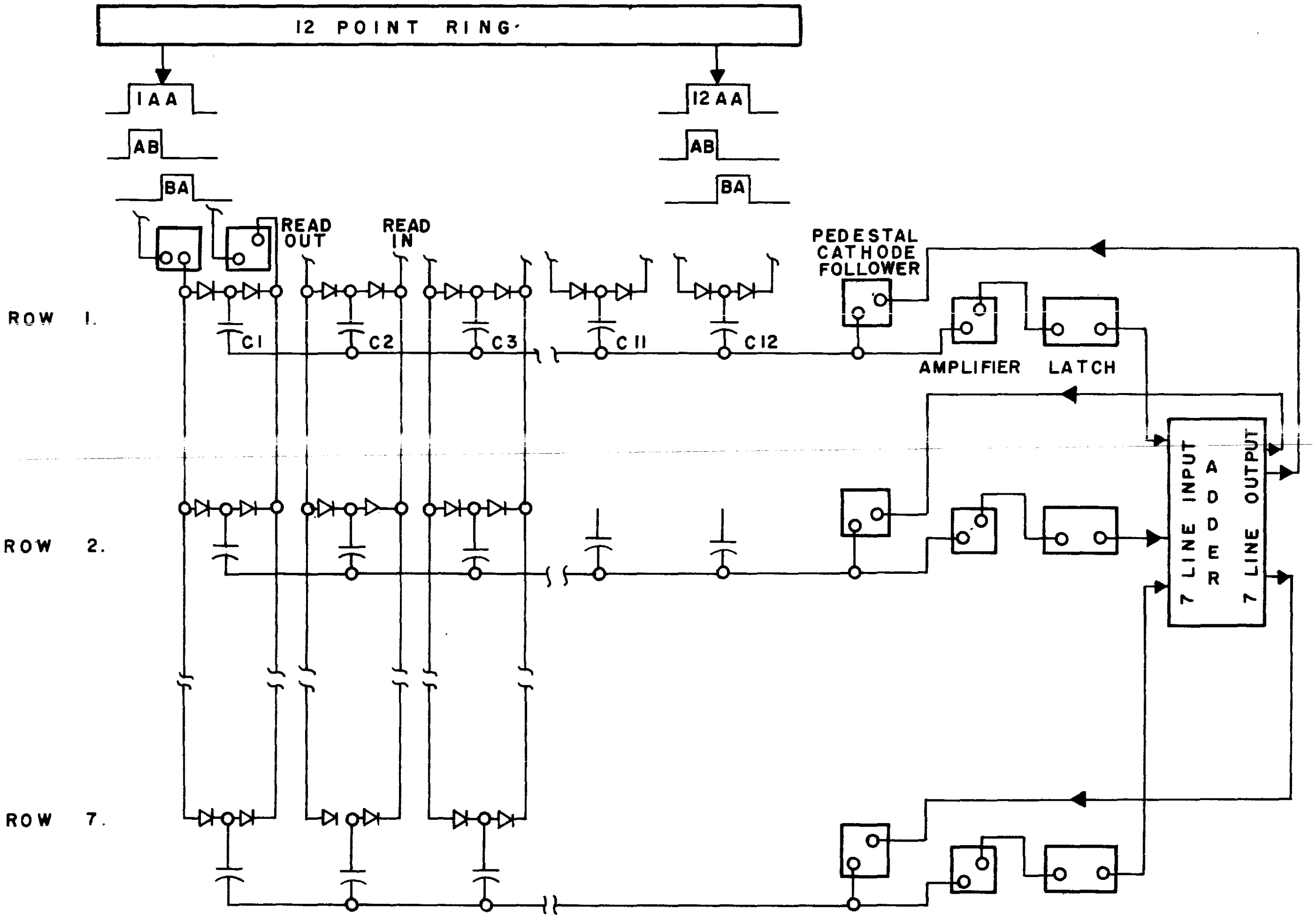


Fig. 12. Capacitor storage, 12 x 7 array

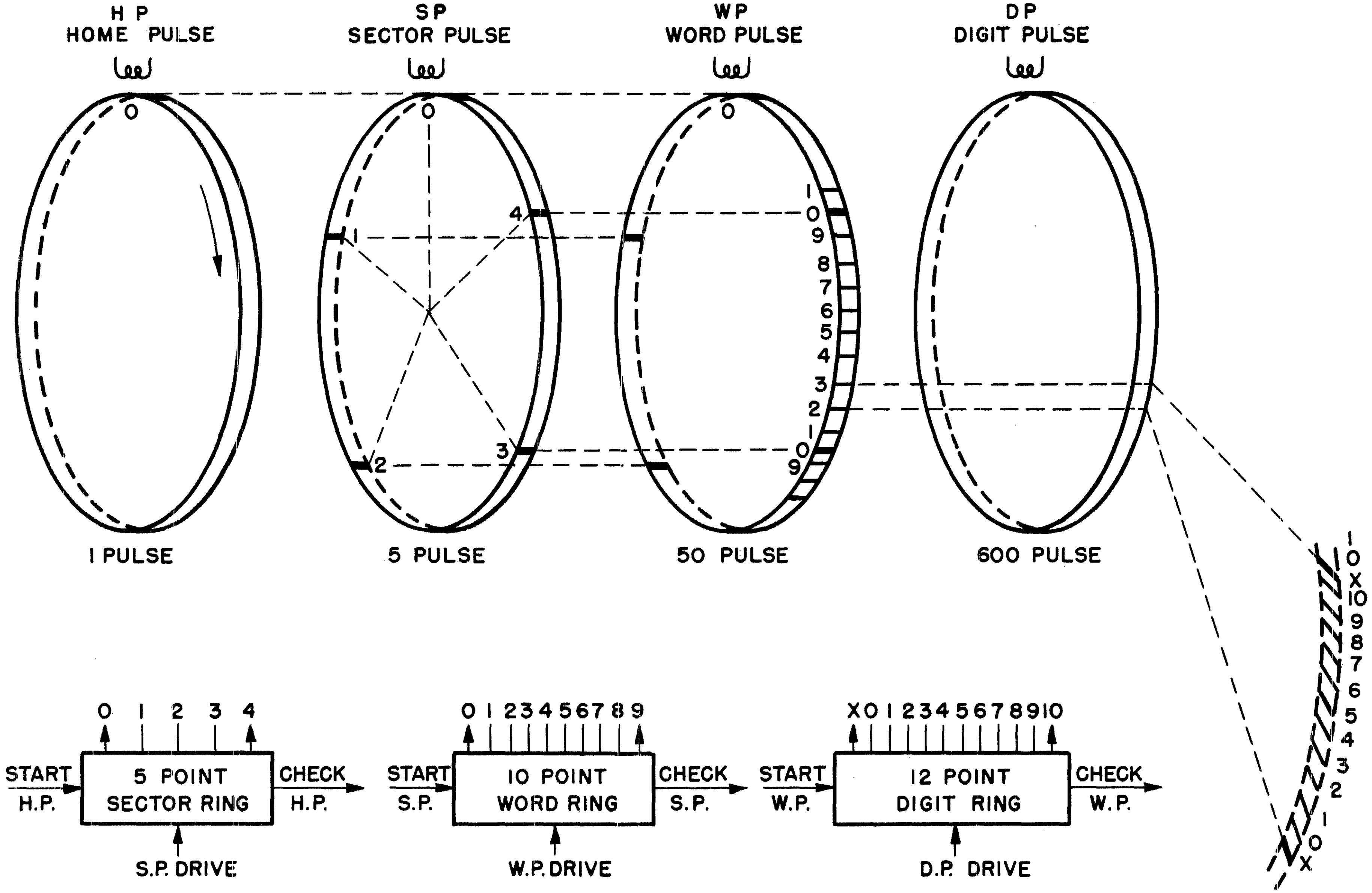


Fig. 13. Recorded timimg pulses

DESIGN FEATURES OF REMINGTON RAND SPEED TALLY

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Engineering Research Associates Division of Remington Rand, Inc.
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Tallying, the recording of the number of occurrences of specific events, although basically a simple repetitive act, has somehow failed to become mechanized in the general trend toward relieving humans of the drudgery of paper work. A tremendous amount of event counting is still recorded in the tally records of modern business establishments in the symbols of the ancients, the four strokes and slash. This system is used especially when the number of different events being tallied is large. It is true that the ticket taker has his thumb-operated counter and the baseball umpire his finger-operated wheels for balls and strikes, but as the number of events grows, the mechanism fails to keep pace. The Electronic Statistical machine has 62 counters and another company makes an analysis machine equipped with 80, but for the problems at hand in the field of merchandising, neither of these is at all adequate. Tens of thousands of counters are required if record of the movement of merchandise bought and sold by even a small mail-order house is to be maintained.

As a means of mechanizing the tallying operations of the John Plain & Company merchandising activity, the Remington Rand Speed Tally has been developed. This machine maintains 39,000 tally totals in an "up-to-the-second" condition while simultaneously receiving 9,000 entries per hour which affect many or all of the totals thus held. Before describing this machine in detail, first let me relate the story of how the development came about.

Early in 1951, Mr. Harold Lachman and Mr. Walter Richter, both of the John Plain Company, became convinced that some electronic methods were ready for introduction into their mail-order business. After a rather comprehensive search of the field, they contracted with Engineering Research Associates, Inc. to design and construct an equipment that eventually became the Speed Tally. Their stated requirements were to provide a mechanism which would permit them to count (or tally) the number of orders they received each day for each of approximately 8,000 catalog items, and to make the result of the counting available at the end of the day. The method they were then using required about 20 tally clerks and required another one or two days for the cross-footing of the 20 sets of 8,000 subtotals thus acquired. Since the activity ran to 75,000 item orders per day, the conventional mechanized approaches appeared to be impractical.

The existence of a rather well developed magnetic drum storage mechanism and its reliable performance in several computing systems immediately dictated its use for the recording of this large number of tally totals. The reasonably short access time of an adequately large drum as well as its non-volatile and selectively alterable characteristics made it appear to be an almost ideal storage device for this purpose. After a considerable amount of compromise, attempting to balance all factors, a capacity of 39,000 three-decimal-digit tally totals was selected. These were subdivided into 13,000 sets of three totals, each set to be specified by a five decimal digit item or catalog number. A ternary[1] digit identifying each of the three tally totals for each item was provided to permit tallying orders, sales and cancellations. Each total was allocated recording space on the drum for three decimal digits which permits the accumulation of tallies up to 999. The location of the total on the drum surface is identified by the five-decimal-digit catalog number plus the ternary or category digit.

To permit the processing of as many as 75,000 tally entries per day, the Speed-Tally was designed to perform its internal operation in the minimum possible time, one and a fraction drum revolutions, since the new total is always restored to the same location from which the old one was obtained. With the addition of the time necessary for a series of cascaded relay operations, the complete operation time becomes just under 400 milliseconds, thus permitting 150 tallies per minute. To match this action time to average human operators, ten keyboard units are provided; however, with skilled operators, six appears to be an adequate number. An allotting mechanism, not unlike automatic telephone exchange practice, seeks each keyboard as the operator completes the tally entry. Approximately 400 milliseconds later the operation is repeated for another keyboard. At this rate, the required 75,000 tallies per day are accomplished.

So long as the 39,000 totals remain only as invisible magnetic marks on the surface of the magnetic drum, they are unusable. To make them available to the users of the Speed-Tally, an output system consisting of an adding machine type printer and a perforated tape reader are provided. During an output sequence, perforated control tapes pass through the tape reader controlling the printing of selected item totals from the magnetic drum. This operation proceeds at a rate of 75 totals per minute, and the record on the magnetic drum may optionally be destroyed or retained. It is, therefore, possible to extract an hourly record of the activity of a few hundred items by only a few minutes interruption of the tallying. A complete record of all 13,000 totals in one category can be printed in less than three hours.

Figure 1 shows a simplified block diagram of the Speed Tally System. In the process of following a single operational cycle, let us presume that the Input Register is already holding the information normally received from one of the keyboards. This consists of a five-digit catalog number, a "one-of-three" designation of the category, and a two-digit quantity. The first two are translated to provide a track selection or magnetic head selection and a specification of the angular position at which the desired existing total is available. As soon as the translation is completed, and at the next drum position which satisfies the angular position criterion, the old total is read out through one of the two reading amplifiers to the Quantity Register. As soon as this occurs, the addition (or subtraction) process begins creating the new total. This operation is exactly analogous to the reading operation just described. The quantity digits are used to make a time selection from a recorded counting pattern on the drum and to pass an appropriate number of pulses into the Quantity Register. The consequence of this action is to form the new total and retain it in the Quantity Register. The new total is completely formed in the two-fifths drum revolution immediately folowing the acquisition of the old total.

---

[1] A ternary digit may have three values, (a decimal digit has ten values).

The actual selection of this old total from among the three hundred present on the selected track is the function of the Address Timing Selector. This same device also directs the assembly of the individual digits of the old total in the Quantity Register. Exactly one drum revolution later, it directs the issuance of the new total from the output terminal of the Quantity Register and its simultaneous recording on the drum in the location of the old total. This operation forever obliterates the record of the old total.

Not shown in this diagram is a control function whereby the originating keyboard directs the arithmetic operation, causing the two-digit quantity either to be added to or subtracted from the old total.

Now let us look at some of the hardware by which the operations are accomplished. Figure 2, shows the completed equipment in service. I believe you will agree that this is one of the most attractive pictures of a computing system you have ever seen! The next picture, Figure 3, shows a close-up of one of the keyboard units. As you can see, it is built around the small keyboard and case of a hand adding machine, with the rear console appended to hold some of the added electrical equipment. The operator's controls consist merely of the ten-key numeral selectors, an add-subtract key and a mechanical clearing key projecting out of the case in the front, and a category switch which is normally fixed. The three vertical apertures are used for a neon lamp display of the new total after each operation, and the two lamps above these are used to display various alarm conditions when an abnormal condition exists.

This keyboard configuration eliminates every possible nonessential and concentrates on the speed of operation. As each numeral key is depressed during the registering of an entry, it is stored in a mechanical memory device, also common to the progenitor adding machine. When the last digit of the entry is registered, a signal is given to the central equipment which stimulates a seeking switch (the allotter) to connect this keyboard to the input register. In approximately 140 milliseconds, the input register is in possession of the entire quantity of information registered in the keyboard, and the internal cycle of operation previously described begins. At the conclusion of the recording of the new total, a reset signal is issued, the input registers are cleared, and the allotter sets out in search of the next keyboard. The mechanical and electrical restoration operations continue under local control in the keyboard unit for another 200 milliseconds.

This resetting of the keyboard has been given an auxiliary operation to perform which is both interesting and of great utility. Besides restoring all of the mechanical memory elements to their original state, the reset operation enters a quantity of one in anticipation of the next operation. This was so designed because almost 90% of the orders being tallied by the John Plain Company call for a quantity of one. Should this anticipatory operation be an incorrect one, the operator merely flicks the clear lever with her thumb and proceeds to make a proper entry of the desired quantity. Should her next operation be the tallying of a quantity of one, she merely enters the five digit catalog number, the machine having spared her the necessity of entering any quantity information.

When an output is desired from the machine, the equipment shown in Figure 4 is put into use which disables operation of any input keyboard for the duration of the output operation. The equipment shown consists of an adding machine type line printer on the left and a tape reader and perforator unit on the right. The operation in process, as this picture was taken, is the preparation of a perforated tape to be used to control a subsequent output operation. By manipulating a keyboard having a pattern identical to that used for input, the operator perforates a sequence of item numbers into the tape in any arbitrary arrangement. In a typical installation, many tapes, each listing a relatively small but related group of items, are prepared and held in a library. Any one or several of these control tapes may be run through the tape reader to produce printed output of the type shown in Figure 5.

This is a sample of both the control tape and the output printing. Binary coded decimal digits in the control tape are read in groups of five by the action of the fifth level control hole causing the printer to print an output tape as shown. The five left-hand digits identify the stock number and the three right-hand digits the quantity recorded in the magnetic drum. As you will note, the stock numbers can be listed in any arbitrary sequence to produce output information exactly fitting the needs of a particular buyer or other administrative official.

The complete tallying process is performed by the central equipment shown in Figure 6. Fifteen pluggable electronic chassis in the upper right portion of the equipment constitute the entire tube complement except for the D.C. power regulators which are shown in the lower left. Immediately below the electronic section are 130 relays used for magnetic drum head selection. The relays shown in the upper left portion of the equipment comprise the input register and the output control group. The twin cabinets housing the central equipment are each 38" wide by 30" deep and 78" high and enclose the entire equipment with the exception of the input and output devices. Approximately three kilowatts of power is consumed from the a-c mains.

Figure 7 is a rear view of the same equipment and shows the magnetic drum, a 17" diameter cylinder having a 10" axial dimension. It is continuously driven at 1750 rpm by a 1/3 horsepower induction motor. At the upper right in this view is shown the address translator which consists of two 10 x 10 crossbar switches and a bank of 1300 miniature selenium rectifiers. Not all of the latter are in fact necessary, but their presence eliminates all concern about sneak circuits. Directly below the translator are two power supplies and below them and not visible is a motor generator. These three power sources provide all d-c for the vacuum tube circuits.

The translator, consisting of the two crossbars and ten other relays, performs a very significant service in this equipment, since it permits the 13,000 item spaces in the magnetic drum to be located by arbitrary combinations of five decimal digits. The only compromise from complete random distribution of these numbers is the requirement that not more than 1300 permutations of the four highest order digits be used. In most stock numbering systems this is almost as acceptable as complete randomness and it significantly reduces the dimensions of the translator. Another way of stating the stock number distribution is that recording space is provided for 1300 item number decades - the decade signifying ten item numbers in which the lowest order digit ranges from zero to nine for a given set of high order digits. The coil circuits of the crossbar switches and the other ten relays constitute the input register for three of the five item number digits and twenty more relays provide the input register function for the other two.

The operation performed by the Speed-Tally equipment which appears to intrigue most technical observers is the location and selection of one specific tally record from the 39,000 present on the drum surface. Figure 8 illustrates the principles employed in performing this locating operation. In the center of the figure in boldface you will note a sample catalog number and category, A1064X. The category, "A" in this case, merely identifies which of three tally totals of the set associated with this item number is to be located. This information comes from the input keyboard or the control-tape reader as one of three electrical signals. The remaining five digits, 1064X, describe a particular item number from among the 13,000. The "X" is merely used to signify one of the values, zero through nine. The higher order three digits, 106, perform two operations. First, they select one of the 130 magnetic heads and thereby reduce the 39,000 candidates to 300 (100 sets of 3). The remaining two digits, 4X in this case, specify a particular set from these 100, however, with the random number system employed, there may be several totals among this 100 which are specified by the same ten's-digit value of four. Therefore, the track selecting digits, 106, also modify the value of the ten's digit to one which avoids having duplicate values in any one track. This is the principal action of the translator referred to in the previous figure.

Since the timing track contains 3600 discrete bit positions, the consecutive action of the category and item number digits reduced these by 1/3, 1/10, 1/2, and 1/5 leaving only twelve bit locations eligible for controlling the output of the reading amplifier into the quantity register. The timing pulse count-down which achieves this selection is performed by four counters, and their relationship is arranged to space each of the twelve bits by an interval of sixty bit positions and to concentrate them in one-fifth of the drum periphery. Our convention is to arbitrarily label the sector containing the desired item space "Sector 1" and the subsequently arriving sectors 2, 3, 4, and 5. This convention does more than merely aid in locating a particular item record, since the programming of the several actions performed during each operational sequence is done by the consecutive existence of the numbered sectors. In this way, by the time Sector 1 returns to the magnetic head on the following drum revolution, the new total is available and is written in place of the old.

Having shown you the machinery of the Speed Tally, I shall conclude with a word or two about applications of machines of this kind. The Speed Tally has been applied to that region of the unit control problem referred to yesterday by Mr. Shaffer, that of recording for analysis, the unfilled demand. Here it has been able to provide information for use by the merchandise buyers quickly enough for them to take some action. It should be evident that this kind of machine is not limited to this work; but is capable of handling many associated portions of the unit control problem. It is my belief that it will only be a short while until its use in a variety of commercial applications will give rise to new concepts of utilization; and, of importance to equipment designers, new concepts of design for an even wider range of applications. I believe we are witnessing the office machine counterpart of the introduction of the internal combustion engine into our lives, and just what and how much change it will bring is as yet unmeasurable.

Our first Speed-Tally machine, and the only one in existence, has now given us six months of experience centered on the Christmas rush business of the John Plain Company. It has provided our industry with another illustration of the potential of electronics in business. To the user, this illustration has been very dramatic and understandable. It has further dispelled any feeling that these computing devices were only for the commercial giants. To the designers and machine builders it is revealing a much clearer picture of commercial requirements which has already resulted in machines of the Speed-Tally type better matched to the unit control problem.

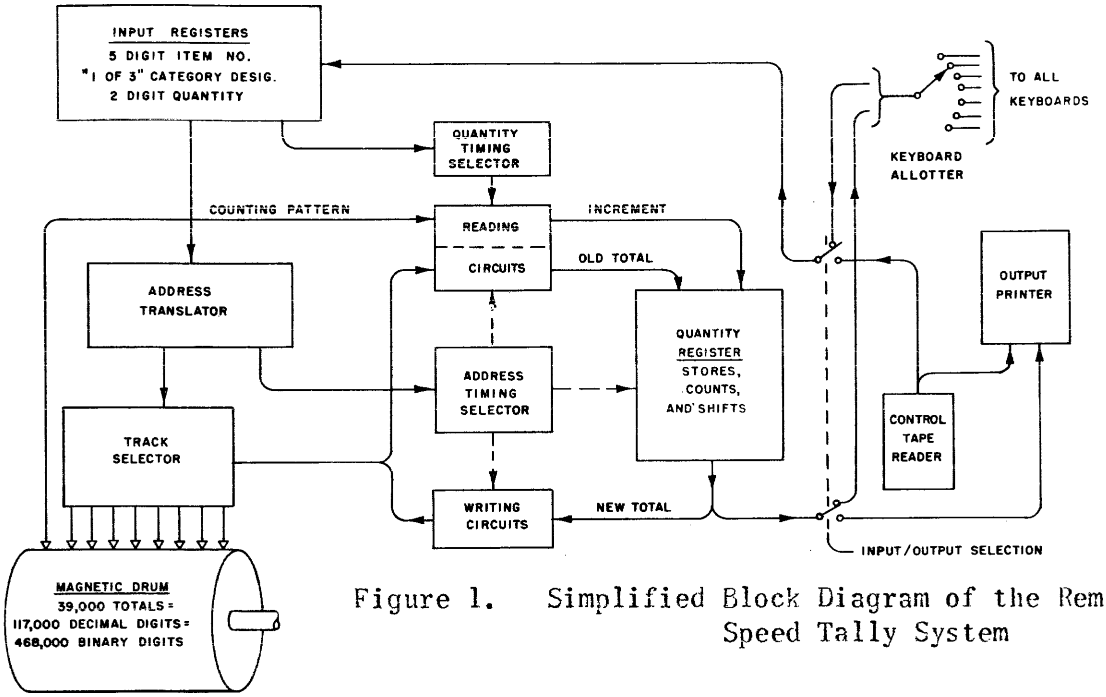
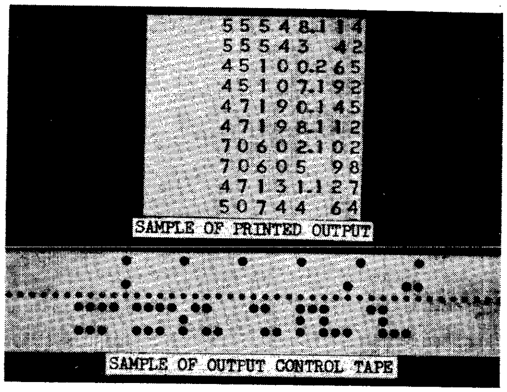


Figure 1. Simplified Block Diagram of the Remington Rand Speed Tally System

Fig. 2. General view of the Remington Rand Speed Tally System

Fig. 3. Keyboard unit

Fig. 4. Output printer and control tape unit



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55548.114
55543   42
45100.265
45107.192
47190.145
47198.112
70602.102
70605   98
47131.127
50744   64
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Fig. 5. Sample control and output tapes

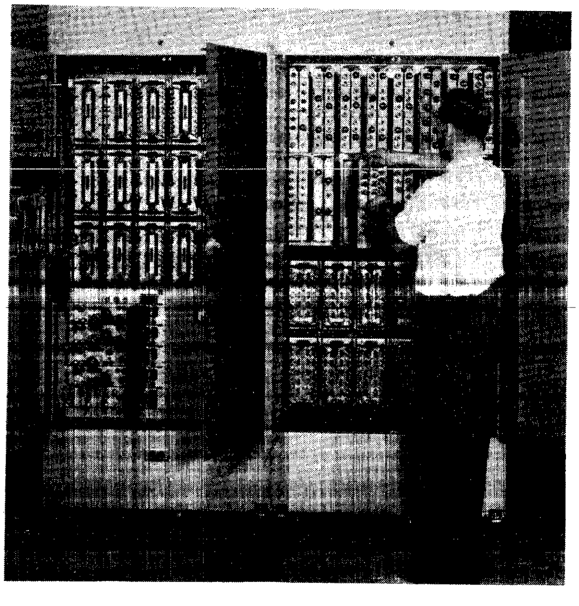

Fig. 6. Front view of Speed Tally Central Equipment

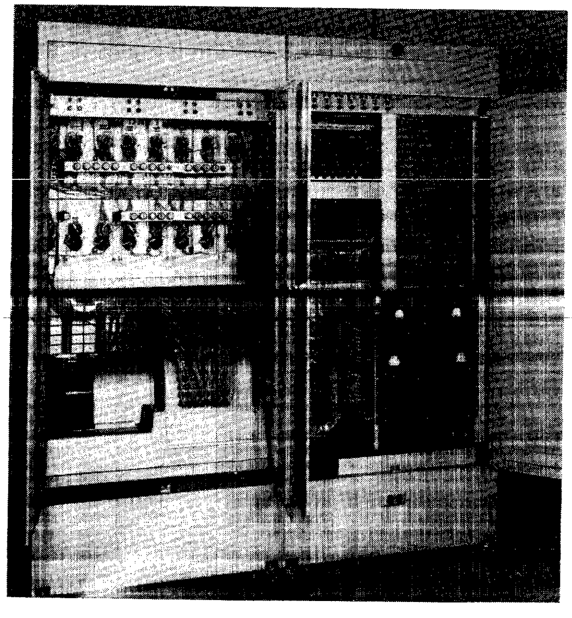

Fig. 7. Rear view of Speed Tally Central Equipment

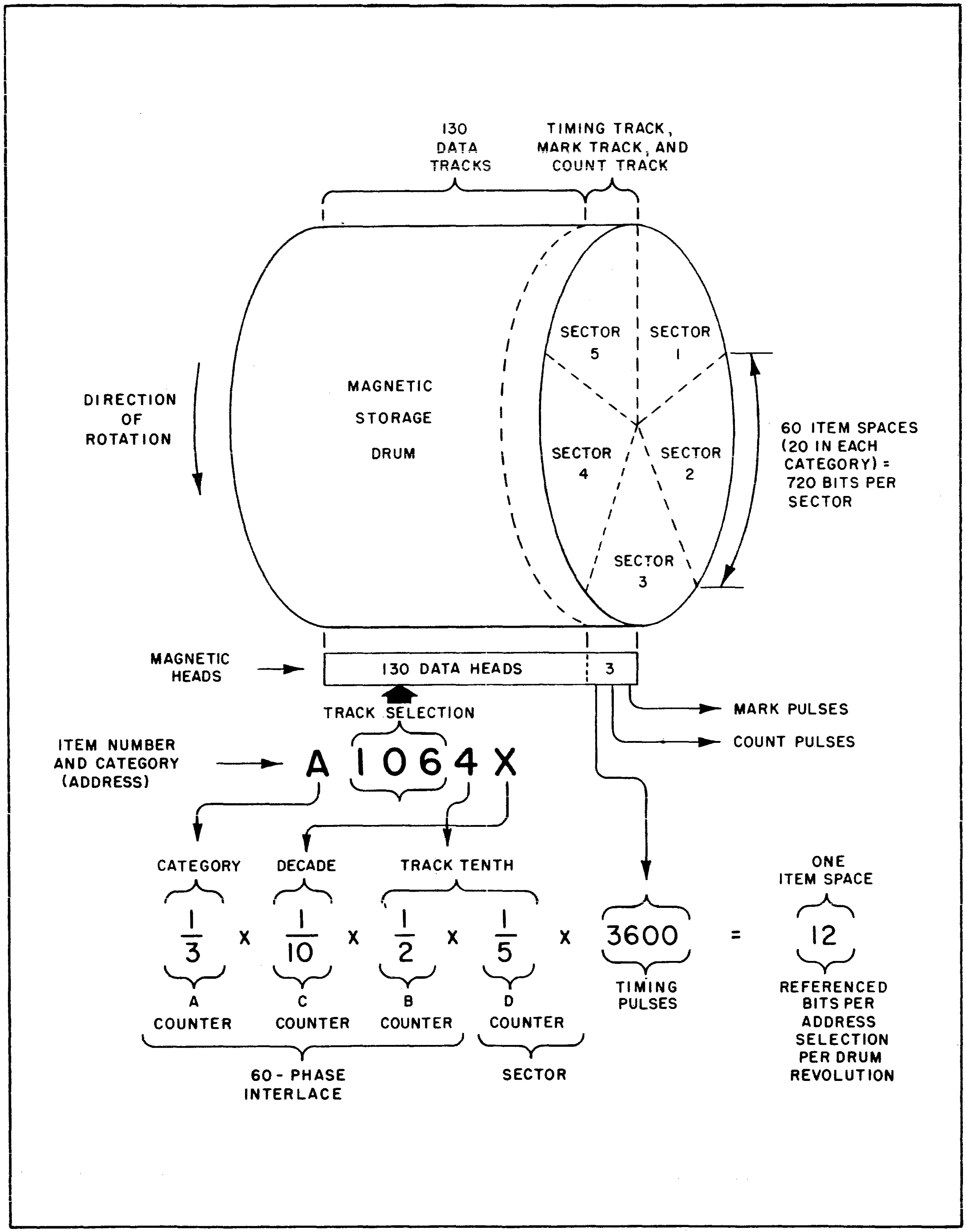

Figure 8. Principles of Speed Tally Locating System

PRODUCTION CONTROL WITH THE ELECOM 125

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Underwood Corporation
Long Island City, New York

The revolution in the office which electronic digital computers eventually will bring about, will not be accomplished by a clash of thunder, charged with 100,000 volts, and accomplished with the speed of light. Instead, it looks to me as if the electronic computer will have to enter the office wearing a blue serge suit with pin stripes, topped off with a Homburg, and acting on the whole very much like timid little Mr. Casper Milquetoast.

By now you have heard many of the objections to electronic computers raised by our hopeful, but sceptical, friends in management engineering, accounting, comptrolling, banking, and associated fields. They hear that we can do 4,000 additions a second, or 40,000, or 40 million, and they ask embarrassing questions like, ''How many copies does it give me for distribution to sales, accounting, manufacturing and the executive offices?'' Or, ''Are you always correct to the last penny?'' Or, ''How do you get the thing into my office without knocking down the walls?''

Bearing all the needs for, and objections to, office electronic computers in mind, the people of the Electronic Computer Division of the Underwood Corporation have taken the attitude that the business data-handling system must come into the office quietly and without fuss. It should look fairly familiar. The people needed to operate it should look more like office clerks, supervisors and potential vice-presidents, rather than the proverbial mad scientist.

With that attitude in mind, a group of 'Elecom' people went up to the Underwood typewriter manufacturing plant in New England some months ago to look over the production control problem and to see what an electronic data-handling system had to offer. Before making the trip, we had been primed with a lot of facts about how expensive the operation was; how many errors were being made daily; how far behind reports and surveys were; and how, in general, the whole procedure was inefficient.

Nobody mentioned beforehand the obvious facts that Underwood had been manufacturing typewriters successfully for more than half a century; that somehow in the process, all the necessary parts got together, and that the Underwood typewriters worked satisfactorily when completed and delivered.

We learned a lot. The results of what we learned are now taking shape as we build the Elecom 125 Electronic Business System.

What did we learn?

First of all, we learned that a million dollars for an electronic system is a lot of money. This was not exactly new to us, since the whole effort in the Elecom line of computers has been to produce relatively low-cost machines.

A million dollars to most average-sized businesses is a lot of money, since, with the exception of very large centralized corporations, and the Federal government, the need for giant, lightning-speed computers usually cannot be justified by the present dimensions of the operation.

Take the Underwood production control operation. The exact number is a commercial secret, but Underwood produces 'hundreds of thousands' of typewriters a year. The number of different parts going into the various models, such as standards, portables, electrics, typewriters with special feed devices, etc., is about 12,000. Fifty different departments at the Underwood factories handle these parts. On the average, any particular part travels among four of the fifty departments. As examples, there are the plating department, the blanking department, the heat treating department, primary press department, secondary press, and some forty-odd others.

The dimensions of the production control paperwork operation were modest. Underwood had some fifty people doing the production control paperwork. The total payroll cost is of the order of $150,000 a year. The savings to be effected by any electronic equipment installed should be able to pay for the equipment in a couple of years, rather than ten or fifteen.

Also, Underwood already has a paperwork system. This system, with all its shortcomings and strong points, has been built up through experience over many years. It involves existing names of parts, part numbers, accounting numbers, department numbers and names. It involves procedures for ordering materials, the various stages of manufacturing the 12,000 parts, assembly, shipping finished typewriters, billing customers, paying Underwood's bills, and so on and so on.

To change the whole system overnight would not be practical. Too many people, too many processes with too many ramifications are involved. Not only in New England and New York, but all over the United States, in Canada, England and around the world. No Underwood vice-president in his right mind would allow everything to stop and be completely changed. The cost in changeover and lost motion would be excessive. And suppose the new system developed some bugs?

Since production control was not the only office problem in Underwood, the electronic data-handling system which we delivered for production control should be general purpose, not limited to the one special application.

Let me break down the lessons we learned, and the results, in terms of hardware.

Input and Output

Input and output units should be completely independent of the central data handler. This allows 'ganging up' on the computer on the 'in' side, and the multiplication of output units to keep ahead of the computer in producing the visual copy.

The input and output devices should be cheap. The work done on the input unit should be capable of easy checking. The input to the computer should be in a form understandable to the office typist. Input to the computer itself should be rapid. The ten digits per second rate achieved by the Flexowriter and other punched hole tapes was not fast enough. Even the Ferranti reader appeared to be too slow.

The economic cost of using present devices to type and simultaneously punch holes in paper tape also appeared to be undesirable. So we designed a new input unit, called the Underwood Tapewriter. The Tapewriter is an Underwood Electric typewriter which produces two typed impressions simultaneously: first, the normal English letters and numbers of the data being inserted. This visual copy is then available for a check against the letters and numbers on the original document from which the data is transcribed.

At the same time, the Tapewriter produces the coded-dot binary pattern for the English letters and numbers which have been typed. Thus, when the typist strikes the keys for 'JOHN JONES', two things happen. The capital letters JOHN JONES are typed on a piece of paper, or any business form inserted into the Tapewriter. At the same time, the dot patterns for the letters JOHN JONES are printed on a strip of half inch wide paper tape. If the girl strikes the correct keys, the correct coded dot pattern is produced automatically, since both letter and coded dot pattern are printed by the same operation.

We expect to produce and sell the Tapewriter at an approximate price of $1,000 each. Thus, multiplication of input units becomes economically feasible. Since a typist can type, handle documents, etc., at an average rate of three digits per second, and since the input from the printed dot paper tape to the computer is at the rate of 600 digits per second, the Elecom 125 data handler can keep up with some 100 to 200 typists.

Once the paper tape is produced and removed from the Tapewriter, it is then inserted into a photoelectric reader attached to the central computer. The reader and computer convert the printed dots into pulse patterns on magnetic tape. Once the information has been transcribed to magnetic tape, the computing system is ready to go to work.

Let me mention one important feature of the input unit. The Tapewriter produces hard copy - the normal number of carbons can be prepared - so that the sceptical business man has data, in visual form, in English letters and numbers, on paper. Carbons can be routed around the office and factory for various purposes. Other copies can be filed where desired. Thus, if the office manager desires to reconstruct an account, audit a set of transactions, or look over his records, he can do so without going to the magnetic tape and calling for a print out. Thus the businessman does not have to depend upon magnetic tape alone.

Checking input data can be done by several methods. Two typists can prepare the same data independently, with the tapes then being compared by the computer. Or, visual checking of the original document against the hard copy can be done. Errors then are corrected by the preparation of a trailer 'correction' tape fed into the computer. Errors which the typist catches as she types can be corrected by backspacing and the use of an 'error' key, which blanks out the data in error.

At the output end, the requirements were much the same. Output should be independent of the computer, cheap, flexible, and of a nature enabling output to keep up with the computer. Like many other computer manufacturers, we are hoping that a cheap, reliable line printer will be available soon, but we are not waiting for the miracle to happen in the next couple of months.

The present Elecom 125 output unit is an Underwood electric typewriter, with a photoelectric reader attached. The photoelectric reader reads the printed dots on the paper tape which has been produced by the computer as the final output. The reels of printed dot paper tape are mounted on the output typewriter, read photoelectrically, and the output typewriter types out hard copy at the rate of ten digits per second. Since the computer can produce printed dot paper tape at a rate of 600 digits per second, theoretically it would take 60 output units to keep abreast of it. In practice, the number is less since the electronic data handler takes time to process tape, convert from magnetic to paper tape, etcetera.

At the proposed price of $2,500 per output typewriter, multiplication of the digit-per-second output rate is feasible and economic in terms of the cost of the entire system. For $25,000, the customer can buy 100 digits per second. Considering present printer costs, the economics are not out of line. The price of the output unit should decline as the quantity produced reduces the unit cost, and we are prepared to go to a line printer as soon as one comes along which fits the bill.

The Elecom 125 Computer

An electronic computer for a modern office must be simple to operate, reliable in operation, easy to maintain, and fast enough for the job. The Elecom 125 computer has grown naturally from its little brothers, the Elecom 100 and the Elecom 120 computers, along those lines.

First, we use what we consider to be the simplest and most reliable type of memory, the magnetic drum. The Elecom 125 has a magnetic drum memory of 1,000 eight-digit words, each plus sign. For more rapid access, we use a ten word recirculating channel.

How reliable is a drum? Nobody really knows. However, we have an Elecom computer which has been operating without any drum trouble for more than two years. The part most likely to wear, the bearings, are estimated by our mechanical engineers to have a normal life of at least 100,000 operating hours. On the basis of a 20-hour computer day, that is something like 20 years. If the computer is used only one shift or less, the life expectancy of the bearings in the drum unit should be of the order of 100 years.

The Elecom computers operate at a fairly sedate pace. Since the pulse rate of the Elecom 125 is 107 KC, compared with over two megacycles in some of the million dollar computers, we have more tolerance in our circuitry, so that the chances for error and failure are reduced sharply.

The primary weak points, to date, of electronic computers seem to be vacuum tube failure and imperfect magnetic tape.

The vacuum tube problem we attack by not using so many. The Elecom 125 computer contains about 350 vacuum tubes. Ninety percent are of two standard types, 6CL6s and 12AT7s, which can be purchased in the local radio shop in case of emergency. The entire Elecom 125 system, including both the computer and the sorter, contains less than 600 vacuum tubes. Statistically, the fewer the tubes, the fewer the chances for tube failure.

As to magnetic tape, Elecom computers utilize a system of presprocketing, developed by our engineers, which eliminates errors caused by faulty magnetic tape. The raw tape received from the manufacturer is run through an electronic sprocketer. The sprocketer examines all areas of the tape, and puts a magnetic pulse in one channel where the tape is discovered to be good. On the areas (one or two percent) of the magnetic tape where faults in the coating are discovered, no sprocket pulse is laid down. Thus, in operation the computing system merely skips these marginal areas of the magnetic tape. The sprocket pulses are permanent, and are never erased or changed during any operation of the data-handling system.

We have included many self-checks in the Elecom 125 system. In addition to pre-sprocketed tape, we have a built-in odd-even check; we check forbidden combinations in the computer; we have a special check for recording and reading on the memory drum; and program checks can be included to the specifications of the most scrupulous auditor. We can, we believe, safely guarantee accuracy to the exact, not the nearest, penny.

Electronic Sorting

I now come to a term which is generally avoided by computer people - sorting. As we all know, data processing is a cinch. The trouble is, the daily inputs of data, the outputs in the form of listings, reports, etc., are all out of sorts.

The production control people at Underwood first wanted the data on typewriter parts in part number order; then they wanted the parts listed by departments. Other reports required certain data on a limited number of critical parts listed in priority order. The input information comes into the production control office in the form of white, blue, pink and yellow slips, letters, phone calls, and reports from the New York Office a hundred miles away. The master library reels are all nicely sorted out when the operation is started. In order to process the master tape reels and come up with new information, the daily inputs have to be sorted into part number order. Then, when the output data is produced, it has to be resorted into the order required by the particular report being prepared.

The requirements for electronic sorting are much the same as for the rest of the system. It must be simple, automatic, reliable and economic. Furthermore, since almost exactly half of the time involved in the production control job turned out to be sorting and resorting, the sorting process should not tie up the central computer.

The electronic sorting unit of the Elecom 125 system is completely independent of the data-handling process. We do not use the central computer for a programmed sort. We have an independent sorter which does all the sorting and collating.

To keep the cost low, we utilized the fact that our memory drum was built for a maximum capacity of 2,000 eight-digit words. Since we found that 1,000 words of memory was more than adequate for programming the simple operations involved in a business paperwork problem, we therefore used the other half of the same drum for sorting.

The cost of manufacturing the drum, turning it, timing, gating and so on had already been incurred in putting the memory drum into the computer. We added magnetic heads and the associated electronic equipment, but we didn't have to build a sorter from scratch. Thereby, we cut the cost of the sorting system considerably.

I will not go into the details of the sorting process. However, the sort is completely automatic. There is no reel handling except at the start and finish of the operation. The sorter is 'programmed' for the particular operation about to be done in a few moments. A switch is set to indicate the length of the items being sorted, data is fed into indicate which digits of the item are being sorted on, and that is all. When the sorter has sorted the data into the desired arrangement, it halts automatically. Collating sorted data, pulling out desired data from a large, sorted file, and similar processes all are done on the sorter, not the computer.

Thus, the Elecom 125 can sort and process data at the same time. Or it can sort alone, or process data alone. Of course, it cannot sort and process the same data simultaneously. Just as you cannot sort and list data contained on punch cards without duplicating the decks.

To sum up the hardware in the Elecom 125 system, we have:

Input Tapewriters, producing hard copy and reels of paper tape on which the coded information is contained in the form of printed dots.

The central computer, a 1,000 word magnetic drum electronic computer of moderate speed, with associated magnetic tape drives, and facilities to handle paper tape input photoelectrically, with a printer at the output end which produces reels of paper tape containing printed dots.

The electronic sorting unit, independent of the electronic computer, with four associated magnetic tape drives.

The output units - Underwood electric typewriters with photoelectric readers attached. The photoelectric readers read the printed dots and activate the typewriter to produce hard copy at the rate of ten digits per second.

The cost of the system, depending upon the number of input and output units, is of the order of $175,000 to $200,000.

The Production Control Operation

At Underwood, we did not attempt to devise an ideal production control process, thereby completely revising the present system. We attempted to handle the data, and produce the reports, listings and documents, at present used in Underwood. This meant dealing with purely alphabetic, purely numeric and alpha-numeric data. This problem of mixed alpha and numeric information is common to most office operations. Therefore the Elecom 125 sorter was designed to sort numbers, letters, or any combination of the two.

We did not attempt to do away with Underwood's existing files. Instead, we built upon the foundation of the existing files, so that the people charged with the responsibility for controlling the production of typewriters would have means for instant access, if emergencies arise, to data covering any part merely by going to the files and looking at the pieces of paper.

We did not attempt any revolutionary method of input. We do not sense spots, read original typed numbers and characters, or try to decipher the handwriting of the New York Office manager by electronics. Our input operation depends upon a human being, sitting at a machine, typing data in the appropriate form for the electronic system.

Although the application did not require it, our system of independent input and output allows for physical removal of input or output operations from the central computer and sorter. The problem of converting paper tape dots to teletype signals, and reproducing the printed dot paper tape at the other end is a simple one, and can be applied where the operation demands it.

We did not, in the main, ask the computer to make judgments or to come up with theoretical optimums. As in most paperwork operations, we found that the problem at Underwood was to get correct information, in time, to the people who have to exercise judgment. At present, with a hand system which is slow and inaccurate, judgments as to which typewriter parts to manufacture, which materials to buy, which departments to speed up and which to slow down, are often made solely on the basis of long experience, or rule of thumb. With the Elecom 125 system, the people who must exercise control will have complete, up-to-date information at eight o'clock every morning as to how everything stood the previous afternoon at quitting time.

As one man, employed by Underwood in the Production Control operation for many years, said; even this relatively modest achievement seemed to him like 'A trip to the moon.'

To accomplish this result, we found the breakdown of operations would be as follows:

Input typing and checking; from sixteen to thirty hours per day, depending upon the type of checking operation.

Electronic sorter time: about two hours per day.

Electronic computer time: about four hours per day.

Output typing time: about twenty-two machine hours.

We had an additional load of detailed reports, in several different forms, to be prepared once every two weeks. We found that such reports would require about twelve hours of computer time, and forty hours on the electronic sorter. By using the Elecom 125 system, as designed, over the weekend, we have ample time to get the necessary reports ready by eight o'clock on Monday morning, current as of 5 p.m. the previous Friday. At the present time, without using electronics, these reports are rushed out in a day or two by assigning twenty or twenty-five typists on a priority basis to do the job.

We analyzed the personnel requirements of the operation and discovered:

We did not reduce the number of higher-trained persons, each exercising some form of judgment, very drastically. We merely gave them the information to do their jobs more intelligently and on an up-to-date basis.

We did reduce sharply the need for clerks, typists and form-handlers.

Thus, the electronic revolution seems to add up to the need for as many or more trained people, and less untrained or lower trained office personnel, at present doing the routine, dull jobs.

The economics worked out to be a maximum saving of about $100,000 per year in personnel costs. This for an investment of $200,000 in electronic equipment, so that the system, used for production control only, should pay for itself in about two years.

However, the total load - four hours per day - on the central computer and sorter are of a magnitude to allow for other work to be converted to the Elecom 125. We believe our equipment should be used twenty hours per day, with four hours for down time and preventive maintenance. That means that the load on the 125 could be multiplied by four or five before the limit is reached. If the factor holds up, and the computing system is utilized fully, the Elecom 125 should be able to take over paperwork operations now involving some two hundred or two hundred and fifty one-shift people, and pay for its costs in something like six months.

For larger jobs, we recommend the use of a number of Elecom 125 systems. There are many advantages to decentralized computers. They can be placed in different locations. If one computer completely breaks down, the others can share the additional load, and so on.

For the million dollar cost of a large computer, we can offer five relatively moderate speed data handlers, five electronic sorters, and some twenty-five input and ten or fifteen output units. Our tape moving speeds, computing speeds, sorting speeds, and in and out volumes become more than comparable and respectable on a dollar for dollar of cost basis.

The computer and sorter work decimally; no conversion to and from binary is required. Programming is done by us, the manufacturer, and included in the system cost. We train both operators and programmers, if desired, and estimate that it takes a couple of weeks to train an intelligent office girl to operate the computer, and three weeks or so to instruct a college mathematician to program the system.

Maintenance will be done by us, or we will train maintenance personnel for the customer. We believe that per shift, one maintenance man, of the order of skill of a radio or television repairman, can successfully keep the Elecom 125 operating. He requires three or four weeks training by us. This is the plan we have followed with Elecom computers now in the field.

Only the future will tell whether or not the trend is to larger, faster, more complex computers, or with the slower, cheaper and more modest data handlers. The answer is that there is probably room for both.

We at the Electronic Computer Division of the Underwood Corporation are confining ourselves to the medium sized and small computing and data handling systems. We are trying to walk before we run, and we hope not to stumble in the process.

A CENTRALIZED DATA PROCESSING SYSTEM

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Early in the spring of 1953 with the activation of a ground telemetering facility at the Air Force Flight Test Center it became evident that there existed a real and continually increasing need for a less expensive, faster and more reliable method of processing extremely large amounts of raw uncorrected data that found its origin in the many diversified activities which were at that time presently being conducted at the Center. Examples of the sources from which this data came were the flight testing of experimental and production aircraft, (i.e. airborne recording), a radar phototheodolite, the aforementioned telemetering station, as well as the high speed experimental track and the USAF experimental rocket engine test station. Figures 1 through 4 illustrate some of the data sources at this Center. Furthermore certain large classified projects were being initiated at the Center at that time and they brought with them their own large data work loads. The problem of reducing this data presented a task almost as large as the problem of correcting the data. However, before the data could be reduced, that is, reduced on IBM machines or desk calculators, it had to be processed; that is, put into a form where it could be handled readily and easily by the IBM card programmed calculators. This processing consisted of reading the data, usually from film or oscillograph records, translating this information into digital form and correcting for any instrument or calibration errors which might be present in the raw data. With the advent of the IBM card programmed calculators, actual calculating time on the data was materially diminished, leaving the problem of reading and processing the data standing as a very real bottleneck. It therefore became evident to responsible personnel concerned that a system would have to be devised that would allow either automatic or semi-automatic processing of much of the data incurred at the Air Force Flight Test Center if the Center was to survive this deluge of data. To this end a centralized automatic data processing system was proposed, based on the philosophy that data should be taken in such a form, that it would be suitable for automatic reduction. It was felt that such a centralized data handling system would be instrumental in effecting significant savings in personnel costs, since it would reduce the number of employees required to reduce data and make unnecessary the constant recruiting and training of large numbers of data reading employees, or, at least enable those assigned to the data reduction task to cope successfully with their expanding work load. Moreover it would increase the reliability of results obtained by eliminating much human contamination in the reading of data which by its very nature was tedious to reduce, highly exacting and demanding of a high order of accuracy in reading. Finally this type of data handling system through its ability to rapidly process large amounts of data would aid materially in expediting the mission of the Air Force Flight Test Center by helping to make more complete and efficient use of its experimental and unique flight test aircraft and equipment.

Thus it was with this philosophy in mind a study contract was initiated with the Ralph M. Parsons Company of Pasadena, California for a careful analysis of the data reduction problem at the Air Force Flight Test Center together with a documented estimation of the data handling requirements of this Center during the next five to ten years and a proposed system solution to the problem. This system as it was envisioned at the time the contract was let (See Figure 5) can be represented by a data flow chart and daily work load estimate. Note how the different data sources with their estimated work load flow toward an all inclusive and extremely comprehensive black box which would be able to accept input in three possible forms; analogue, frequency modulation, or digital coding. The black box would then read the information, apply necessary calibration and instrument corrections and then read out the information in any or all of four possible output forms; they are, digital typed, digital punched cards, analogue (for large amounts of data), and, finally, magnetic tape for input to an analogue or digital computer. Note the emphasis at this time on digitalization.

The block diagram at the bottom of this figure is a representation of the system concept. All steps are included and considered from transducer to final presentation of the data to the engineer. How this idealized concept as shown in Figure 5 differs from the final proposal will be discussed later.

The Ralph M. Parsons Company required over six months and many engineering man-hours to deliver four monthly reports and one final report on the proposed data reducing system for the Air Force Flight Test Center. It might be stated at this time that the system philosophy as developed by the Parsons Company during this period was one that evolved necessarily from the conditions under which data processing and reduction must be performed at the Air Force Flight Test Center. One of the most important distinctions or facets of this philosophy and one that was discovered early in the investigation was that in the course of an attempt to estimate the data reduction work load at this Center, one had to carefully distinguish between three levels of data and that they are in order of decreasing magnitude. These levels were; one, the amount of data actually recorded; two, the amount of data which had to be examined for trends, that is, inspected in analogue plot form; three, the amount of data that had to be actually tabulated and accurately measured with resultant accurate determination of specific values for further computation. In any of the categories one could, of course, speak of either present and future work loads; however, there is neither now or expected to be anytime in the foreseeable future a practical data handling system capable of reducing to the most advanced digital form all the data which the data sources might justifiably record. It is in speculations like these that one runs into astronomical numbers of data points involving stacks of IBM cards literally miles high.

Therefore, the concept of a human filter was evolved. By human filter, it was meant, of course, critical human discrimination at any point where the data passes from one class to another, that is, from recording to analogue plot or plot to tabulation. This philosophy also advocated a grouping or centralizing of the various data handling groups at Edwards for the obvious advantage of the application of mass production methods to data processing techniques. It must be carefully pointed out, however, that there were other disadvantages that could, if not properly anticipated, offset all the advantages of centralization. The main disadvantage would be the tendency of the now remote Project Engineer or responsible test designer to relax his sense of restraint in requesting data reduction services and unless a direct sense of responsibility could be enforced on him by distributing the cost of operation of the data reduction facility according to the work demands of the various test projects, it was felt that the requests for data reduction might very conceivably swamp the system, however large its initial capacity. These facts lead then to one of the initial decisions. This decision was to present to the Engineer in raw uncorrected analogue form the results of the test with which he was concerned, and charge him with the responsibility of eliminating the large mass of information that in most cases need not be further reduced. The recommendation was toward the simplest possible system that would provide efficient information to the responsible test engineer and enable him to specify those portions of data requiring further reduction. Specifically this first presentation was visualized as taking the form of low speed, direct writing, oscillograph records of analogue form. Rough calibration scales could be provided by the processing agency at the beginning and end of the data. FM data could be plotted as a function in terms of frequency deviation versus time. Wherever possible, this could include cases of fairly high frequency data, the length of record presenting a single test could be held down to a size easily comprehended in a glance, that is about 17 inches. Each group of analogue plots would include a time trace capable of uniquely identifying any portion of a record requiring further reduction.

The next step was then to consider a magnetic tape handling system. It was considered because magnetic tape is now used to record information in both the Track Branch and Telemetering Ground Station and in addition has been proposed for the new High Thrust Rocket Test Stand. The review of sources of data by type indicated that oscillograph and photo panel records presented the greatest portion of the present manual processing work load at the Air Force Flight Test Center. Substitution of this magnetic tape system for these sources was then certainly considered feasible and consequently careful consideration of the processing equipment for data recording on magnetic tape was one of the prime development recommendations of this contract. The system as eventually determined is shown in Figure 6, and has two primary functions. These functions are, first, to provide quick look graphical records of tape recorded information, and second, to provide necessary digital output tabulation, computation or cross plotting. It is designed for an average utilization factor of about 50%.

A word here about the problems of the design of such a system. Remembering that it is designed for an average utilization factor of about 50%, the difference between complete success and failure of such a design is a factor as small as 50% in the estimated work load. In light of this fact it was obvious why one should hesitate to design a data handling system based on the accuracy of the estimated work load. Current attempts to estimate the average work load in periods of two to five years in the future have proved practically impossible. This is why the "quick look" philosophy is emphasized. Doubling or even tripling the number of complete systems (i.e. paralleling) represents only a fractional change in the magnitude order of the output, yet the system work load can be changed many orders of magnitude by an incremental change in the percentage of data to be handled on a digital basis. However, let us return to the proposed central data processing system.

Notice that the proposed system is an integrated arrangement of some equipments now in use at the Air Force Flight Test Center, a few commercially built units and certain specified recommended developments. The basic functions to be performed are indicated in the block diagram of the system (Figure 6). The actual success of the system is dependent upon the methods by which the components are integrated. It is realized that the task of integration is a considerable one and, therefore, it has been recommended that implementation of the entire system be delegated to one prime contractor for detailed design, development, coordination of subdevelopment, installation check out and evaluation.

A review of the over all system and the gross performance specifications of various components are as follows: Play back: Note that the system requires complete equipment for play back of FM/FM and PWM/FM magnetic tape, decommutation, and demodulation units that are all standard manufacture to RDB specifications. One note about head characteristics of the tape play back mechanisms; they should match those of the airborne recorders as well as ground recorders. More will be said about the airborne recorder later. Analogue conversion and presentation can be of modified standard design or developed with a view toward the flexible approach stressed in the philosophy, that is, provisions for scale factors, zero suppression and provisions for a rather limited linearization. Routine use of linearization was not recommended, however, due to the fact that this might prove a bottleneck in what must essentially be one of the most streamlined phases of the operation. A patch board for decommutation and discrimination outputs, digital and recorder inputs, and special amplifier and linearization inputs and outputs should be provided. This patch board should provide the most flexible possible arrangement of components. Present planning for recorder output should probably be something of the Sanborne 4-channel recorder type or possibly one with a higher response rate for certain high frequency response work.

The suggested digital conversion system is built around the Millisadic equipment developed jointly by the Naval Ordnance Laboratory, Corona, Calif., and Consolidated Engineering Corporation of Pasadena Calif. Certain auxiliary input conversion equipment is necessary, however, and consists of DC to PWM converters with repetition rates at least as high as 500 samples per second, a clock pulse generator at a frequency of 2.5 megacycles and a suitable gated amplifier to operate in conjunction with the clock pulse generator and pulse from the DC to PWM converter. A time selector must of necessity be designed to direct time information pulses to the incremental time or elapsed time register. The specifications for this unit will be dependent upon a timing system to be installed at the Air Force Flight Test Center under a different development project. Another necessity is an events timer required to synchronize the various equipments. This unit initiates sampling by the DC to PWM converter at a pre-set rate and signals the millisadic unit to store and read out the information. The events timer begins to function upon receiving a start signal from the coincidence gate and gives out a final set of control impulses upon receiving a stop pulse from the second coincidence gate. A clock timer generator within the events timer governs the rate at which events occur and thus the sampling rate. The clock can operate independently or in synchronization with the time input signal via the time selector. Figure 7 shows the programmer which consists of the manual adjustments to the following components in that figure: the time selector, the coincidence gates, the events timer, clock pulse generator and the time base multiplier. The programmer is essentially a control and editing device that selects certain specific sections out of a group of data to be digitalized and printed. The millisadic equipment manufactured by Consolidated Engineering Corporation is commercially available only in the sense that a completed design is available which can be used to duplicate the unit now installed at Naval Ordnance Laboratory, Corona, California. The system conceived by Consolidated, however, does not include all the functions required at the Air Force Flight Test

Center and considerable development work in both input output devices will be required. The complement of this ground magnetic tape handling development is the development of a suitable airborne magnetic tape recorder. It is one of the more interesting recommendations under this project and one that stems from the desire to record information in a form that lends itself to high speed automatic data processing. It should eventually lead to eliminating the oscillograph and photopanel data records almost completely and replacing them with magnetic tape recording. In order to proceed with this development several basic decisions had to be made. They were as follows: First, what was the data work load to be expected or minimum number of data points to be recorded; second, the range of frequencies being measured; and third, the system accuracy with particular regard to the accuracy of the end instruments whose outputs were being recorded. To aid in this estimation a survey of several typical flight test programs as conducted at the Air Force Flight Test Center was made. It was determined that a representative flight data work load was about 1200 data points, these being divided approximately among 40 channels. The range of frequency in terms of percent of channels was as follows: 1.0 to 2 cycles per second 70%; 2.0 to 40 cycles per second 20%; above 40 cycles per second 10%. Now the basic accuracy requirements on such a recorder are tied directly to the available accuracy in the sensing elements or transducers where the data originates. The best available accuracy obtainable with any of the number of types of transducers is of the order of 1%. Therefore, it was felt that it would be inconsistent to attempt to design a data recorder with a much higher degree of accuracy, particularly when it was realized that the price to be paid in cost, space, and weight would be rather prohibitive.

A comparison was made of different methods of recording on tape in the aircraft. These considerations included not only data resolution, that is, economy of tape usage, frequency response available, but also complexity and bulk of attendant electronics. No attempt was made in the evaluation of present systems to maximize or minimize the importance of any one of the above listed factors but dealt with these characteristics solely as they related to the choice for a generalized flight test recorder.

The methods considered were as follows: Recording by digital coding, pulse width recording, FM carrier recording, and direct or biased analogue recordings. Digital recording is probably inherently the most accurate of all possible methods. This is due chiefly to the fact that the data recording and playback is virtually independent of tape speed variations and is unaffected by relatively high noise levels. In keeping with the aforementioned accuracy requirements the recording of two digits per word would be recommended. Based on a standard tape length 2400 feet and a recording time of 16 minutes, a tape speed of about eight inches per second is called for. The resulting sampling rate of about 800 words per second is also compatible with the commutation rate of available mechanic commutators which would be required. Unfortunately none of the presently known airborne recorder types are well suited to the requirements imposed by a system of this type. Probably the North American Aircraft development NADAR, is closest, but would require a development of a suitable tape transport mechanism. The electronics of analogue voltage to digital conversions for airborne use are relatively scarce, the only known development being at Hughes Aircraft Company. This application is for quite a different purpose and the results of this development were not available for the study. One of the penalties paid for this luxury of airborne digital recording is the complexity of ground based digital to analogue conversions which the "quick look" philosophy requires. As a result of general considerations outlined previously it can be stated quite emphatically that all such recorded data should be plotted while only a small portion would require digital tabulation. Thus it would appear unreasonable to undertake such a development (digital airborne recording) if the data were not to be tabulated but the majority presented in analogue form. Remember we are dealing with data on the order of 7000 channel minutes per day (± 50%) or about 300,000 points per day.

The pulse width recording of data proved to have several system wise advantages over other forms and they may be listed as follows: first, it provides good accuracy and stability; second, it may be readily processed into straight analogue and/or digital forms; third, the associated electronics are relatively simple and can be made quite reliable. Past experience seems to bear out these statements. Along with some direct analogue recording (about 10% of the total) the recommendations seem to point to the development of an in-flight magnetic tape recorder using PWM coding on 90% of the data channels. Here the difference between PWM and digital recording lies chiefly in the fact that all the information contained in PWM is the leading and trailing edges of the pulse and the reproducability of these edges determines the accuracy of the system. Since in PWM a single pulse represents one word the ultimate tape economy is roughly seven times that of digital recording. Similar advantages of near complete independence of tape wow and flutter characteristics can be achieved in the PWM system by the simple expedient of using one recording channel to record a clock signal which serves as a reference for tape speed variation.

Frequency modulation coding using the standard RDB/FM system indicates the feasibility of recording carrier frequency of the order 1.3 KC per inch per second of tape speed and at a standard deviation ratio of 5 and a tape speed of eight inches per second (for the comparison with PWM or digital). This would make possible a total information band width of approximately 1 KC within the requisite accuracy of 1%. However, in this regard it must also be remembered that airborne subcarrier oscillators presently used in the FM/FM systems are known to have minimum drift figures of higher than 2% and in some cases as high as 5%. Thus the possibility of recording standard RDB subchannels has been considered as subsequently unfeasible for the principle reason of the limitation of maximum recording time imposed by high tape speeds necessary for recording of the higher subcarrier frequencies. The requirement seems quite definitely to be in the direction of a larger number of lower frequency channels than can be accommodated in the standard RDB/FM system and still have a reasonable tape speed. The second serious objection to FM coding is its limited accuracy. Certainly there would be a strong nostalgic feeling among the flight test engineers against exchanging the present tried and true photo panel and oscillograph systems for anything less accurate. Now there are certain tape recorders, either on the shelf items or presently under development that may fulfill certain of these requirements but generally all fail in some degree to meet these specifications. Principally the most important direction for improvement is in that of miniaturization. The Cook and NADAR recorders appear to be the only reasonable approach to the critical size and weight problem but both have other disadvantages in limited recording and in varying tape speed. What several other manufacturers have presently under development at this time has not been reported or publicized so they could not be reported in the study.

As one result of this study program the Air Force Flight Test Center will consider the development of a generalized flight magnetic tape data recorder having the following specifications. Before presenting these specifications, it might be interesting to view the average flight test engineer's concept of what the complete flight test recorder should look like, electronics and all. This is shown in Figure 8; however, we believe Figure 9 presents a more realistic picture of this recorder. Note that the specifications include the use of standard NAB $10\frac{1}{2}$ inch, 2400 tape reels $\frac{1}{2}$ inch tape size, a maximum continuous recording time of 60 minutes, an interchangeable tape speed gearing arrangement that provides for 7.5, 15, and 30 inches per second tape speeds, 7 data tracks with 3 PWM tracks recording up to 150 channels of 0 to 2 cps information and as many as 30 channels of 0 to 40 cps information. Three additional tracks will include direct biased analogue recording for frequency response up to 25000 cps and the 7th channel should be a 1000 cps CW channel. Certainly it should contain provisions for other heads and for modification to heads other than the examples specified above. To this end the means and procedures for head alignment should be as simple as possible. Maximum speed variations in the recording of 0 to 1 cps information should be of the order of 2% peak to peak, while those channels having 1 cps to 2 KC frequency response only .5% peak to peak speed variation can be tolerated. Power supply should be the usual 400 cycle 115V or DC 26V. Weight should be under 25 pounds and size approximately .5 cu. ft. It is felt that this size can be obtained by concentric reel alignment. Of course all construction should be according to MIL-E-5400 or equivalent.

The need for this in-flight magnetic tape recorder has been felt and voiced by many in the field of flight test engineering; however, no concentrated effort has been made to develop a standard unit that can be used for the recording of all types of flight test data and that will gather the information in such a way as to lend itself more completely to automatic data reduction.

With the development of such a magnetic handling system for large data work loads based on the philosophy of human filtering and quick look presentation to the responsible engineer, it is felt that the data handling problem as recognized at the Air Force Flight Test Center can be effectively solved and that the constantly increasing work load of data processing can be met and alleviated.

Those that are left of the grandfather flight test engineers tell us that during the early years of flight testing the speed with which a flight test proceeded was limited only by the ability of the engineer to absorb the flight test information and the mechanics to keep the aircraft flying. We admit that at present the rate at which some flight testing programs proceed is limited by the speed with which data can be processed. It will be the aim of our development program to return flight testing to this optimum condition, namely that flight testing will be limited only by the ability of the engineer in charge and not by obsolete data processing methods.

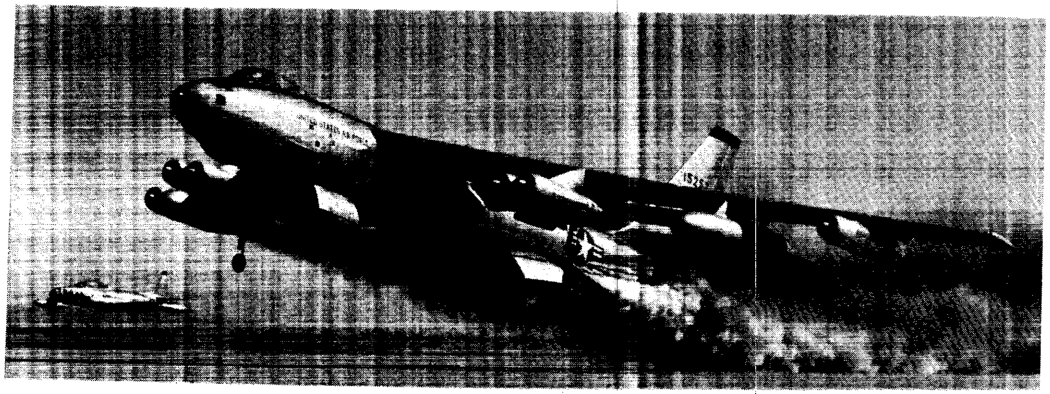

Fig. 1. Example of flight test data source

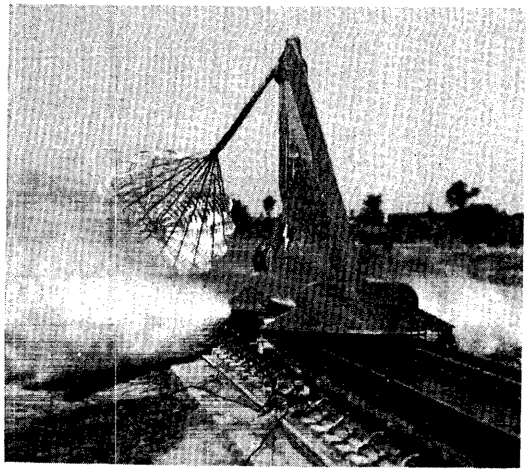

Fig. 2. Ground telemetering station-data source

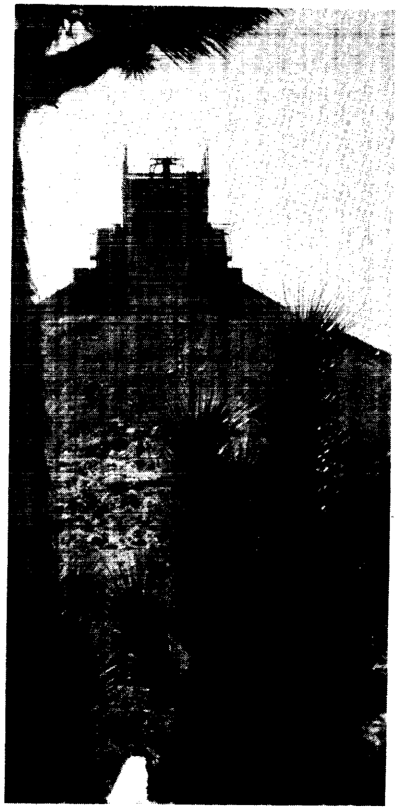

Fig. 3. Experimental rocket engine test station-data source

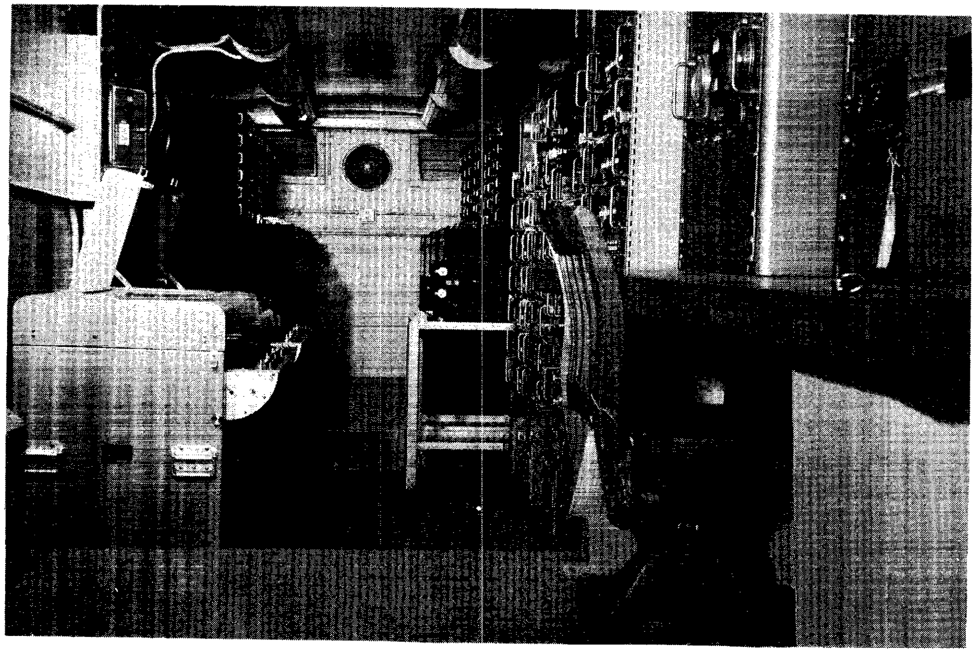

Fig. 4. Experimental high-speed track sled-data source

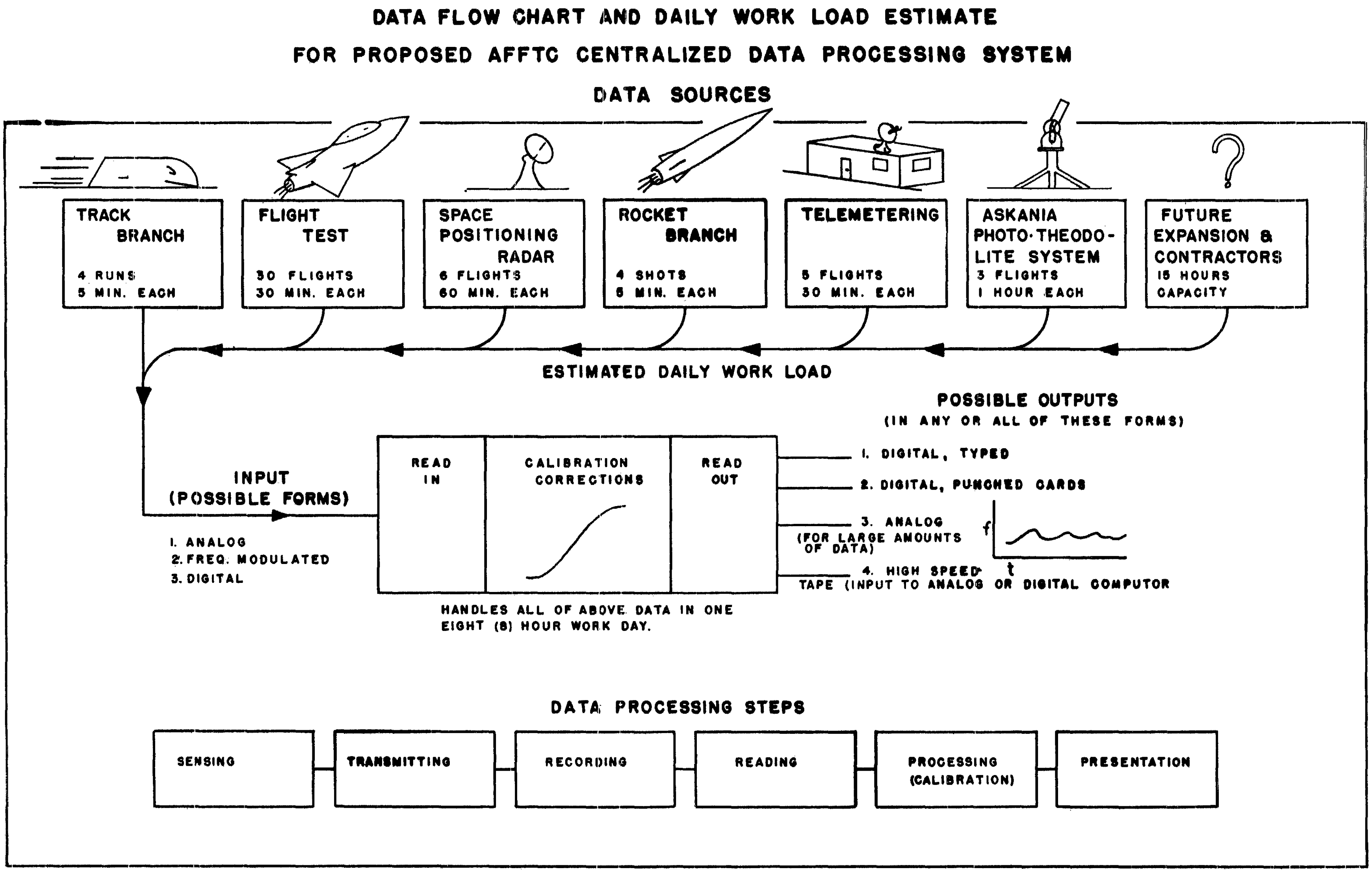

Fig. 5. Initial system concept

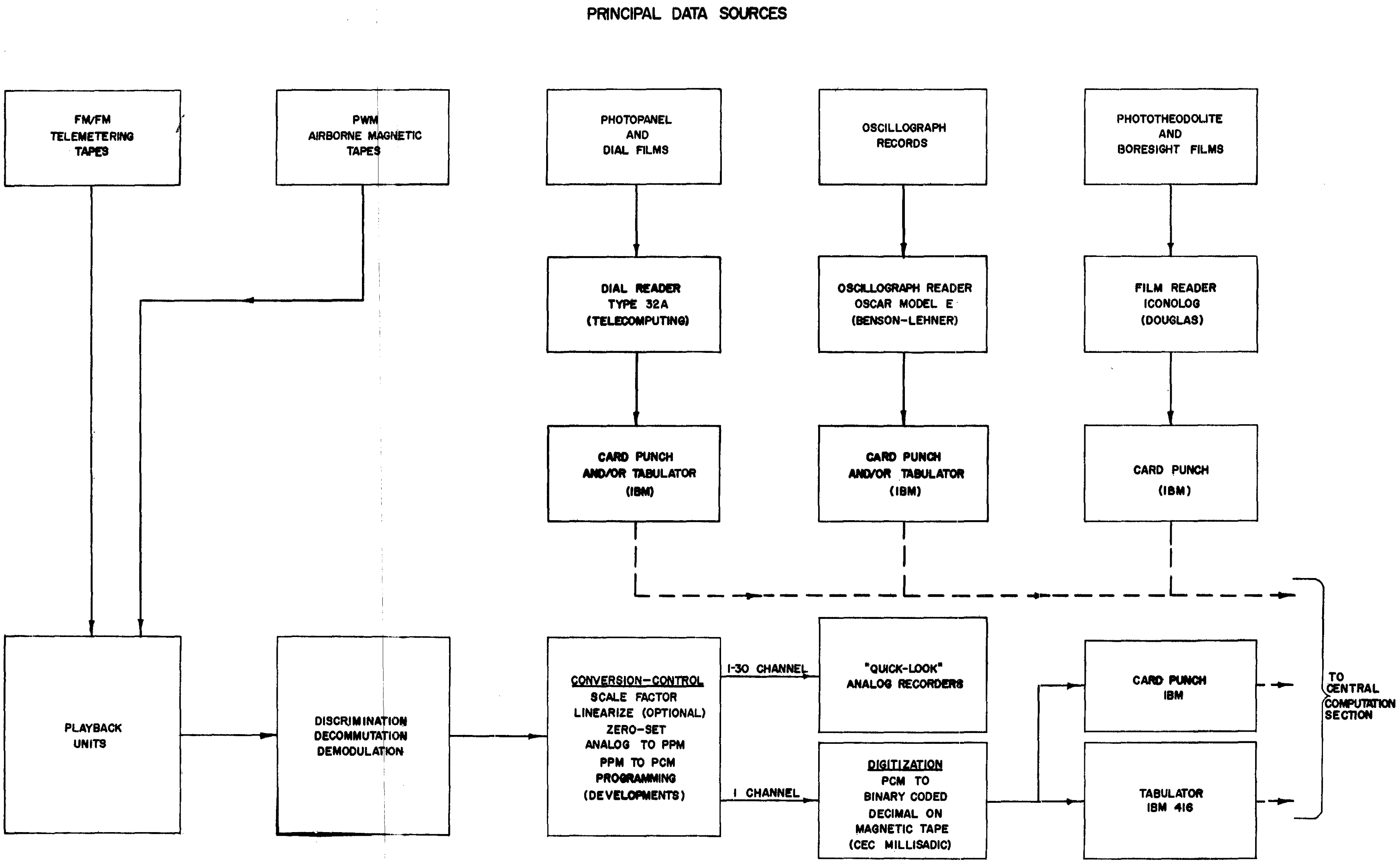

Fig. 6. Proposed central data processing system

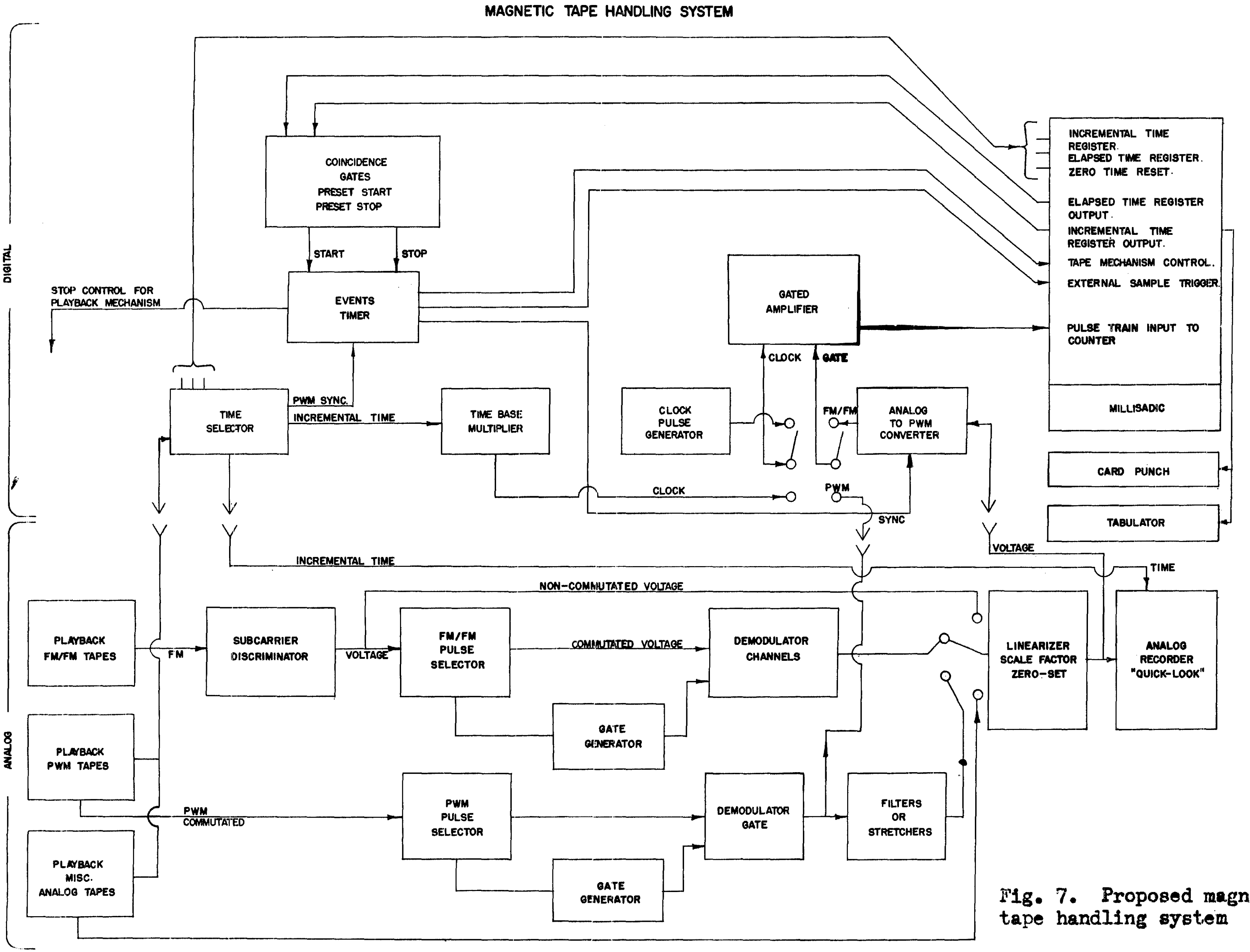

Fig. 7. Proposed magnetic tape handling system

Fig. 8. Average flight test engineer's concept of Airborne Tape Recorder

Fig. 9. Proposed specifications for Airborne Tape Recorder
Size: .5 to 1 cu. ft.
Weight: Under 25 lbs.
Maximum Recording Time: 60 Min.
No. of Tracks - 7. (6 Information and 1 Timing)
Power Supply: 400 Cycle 115 V.
Tape Speed: 7.5 - 15 and 30 Ips.
Frequency Response Requirements:

70% of Channels	0 - 2 Cps.
20% of Channels	0 - 40 Cps.
10% of Channels	0 - 400 Cps.

A MERCHANDISE CONTROL SYSTEM

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Introduction

Merchandise control operations promise to be benefited by the application of electronic data processing equipment. Such equipment offers a new concept of speed and accuracy in reporting. It makes possible data summaries and analyses which to date have not been economically justifiable.

Inventory control represents one of the most rewarding and interesting problems for which electronic equipment is feasible. Such equipment will reduce the costs of preparing and maintaining inventory records, and will also make it possible to maintain reduced inventory because of the inherent speed of reporting.

Business organizations, in general, operate by purchasing according to predicted needs, performing some operation on the purchased goods (if only sorting and storing) and then distributing it to purchasers. Purchasing is conducted by means of management reports which aid in predicting future needs. This information is usually obtained from the past history of sales records, the current inventory status, or both. In general rapid reporting permits reduced inventory with associated savings by giving a more immediate picture of current status.

Reports on current operations give management the opportunity to monitor the efficiency of their organization. Unfortunately such reports are often voluminous, and the time of high-salaried talent is required to extract the attention-requiring items. The selection of these items can be made by the decision apparatus available in electronic computers. For example, inventory reporting can be reduced to those items which do not fall within an established stock tolerance. Reports on receipts and shortages can be reduced to the data on those venders which are overdue. Reports on sales can be reduced to those items not meeting the sales rate tolerances set by management, etc. Special treatment can be given certain items as is required.

One of the major items in large scale business operations is the filling of a customer order. In large retail businesses the paperwork for individual customer orders may be processed under one roof at rates around ten orders per second. In chain store operations paperwork resulting from sales may be processed at a central operations location at near the same speed. In one application the central location is a warehouse which uses the sales information coming from the stores to effect restocking of the stores. In such a case the warehouse is filling an order for the individual store.

The number of people required by large organizations for their order-filling operations may vary from under one hundred to many thousands. A good share of these people are entirely concerned with the routine processing of paperwork. Often the business has grown up in such a manner that stock clerks and sales people are partially occupied with paperwork. By automatizing the clerical functions the effectiveness and productivity of the personnel can often be increased or, if the volume of work does not warrant, the staff diminished.

Another important inventory application is keeping track of in-process inventory in manufacturing plants. It is important to know the number of acceptable subassemblies and parts in process at each stage of production. Such records can be maintained by electronic equipment.

In actual case studies it is apparent that the application of appropriate electronic equipment will result in large savings in indirect labor in addition to the advantages manifest in faster operations. Through savings in indirect labor such equipment often promises to amortize itself within two years.

To meet the requirements of business organizations several basic functions must be performed. Equipment must be provided to encode the business information into machine language. Means must be provided to enter the encoded information into the system in proper order using it to fill orders, update records, or perform other required functions. Means must be provided to process this summarized data into management reports for purchasing, financial records, and other purposes. Printing facilities are required to prepare the reports. In many cases facility for interrogating the equipment memory for particular information is important.

So-called general purpose electronic computing equipment does not fulfill many of the needs encountered in the operation of large scale business. In particular the instantaneous selection of data regarding any one of a large number of items is beyond the current capabilities of these equipments. To perform this function either the capabilities of the general purpose units must be greatly extended or special purpose equipment must be developed.

Companies designing special purpose equipment to fill these needs are confronted with a serious problem. The many advantages and unique character of electronic data processing equipment indicate that its adoption will cause improvements in the information flow procedures in many businesses. These improvements will suggest changes in business procedures which, in turn, in the course of time may obsolete the special purpose equipment. In order to avoid such obsolescence, the electronic equipment manufacturer is faced with the problem of designing his equipment to accommodate optimum management data processing procedures. Unfortunately, today no one knows these optimum procedures. An expedient solution might be for the equipment manufacturer to utilize operations research methods to design optimum data processing procedures for his prospective client. He must then sell the client on converting his business methods over to these procedures which the equipment can accommodate.

The client, on the other hand, who has presumably operated at a profit in the past, is faced with evaluating this proposed operating method and deciding whether it will effect a savings or, indeed, still permit him to operate at a profit. A mistake on the part of the operations research team could put quite a dent in the promised savings of the new system and apparatus.

A more acceptable and reliable approach to this problem would be to supply equipment that would permit the operating business to utilize electronic data processing techniques in its current data processing system. If the equipment were suitably flexible, an operations research team within the organization, or working in conjunction with the equipment manufacturer, could modify the client's procedures a step at a time, monitoring the effects on the business operation. Thus by an evolutionary rather than a revolutionary approach a more efficient operation could be achieved. The equipment thus grows with the client's procedures. As in general purpose scientific computers, the use of an internally stored modifiable program, together with a set of well-chosen operational commands, should permit this approach to be used. This programming or, in other words, procedural flexibility also permits many types of organizations to use similar equipment.

With this design philosophy in mind hardware is under development. Two computers form the nucleus of a system that will fit many applications. One, called an Inventory Computer, serves the function of entering the input information making preliminary calculations, preliminary summarizing, sorting, and making elementary decisions. The other, the Management Computer, serves the function of updating seasonal records according to the information supplied by the Inventory Computer, performing business-type calculations on the categories being processed and controlling the operation of an associated high-speed printer.

Application of this equipment can best be illustrated by an example of a large scale operation. Although systems have been designed for warehousing and distribution organizations, retail businesses, manufacturing concerns, and others, the case illustrated will be that of a mail order house.

Mail Order Operation

A block diagram of the flow of information in a mail order house operation is shown in Figure 1.

Incoming orders are processed through cash analyzing or credit as appropriate, and then proceed to a ticket-pulling operation. Here paperwork in the form of tickets, preprinted with the appropriate information such as price, weight, and description, is available in racks by catalog number. A clerk processes a given customer order, selecting the appropriate ticket for each catalog number on the order. The tickets are then manually marked for color, size, catalog by which purchased, and quantity. Mailing labels are prepared and the orders are scheduled and stamped with a packer number so that the people who will wrap the orders for mailing are uniformly scheduled. The tickets are then separated from the customer orders, sorted by the various merchandise departments, and dispatched thereto. At each department they are tallied by size, color, and catalog number, flagged if out of stock, and released for stock pulling. Each merchandise item is placed, together with its pull ticket, on a conveyor belt system for transportation to the wrappers. Customer orders are separately routed to the packer. The packer number determines the time and the packer station which is to receive the merchandise and order. The complete order is merged and packed at a packing station. It is then weighed, stamped, the customer billed, and the merchandise shipped. Data gathered at the tally stations serve to prepare management reports on stock condition, sales by item, sales by catalog, etc.

Receiving and transfer information is routed to the tally stations to correct their inventory figure. The same data is also used to prepare reports on purchases, receivals, and shortages.

The tally operation often proves troublesome because of seasonal rushes and the resultant human errors they induce into the system. The speed-tally equipment described in a previous paper ideally suits a situation where it is necessary to replace a tally operation. A logical extension of tally equipment is a system which automatizes many of the clerical operations concerned with utilizing data such as produced by tally in the control of merchandising. The equipment to be described in the following material is directed toward a large operation requiring high entry rates, complex entry operations, detailed management reports, and preliminary accounting data.

Electronic Control of a Mail Order Operation

The application of electronic equipment to the mail order operation is illustrated in Figure 2. The ticket-pulling and preadjusting functions are replaced with electrical typewriters directly connected through buffer storage facilities to the Inventory Computer. A typewritten form as shown in Figure 3 is prepared at this station, this form replacing the preadjusted pull ticket. The form also provides for an indication as to whether the sale can be made or must be canceled. The top portion of the ticket is manually typed directly from the customer order. The data is accepted by the Inventory Computer which then refers to its memory, looking up description, weight, price, available inventory, and tallies. If stock is available the machine indicates that the item can be sold and corrects inventory and tallies accordingly. Tallies on both sales and cancels are maintained. If the item is out of stock the machine corrects only the cancel tally. The updated tallies and inventory data are replaced in the Inventory Computer memory and the results of the decision, the price extension, and the data looked up are routed back to the buffer and thence to the typewriter. One entire operation of the Inventory Computer is completed in approximately 1/10 of a second. Data on bulk operations involving venders is entered through typewriter-prepared perforated tape. A complete record of vender information, including purchase orders, due dates, quantities, and financial data is maintained in the memory. The typewriter-created tickets are now routed through the same operation as the old form of tickets except that no manual tally function is required. A special station at billing serves to correct the computer inventory for those cases where a sell decision is made and no merchandise was found on the shelf. Such a condition can be caused by the usual factors creating shrinkage.

Periodically the contents of the memory are read off onto magnetic tape in ordered form. This tape is fed into the Management Computer, together with a master record tape containing detailed data on every item sold. The master record tape is ordered in the same manner as the updating information on the tape prepared by the Inventory Computer. The updating data, together with the master record tape, is processed by the Management Computer, using a fixed program to create an updated master record tape. No sorting problem is encountered because the data is processed by a preset fixed sort. During the updating operation report data is placed on magnetic tapes controlled by the Management Computer, each report on a separate tape. All output tapes, updated master record, and reports are prepared simultaneously. The report tapes, which contain information in the correct format sequence for the report, are applied to the printer controller which, via the high-speed printer, prepares the reports.

The Inventory Computer can be interrogated at will for current inventory on any item.

Equipment

Merchandise control systems of the type described above fit a wide variety of applications. The chief difference in the equipment to fill these various applications is in the input apparatus. For many types of retail operations perforated tape prepared by a cash register or label reader is more appropriate. Punch card equipment, direct-connected numeric keyboards, or direct-connected label reading devices may be appropriate in other applications. The Inventory and Management Computers, which form the nucleus of the system, should fit any of these systems when suitably programmed.

Medium access large scale memory facilities are a key part of the Inventory Computer. Facilities for handling variable word lengths with no particular requirements on stock number arrangements are fundamental to flexible operation. In one application a memory having an average access time of 25 milliseconds and having storage facilities for $16 \cdot 10^6$ bits is required. Drum equipment currently available could supply this need. Flexible memory addressing requirements are achieved by storing the respective customer number along with each group of data in the memory and selecting the right group of data by achieving comparison with the address number and the number stored in the memory location.

The Management Computer utilizes rapid access memory of a more modest capacity to store its instructions and data. It stores the data on one particular group of information and processes it according to a fixed instruction sequence. In one application 10,000 binary digits of magnetic core memory are required to hold the data, along with an additional 50,000 bits of drum memory to hold instructions. Data is processed on a continuous basis from magnetic tape input to magnetic tape output. Both input and output tapes operate at a maximum rate of approximately 1,000 decimal digits per second. The Management Computer is capable of controlling ten output tapes simultaneously. By means of these auxiliary output tapes the data for different management reports can be separately organized. These tapes can then be detached from the computer and introduced to the printer controller where memory facilities for one complete line of information are provided to operate the printer. The printer controls the operation of the tape, transferring in a line of data at a time. Tape motion is intermittent.

For those applications requiring larger memory capacity with more modest access speed requirements a device is in development capable of storing $50 \cdot 10^6$ bits each with an access time of less than one second. Such a device when coupled with a modest drum memory greatly extends the flexibility of the Inventory Computer.

All of the equipment and techniques used in achieving the computers and systems components described above have been developed and put into use by laboratories throughout the country. The development of the Inventory and Management Computers involve the organization of these components and techniques in a manner which has direct application to inventory type problems.

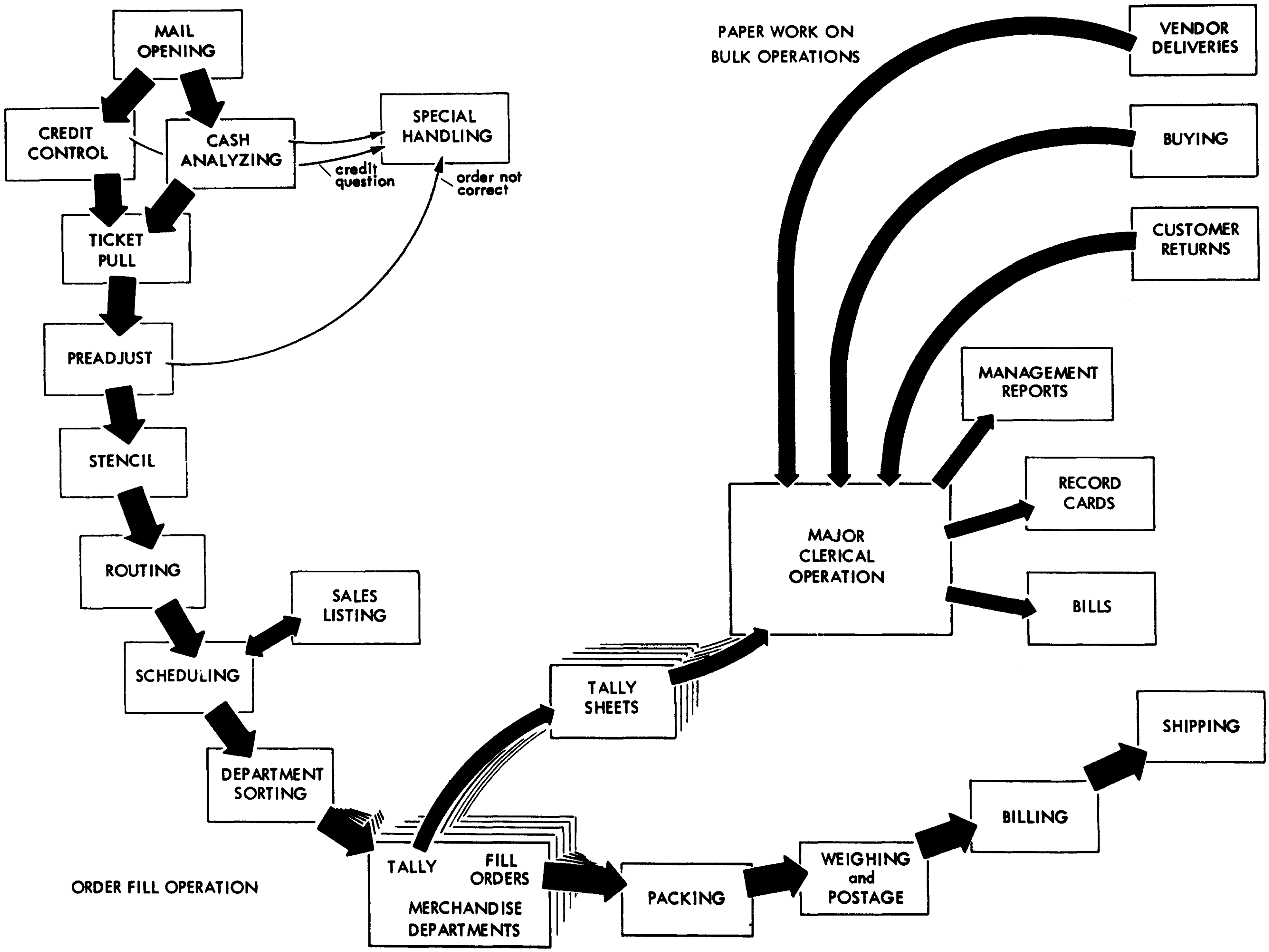


Fig. 1. A mail order operation

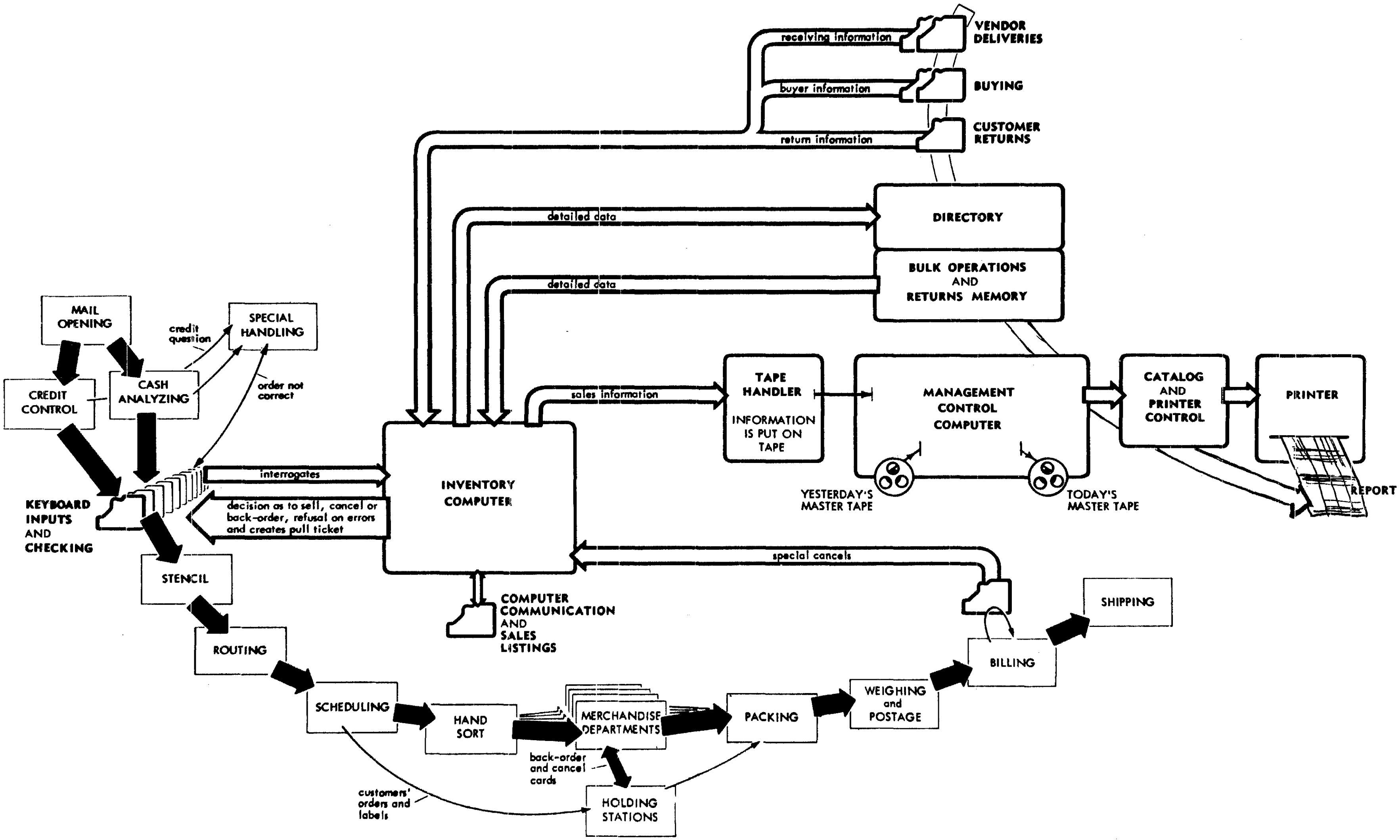
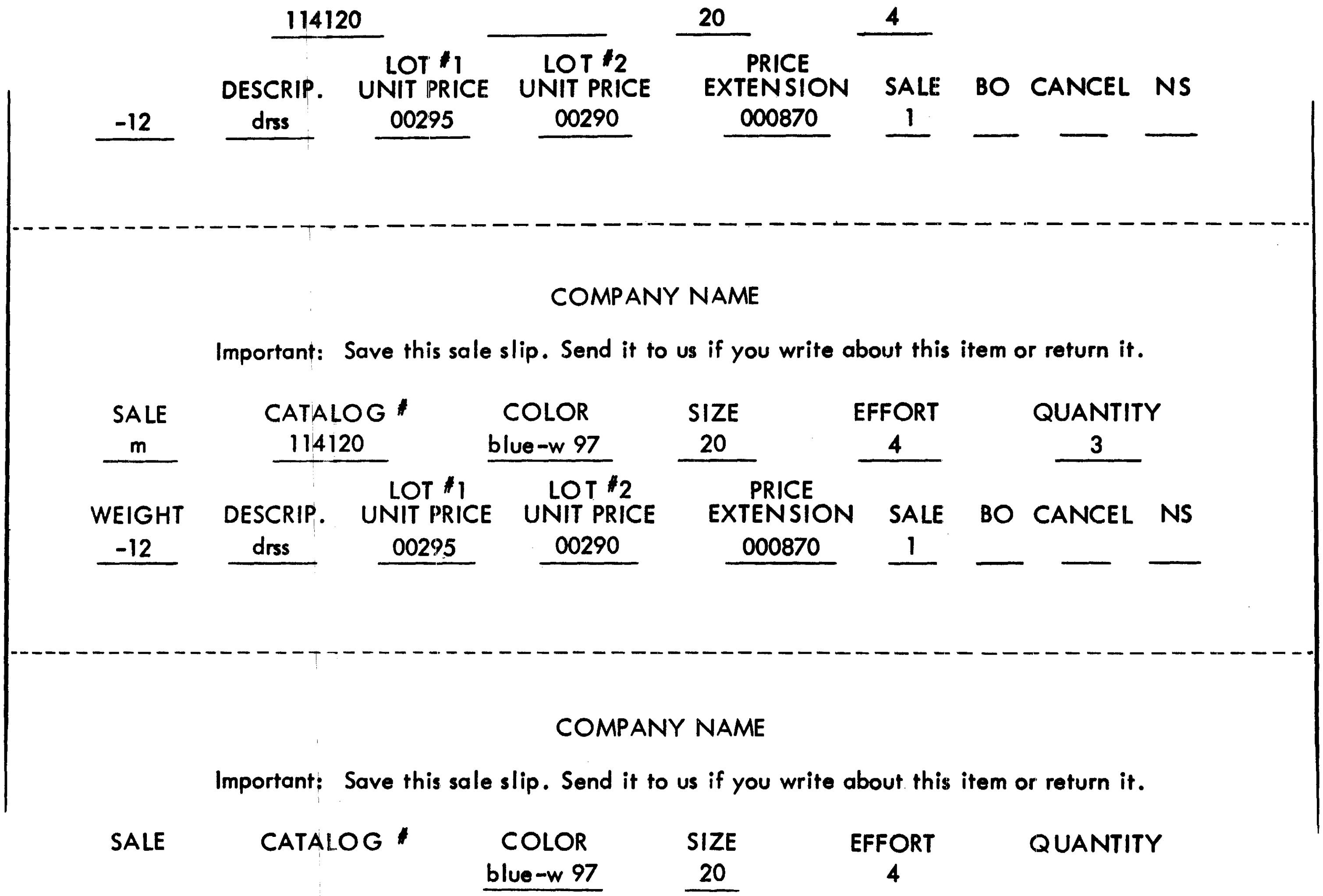


Fig. 2. A merchandising control system



	114120			20	4			
	DESCRIP.	LOT #1 UNIT PRICE	LOT #2 UNIT PRICE	PRICE EXTENSION	SALE	BO	CANCEL	NS
-12	drss	00295	00290	000870	1			

COMPANY NAME

Important: Save this sale slip. Send it to us if you write about this item or return it.

SALE	CATALOG #	COLOR	SIZE	EFFORT	QUANTITY			
m	114120	blue-w 97	20	4	3			
WEIGHT	DESCRIP.	LOT #1 UNIT PRICE	LOT #2 UNIT PRICE	PRICE EXTENSION	SALE	BO	CANCEL	NS
-12	drss	00295	00290	000870	1			

COMPANY NAME

Important: Save this sale slip. Send it to us if you write about this item or return it.

SALE	CATALOG #	COLOR	SIZE	EFFORT	QUANTITY
		blue-w 97	20	4	

Fig. 3. Sample input form