THE AUTOMATICALLY PROGRAMMED TOOL SYSTEM

VOLUME I

GENERAL DESCRIPTION OF THE APT SYSTEM

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FOREWORD

This document is one of several describing the APT System for automatic programming of numerically controlled machine tools. The APT Joint Effort is sponsored by the Numerical Control Panel of the Aircraft Manufacturing Equipment Committee of the Aircraft Industries Association, and contributions of individual companies have been made on a voluntary basis. Participation of the Servomechanisms Laboratory, M. I. T., has been made possible through support extended to M. I. T. by the Air Materiel Command through Contract No. AF33(038)-24007. Information concerning the organization and objectives of the APT Joint Effort, including membership arrangements and procedures for obtaining documents and programs, is given in Volume I.

Most of the documentation has been prepared by personnel of the Servomechanisms Laboratory at M. I. T., although the system itself is the result of the combined efforts of computer programmers from the following aircraft company plants. Contributions of individual programmers are listed in Volume I and the assistance of these individuals in preparing the documentation is gratefully acknowledged.

List of cooperating companies . . . .

Boeing Renton
Boeing Seattle
Boeing Wichita
Chance Vought
Convair San Diego
Convair Ft. Worth
Douglas Long Beach
I. B. M. White Plains
Lockheed Marietta
Martin Baltimore
Martin Denver
North American
Northrop Hawthorne
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CHAPTER 1

A GENERAL SURVEY OF APT

1A. INTRODUCTION

APT is an abbreviation for Automatically Programmed Tools. It is the name given to a technique for producing complex metal parts efficiently and reliably through the combination of modern data processing and numerically controlled machine tools. A numerically controlled machine tool is a machine tool to which have been added servomechanisms and electronic control circuitry so that the motions of the tool will respond to numerically coded instructions on punched tape or some other suitable control medium. The preparation of the instructions which specify the machine motions required to produce a particular part is called programming the machine tool, or part programming. Automatic programming is a new technique, made possible by modern computers, in which the instructions are not given in detailed numerical form, but in terms of English-like language convenient for people to use. Automatic programming also permits all of the difficult mathematical computations associated with the use of numerical control to be performed automatically by the computer so that the job of the human part programmer is greatly simplified.

The APT system is an automatic programming system for numerically controlled machine tools which shows great promise for providing a means for realizing the full potential of numerical control. The concept originated at the Servomechanisms Laboratory, M.I.T., in a project sponsored by the Air Materiel Command, United States Air Force, but the development of a complete system for industry-wide use has resulted from a cooperative programming venture sponsored by the Aircraft Industries Association. This is one of six volumes which describe the initial system, the APT II Phase I System, resulting from this group effort. Further expansion of the initial system will be carried out through the APT project of the AIA. Membership in the APT project is open to any organization willing to actively participate and support the group effort. It is hoped that the APT project will provide the means for fully exploiting the potentialities of numerical control.

1B. BACKGROUND AND PERSPECTIVE

In order to place APT developments in the proper perspective it is necessary to start with the original problem of machining complex parts to high precision in small quantities. By presenting a brief history of the problem of applying some sort of automation to this area, not only is the subject matter of the APT system introduced, but also it is clearly implied that the present level of APT system development, significant though it may be, is only an intermediate stage in a continuing and rapidly developing new technology. By establishing this perspective it is hoped that those who are unfamiliar with the APT concept will not expect too much of the initial systems, but also that they will gain appreciation of the significant future potential of this new technology.

1B.1 Tracer Control

There are many possible ways to fabricate complex metal parts, but perhaps the most intricate is continuous path three-dimensional milling. In this process a spinning cutter, capable of cutting in any direction, is moved in space in a continuous path to sculpture the finished product from either a partially formed blank such as a forging or casting, or from a solid piece of metal. Almost every machine shop contains three coordinate milling machines of this type, but with manual control the complexity of parts which can be produced and the precision of control is limited even with highly skilled machinists. An early step toward automatic operation of these machine tools was the addition of control servomechanisms so that the cutter could be made to follow the motion of a stylus as it traced out a template prescribing the required tool motion. Template controlled machine tools exist in great abundance; some using linear two-dimensional templates, some using circular cams, and still others using three-dimensional templates. Not only do these devices improve the productivity of the machine tool, but they also permit complex parts to be produced with good accuracy. Although the skill level required for template controlled machine tools may not be as great as for manual control, the discrepancy in operator skill is replaced by the other skills of the tool makers required to produce the templates. Templates for complex parts are extremely costly items, difficult to produce, and time consuming to set up and adjust. They are not well adapted in

general to accommodating engineering changes in part design so that, although they represent considerable advance over manual operation of the machine tool, they still leave much to be desired.

1B.2 Numerical Control

The shortcomings of tracer-controlled machine tools have been largely overcome by the development of numerically controlled machine tools. Like a tracer controlled machine, the numerically controlled machine tool employs servomechanisms to actually operate the running members of the machine. Instead of following a physical template, however, the servomechanisms obtain their control information from special electronic circuitry which translates coded information on punched tape or some other suitable control medium into desired position information. The mechanism which reads the numerical instructions and translates them into equivalent machine tool commands is called the director, and the input "language" usually consists of one number for each controlled axis of motion in the machine tool, and another number representing time. Upon receipt of a set of numerical instructions, the director causes the machine tool cutter to move in the specified time interval from its present location to a new point along some simple curve, usually a straight line. By a sequence of such commands the cutting tool can be "programmed" to follow an arbitrary broken line path. Since the individual motions can be made very small, the broken line path can be made to approximate almost any curvilinear motion of the tool.

In the case of numerical control, the flexibility of the machine tool-control system combination is greatly increased. There is no complex setup time required as in the case of templates. It is necessary merely to substitute one control tape for another. The added versatility of the tool motions (template controlled tool motions are frequently restricted to a sequence of plane curve motions) means also that jigs and fixtures for holding the part can in many cases be simplified. Although at the present time highly skilled machinists are employed to operate numerically controlled machine tools, in theory personnel of low skill can be employed, since the system's operation is fully automatic.

Numerical control by itself, however, still presents problems.

The skill of the machinists and the skill of the template maker have now been transferred to the person who plans or programs the numerical instructions on punched tape. Here, again, the skill level, although different, must be very high since not only must the metal cutting and tool sequencing knowledge be incorporated into the numerical instructions, but also a new class of highly complex mathematical problems is introduced. Complex curves must be approximated accurately by suitable straight line segments, and tool center corrections must be calculated since the tool center is actually controlled whereas the point of contact with the workpiece is some point on the outside of the tool. In general it takes many thousands of individual straight line cut vectors, each of which requires complex calculations, to produce a complex two- or three-dimensional part by numerical control.

1B.3 Computer Assistance

The varied problems which are tedious and time-consuming for the human part programmer to perform are ideally suited to the calculating abilities of modern digital computers. Therefore the next step in automating the production of complex parts in small-lot production quantities was to supplement the desk calculator employed by the part programmer by a library of subroutines written for a general purpose digital computer. Each subroutine is capable of forming a necessary task economically and at high speed, and with great reliability. The digital computer can also be made to punch the pattern of holes on the control tape so that a large portion of the part programmer's burden is taken over by the digital computer programs. Once again, however, the skill level has been transferred to another human being. Now the part programmer must not only be familiar with metal cutting, tooling, and mathematics, but he must also be a computer programmer as well, well versed in the intricacies of instructing and controlling the complex operations of these "giant brains."

1B.4 Automatic Programming

The requirement that the part programmer be familiar with mathematics and computer programming is further alleviated, however, by adding to the library of computer subroutines executive routines which

permit the digital computer itself to set up and sequence automatically the appropriate subroutines in response to instructions given by the part programmer in a more convenient language especially designed for the problems of numerical control part programming. This is the introduction of automatic programming, since most of the detailed decisions and calculations concerning the preparation of numerical instructions for the machine tool director system are automatically programmed (i.e., selected and sequenced) by the computer's executive routines and subroutines. There are many systems of this type in daily use and the wide applicability of numerical control as a production technique is strongly dependent upon these automatic programming systems.

With the introduction of automatic programming through the use of executive routines and libraries of subroutines, it would appear that the problem of applying automation to the production of small numbers of complex parts has been satisfactorily solved. The numerically controlled machine tool represents a production system of very great flexibility and high productivity, and the tedious task of preparing the thousands of numerical instructions for production of complex parts has mostly been taken over by the general purpose digital computer in such a way that the human part programmer need be concerned only with general problems of geometry and metal cutting as represented in the specially designed language of the automatic programming system. It would therefore seem that the original objectives have been met admirably. There is however an essential weakness in the internal design of automatic programming systems as developed to this point in the discussion, i.e., based upon executive routines, controlling libraries of subroutines. This weakness is not apparent in the initial operation of these automatic programming systems, but it is there nonetheless.

1B.5 Problems of Expansion

One of the startling aspects of numerical control combined with automatic part programming is that it can perform so many jobs so well that once the technique is applied to one area, an irresistible pressure to apply these techniques to more and more complicated parts and new production areas develops. As the subroutine library is expanded to encompass these new problem areas, and as the executive routines expand in

turn to establish more and more complex control over the use of the subroutines, a very difficult situation arises for the system designer. It becomes increasingly difficult to add new routines and insure that they mesh properly with all the other routines in the system. Suggestions for improvement which seem simple and straightforward to the users of the system may be virtually impossible to incorporate without scrapping the entire system and building again from scratch. In general, since the library and the executive routines were developed more or less independently (except for superficial similarities necessary to make them work together), this type of automatic programming system is doomed to clogging and congestion as expansion to meet the needs of the users is attempted. Automatic programming as such is not the panacea that it at first appeared to be if it is approached through the library of subroutines concept. The urge to apply numerical control to wider and wider classes of parts cannot be controlled or stemmed. The automatic programming system must be able to expand to encompass ever growing requirements. The very success of the technique of automatic programming and numerical control imposes new and far reaching requirements on the original problem, and these requirements for growth and flexibility must be decisively met.

1C. THE APT SYSTEM CONCEPT

This, then, is the background for the APT system. This is the vantage point from which APT developments can be viewed in proper perspective. Contour machining had been greatly advanced in flexibility and precision by the advent of numerical control. The utilization of digital computers for data processing, and in particular the introduction of automatic programming techniques with their inherent convenience, reliability, and efficiency made it possible to consider this new technique for the automatic production of complex parts an economic and productive reality for actual industrial applications. Although its effects were not yet apparent in the dramatic successes of the early automatic programming systems, a subtle, seemingly inconsequential weakness was present in the internal organization of these systems. This weakness of internal organization (or perhaps lack of sufficient organization) had no ill effect on the usefulness and performance of initial systems with

restricted and well-defined boundaries of application. But with further expansion of the systems, the difficulties caused by this small flaw would grow to large proportions.

Expansion was inevitable. The success of automatic programming and numerical control could not but stimulate requests for further applications of the new technique to new and more complex areas. Therefore, a new organization for automatic programming systems was needed. Such a system must be purposely designed from the beginning for future growth, expansion, and modification. These are the goals of the APT system.

1C.1 The M.I.T. Project

The Servomechanisms Laboratory, M.I.T., has played a leading role in the development of numerical control from the beginning. In 1952 the Laboratory demonstrated the first numerically controlled milling machine, between 1952 and 1954 the first set of digital computer subroutines were developed for the Whirlwind I Computer by John H. Runyon, and in 1955 Arnold Siegel of the M.I.T. Digital Computer Laboratory demonstrated the first pilot model automatic programming system for numerical control, sponsored by the Servomechanisms Laboratory. In June of 1956 the Air Materiel Command contract, under which all previous Servomechanisms Laboratory work in this field had been performed, was reoriented for research into general automatic programming techniques for three- and five-axis continuous path milling machines.

The new contract was interpreted by the project as a mandate to pursue automatic programming research in a way which would be of direct use to the industrial application of numerical control. Thus the research should not be merely another pilot study, but should lead to directly applicable techniques. Preliminary investigations disclosed that the techniques which had been used in the earlier computer studies were not readily extendable to three dimensions so that a new approach was required.

It soon became clear that the small number of personnel in the project could not hope to create a complete automatic system which would meet all the needs of all industrial users. Therefore attention was focused on techniques which would lead to a system with the inherent

structure for solving any of a wide variety of problems which would
arise in industry. The basic system could be completed or fleshed out
by the actual user by the addition of straightforward specialized routines.
In this way the small project at the Servomechanisms Laboratory could,
it was thought, cover a large territory without becoming unnecessarily
embroiled in the details of any one restricted problem area. This type
of thinking also fostered an overall systems approach to the design of
automatic programming systems, and in a short time the name APT
System, an abbreviation of Automatically Programmed Tool System,
was introduced. Therefore, although in the fall of 1956 the overall per-
spective of automatic programming as described in the preceding sec-
tions was not yet clear, providentially the small size of the M.I.T. pro-
ject, coupled with the background of the personnel involved, led to the
formulation of a system concept which was the next logical link in the
continuing development of the new technology.

1C. 2 Systematized Solutions

The heart of the APT system concept is the notion of a systema-
tized solution. Although it seems impossible for those familiar with the
idea of a systematized solution to agree on a suitable definition for the
term, the general idea is concerned with methods for solving individual
problems which are elements of a more general class of related prob-
lems. In the subroutine library approach, the technique for solving an
individual problem is achieved by assembling blocks as in the construc-
tion of a stone wall. The individual blocks or subroutines are of various
sizes and shapes, but the executive routines, representing the mortar,
can be used to construct a desired solution procedure (type of wall) by
drawing from the library (supply of rocks). The systematized solution
concept, however, states that one central solution procedure which
represents most of the solution of all of the problems, i. e., an incom-
plete, but generally applicable skeleton solution, be constructed first.
Particular solution procedures may then be achieved by "fleshing out"
this skeleton by attaching to the central systematized structure, sub-
routines of only one or two simple types. The effect is that the difficult
part of all of the related problems is solved once and for all by the cen-
tral skeleton, and the solution of any particular problem consists merely

of attaching the appropriate simple routines. Since there are only one
or two types of routines required, it is an easy matter to expand the
system to encompass new problems, since only the rather straightfor-
ward development of the simple routines is required. It is in this way
that the APT system obtains its growth potential.

There are in fact many possible APT systems, each appropriate
for different classes of problems. In actual practice it is quite difficult
to discover systematized solutions because all of the distinguishing fea-
tures of a problem, which form the normal starting points for solutions,
must be discarded leaving only the "essence" of the problem for solution
in skeleton form. For this reason, there are portions or branches of
present-day APT systems which have not yet succumbed to the notion of
systematized solution. These areas are being worked on, however, and
there is reason to believe that with further investigations these efforts
will ultimately meet with success.

In summary, it may be said that although an APT system looks
very much the same as any other automatic programming system on the
outside, the internal organization of the system gives it a capability for
growth which cannot be matched by the ordinary type of automatic pro-
gramming system based strictly upon a large library of subroutines with
associated executive routines.

1C.3 The Simulated APT Computer

We have now described in general terms how an APT system dif-
fers internally from an ordinary type of automatic programming system.
But just what is an APT system? The use of the word "system" implies
that there are several component parts which are interrelated and con-
nected together. We shall now consider the principle parts of an APT
system and how they work together to facilitate the production of parts
by numerical control.

Recall that with the advent of numerical control, it was possible
to control the motions of a cutting tool in space by feeding numerically
coded instructions into a special piece of electronic equipment, called
the machine tool director. The purpose of an APT system is to permit
the human part programmer to specify these instructions, not in the
awkward detailed numerical code of the machine tool director, but in

terms of an easy-to-use English-like language. This means that some mechanism must be inserted between the part programmer and the director to carry out the necessary language translation and data processing operations, and automatically program the machine tool director in accordance with the English-like instructions.

The operations of language translation and numerical calculations are the province of modern computers so that the problem resolves itself into the design of a computer which is specially adapted to the part programming task. We call this computer the APT computer. Once the operations which the APT computer is to perform have been completely defined, it would be perfectly feasible to go into the laboratory or production facility and actually manufacture a special computer out of transistors, wires, and magnetic elements just as is done with other computers. This would be an expensive and lengthy process, however, even if we knew the complete specifications for the APT computer. The design specifications of the APT computer are in continual state of flux and further development, so some other means must be found to construct APT computers.

The great flexibility of modern day general purpose digital computers provides a convenient solution to this dilemma. These machines are so versatile that by employing special programming techniques it is possible to simulate, using any available general purpose digital computer, any particular special purpose computer. In other words it is possible to make the general purpose computer masquerade in such a way that its actions are exactly those desired of the special computer. This is the approach which has been taken in APT system development. Special programs are written for a general purpose computer, and this master program in effect transforms the general purpose computer into the APT computer which is the central portion of the APT system. In this way great flexibility can be achieved in the design and construction of APT computers without excessively long lead times and excessive cost. Furthermore, by making use of general purpose computers which are widely available, APT computers can be duplicated in any location merely by reading in a copy of the master program.

The overall organization of an APT system is shown in Fig. 1-1. The information on the part drawing is expressed in the convenient part

APT SYSTEM ORGANIZATION

THE MASTER CARDS

APT PROJECT

PART DESIGN

WORD DESCRIPTION OF WORK WRITTEN IN APT LANGUAGE

PART PROGRAM CARDS

CONVERT

GENERAL PURPOSE COMPUTER

TO

THE APT COMPUTER

AUTOMATICALLY CONTROLLED TOOL
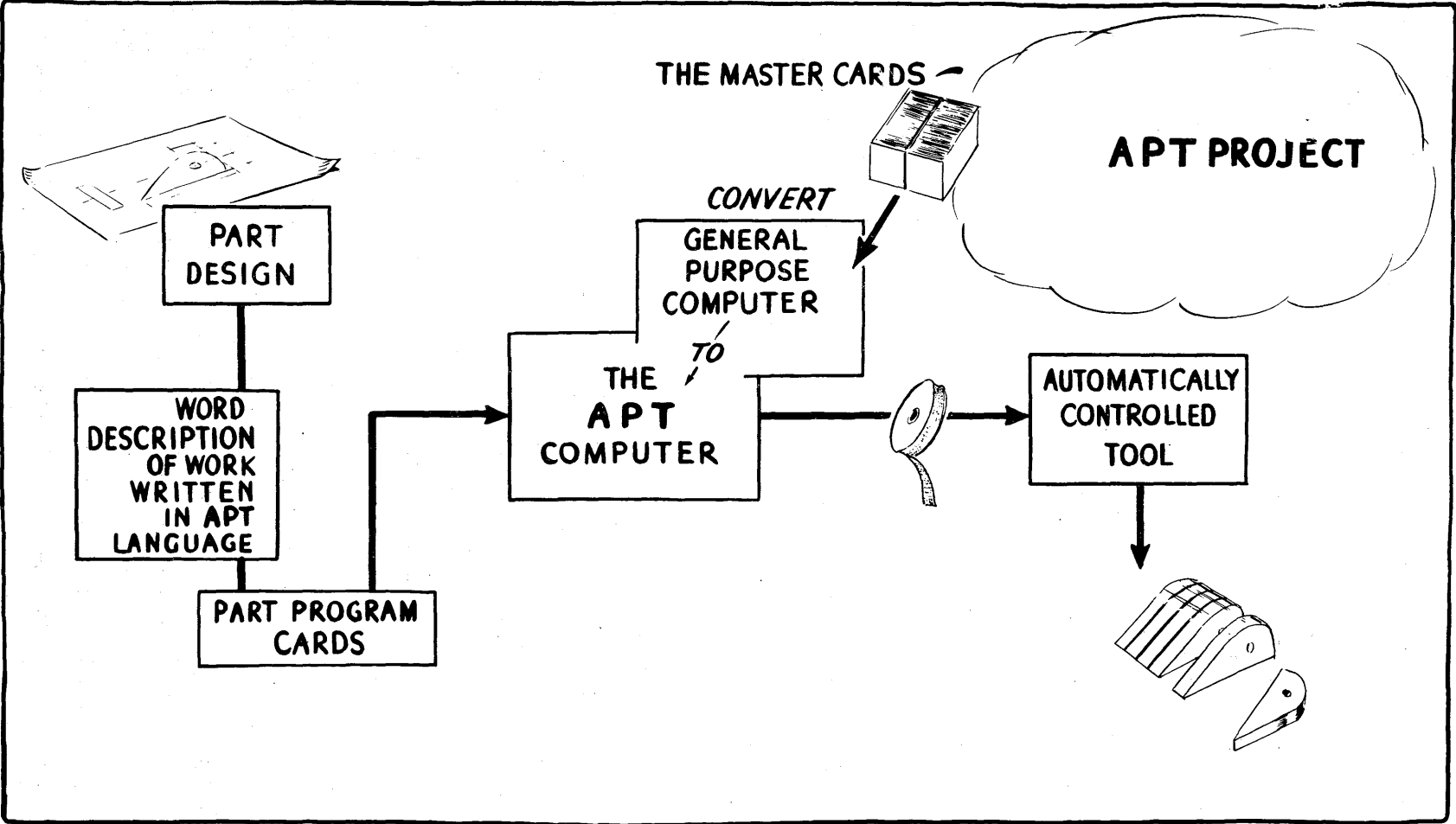
Fig. 1-11 APT System Organization

programming language and the resulting statements are processed auto-
matically by the APT computer to supply the required detailed instruc-
tions to the machine tool director, after which the part is automatically
produced. The figure also shows that the particular APT system, called
the APT II Phase I system, which is described in this set of documenta-
tion, has actually resulted from the cooperative efforts of a large number
of computer programmers working through the APT Project of the Air-
craft Industries Association. The organization and purpose of the APT
Project are described in detail in a later chapter of this volume. Before
considering the principal features of the APT II Phase I system, we first
describe how any APT system is used in an actual application.

1C.4 How the APT System is Used

Figure 1-2 shows the principal steps in the data processing which
takes place in the APT system to go from the conception of a part in the
mind of a designer to the finished piece. After the initial conception of
the part, the designer conveys the information to a draftsman who makes
a detailed working drawing of the part. At the present time the difference
between a drawing made for numerical control programming and an ordi-
nary shop drawing is only slight. Dimensioning of the drawing is usually
modified to make use of a coordinate system so that the part program-
ming task is made easier, and certain other changes in drafting conven-
tions are frequently employed. As the capability of the APT system
grows, however, profound changes will be possible in the drafting pro-
cedure. The amount of detail which must be conveyed by the drawing
will be decreased greatly, since many of the functions which the drafts-
man normally performs can be carried out automatically through the
facilities of the language. In fact, it is quite possible that instead of
precision drawings constructed exactly to scale, freehand or sketched
drawings can be used in which the primary function of the draftsman will
be, through his artistic ability, to convey to the part programmer the
many intricate aspects of the part in clear and concise form. These
changes will come about slowly, however, since a new level of communi-
cation must be learned by the designer, the draftsman, and the part pro-
grammer. In any case, whatever the level of detail, the creation of a
working drawing by a draftsman is an essential step in expressing the

HOW THE APT SYSTEM IS USED
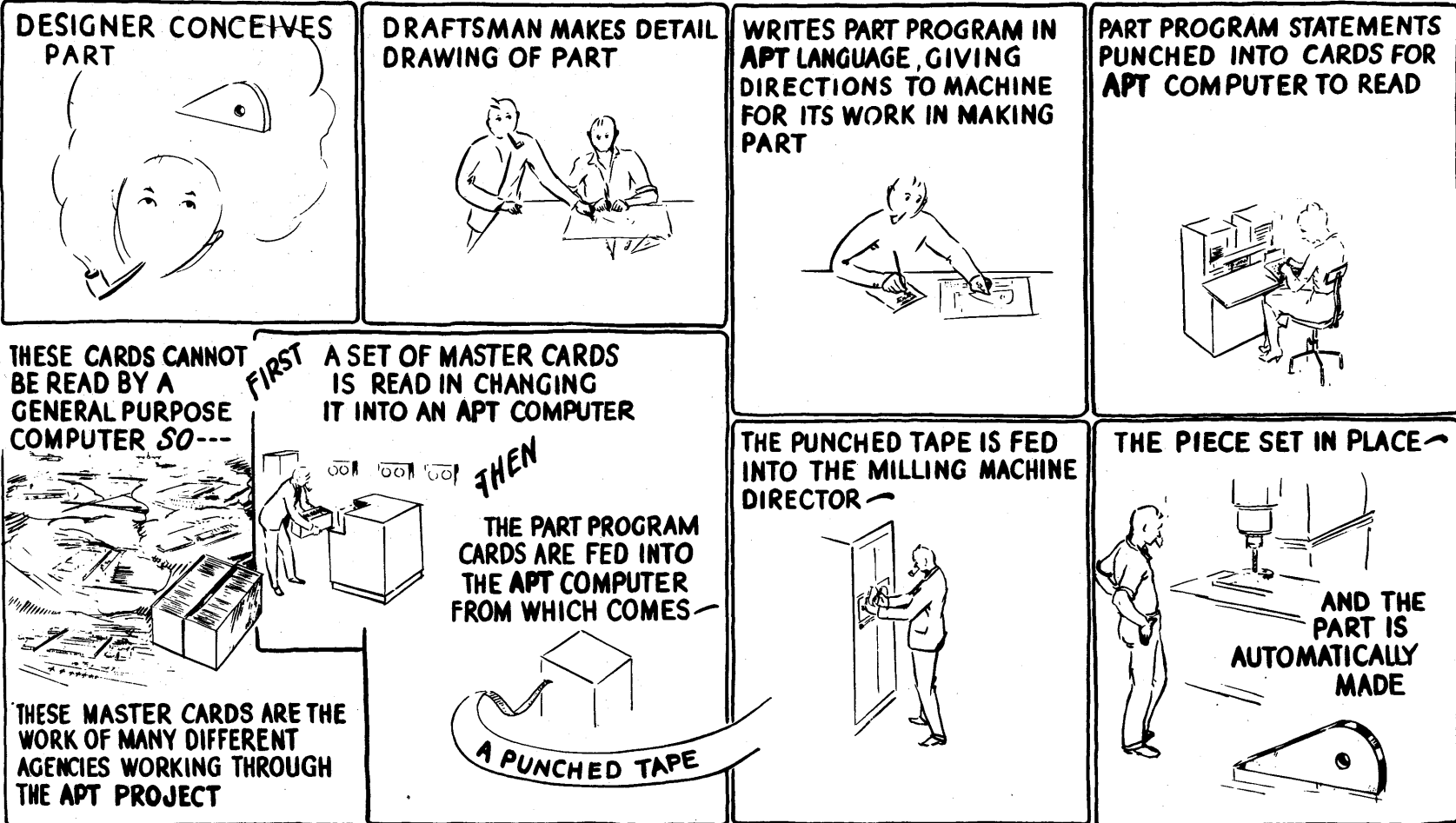
Fig. 1- 13 How the APT System is Used

ideas of the designer in sufficient detail for the part programmer to perform his task.

It is a function of the part programmer to take all of the information contained in the part drawing and express it appropriately in terms of APT language statements. The part programmer normally also must be familiar with tooling and metal cutting practices, since he supplements the design information by actual production information as well. By making the APT language more and more English-like, the task of the part programmer is made more natural and reliable. Also, necessary retraining to learn how to use the APT language is greatly decreased so that individuals with the requisite tooling and metal cutting knowledge can easily learn to become proficient part programmers. An important feature of the language is that great freedom is provided in the choice of methods and statement forms. Most operations can be programmed using the APT language in many different but equivalent ways, so that the part programmer can choose methods which are best suited to his current task. It is this aspect of the language which, as it develops further, will have the greatest effect on both drafting and part programming practices. Without this feature of broad redundancy the part programmer would be forced to make his problem conform to the limitations of the system, whereas with many possible ways to achieve the same results, in most cases he will be able to select a direct approach requiring little or no intermediate operations.

The result of the part programmer's work is a part program manuscript listing all of the English-like APT statements necessary to describe both the geometry and the cutting sequence to produce the part. The next operation is to transcribe this manuscript onto punched cards or some other medium so it can be read and processed by the computer. This is a completely routine operation since the statements are merely typed on a typewriter keyboard in exactly the form they are written on the manuscript. The punched cards are automatically produced, with each letter or character being represented by a unique combination of punched holes. Normally special verification procedures are also employed in a routine fashion to ensure that the transcription is accurate.

The punched cards which result from the manuscript transcription process can be read and manipulated by the card reader of a general

purpose computer, but in order for the computer to make meaningful
sense out of the APT language statements, it must first be supplied with
a master program. The master program consists of a large number of
punched cards representing the instructions to the general purpose
computer which will allow it to masquerade as the specially designed
APT computer. The APT computer is capable of reading the part pro-
gram cards, translating the information contained on them, performing
complex calculations, and finally producing output tapes containing the
instructions which the machine tool director system is to obey. The
sequence in actually processing the part program cards on the computer
then involves first reading in the master program deck to transform the
general purpose computer into the APT computer, and then causing the
simulated APT computer to read the part program cards and translate
the information into machine tool director terms.

Just as a large general purpose computer frequently consists of
separate cabinets performing the distinct functions of input and output,
control, calculations, and storage, connected together by cables, the
simulation program represented by the master deck contains main pro-
grams representing the same functions connected by logical pathways.
This structure of the master program has important consequences.
Additions and modifications can be made to one main portion of the pro-
gram with very little interference from other programs, so that modifi-
cation and expansion is greatly facilitated. Another less obvious impli-
cation of this structure is that the mathematical and data processing
techniques used in the main programs are necessarily general in nature
and not restricted to areas of limited application. Thus, for example,
the main program for calculating the motion of a cutting tool in space
applies to any curve which can be defined as the intersection of any two
surfaces for which the system can perform calculations, without regard
to what those surfaces are. Therefore if new surface calculating pro-
grams are added, entire new classes of curves are automatically made
possible. This capability for expansion is one of the main advantages
of the APT system approach.

Once the simulated APT computer has processed the part program
statements into the equivalent detailed numerical instructions on punched
tape, the standard operations of numerical control take over. It is

necessary merely to place the control tape in the machine tool director and the work piece in the machine tool itself, after which the part is automatically produced. This brief description of the use of the APT system has not made mention of the important auxiliary problems of designing appropriate tooling, such as jigs and fixtures for holding the work piece, choice of cutter shape, spindle speed, etc., all of which are essential to proper application of the technique. Consideration of these problems begins with the original design of the part, since such things as producibility must be considered, and progresses in a parallel stream down to the actual production of the part. However, since these problems are only indirectly affected by the APT system at the present time, no extensive discussion is presented here.

One other item, which is shown in Figure 1-2, is the fact that the master program deck which in effect transforms the general purpose computer into the APT computer is actually the result of the combined efforts of many different agencies working through the APT Project of the Aircraft Industries Association. We now proceed to a brief discussion of this project and its importance in APT system development and application.

1D. THE APT PROJECT OF THE AIA

1D.1 The Beginnings of the Joint Effort

Previous sections have described why a system patterned after the APT concept is necessary and in general terms how such a system is organized and used. We now consider the equally important problem of how such a system can be brought into being on a broad enough scope to be truly applicable to the majority of industrial problems. It will be recalled that the APT concept was originated by the M.I.T. project as a result of the interpretation of the reoriented AMC contract as a mandate not merely to perform yet another feasibility study, but to develop practical techniques for automatic programming of numerically controlled machine tools. With the small manpower and funds available, it appeared that the only solution would be to form a nucleus of basic techniques on which could be built other systems of sufficient capability to actually be applicable to industrial problems. Just as the structure of a crystal or

snowflake is begun by an elementary crystal and then develops naturally in accordance with the basic pattern, it was hoped that the basic research could form the foundation for many systems based on a common foundation but applicable to different problem areas.

There was one flaw, however, in this thinking which could have invalidated the approach with respect to the overall goal of creating techniques which would be applicable to industry. Automatic programming systems such as the APT system are necessarily extremely large and extremely complex. This means that they are both difficult and expensive to construct. A few individual companies might have been willing and able to take the incomplete results of the M.I.T. research project and build on them systems of practical applicability. It is unlikely, however, that the improved performance made possible by the APT system concept would have been widely available in a reasonable length of time, due solely to the complexity and expense of making such a system in toto.

Actual progress in the M.I.T. project did not get underway until the fall of 1956. In early 1957 at about the time when the project had completed its general formulation of the APT system concept and had a limited prototype system operating on the Whirlwind Computer, members of the project attended a meeting of the Subcommittee for Numerical Control (now the Numerical Control Panel) of the Aircraft Manufacturing Equipment Committee of the Aircraft Industries Association. The Subcommittee for Numerical Control had been formed to study how numerical control would affect the aircraft industry, and to study the possibility of standards and specifications in the field of numerical control. One of the many projects actively under study was the problem of part programming, and a brief report of progress of the M.I.T. Project was made for the information of Subcommittee members. The comprehensive approach of the APT system concept, its facilities for future growth and expansion, plus the fact that the concept included provisions for preparing cutter center output in any one of a number of machine tool director language codes, made it appear that if an industry-wide APT system and part programming language could be agreed upon, most of the objectives of the Subcommittee could be met. It was therefore decided to pool computer programming manpower and resources to produce a complete APT

system for industry-wide use.

The idea of a joint programming effort satisfied the needs of both industry and M.I.T. Industry could obtain compatibility and avoid duplication of effort. M.I.T. could feel that its mandate would be fulfilled not through its own efforts, but through the combined efforts of those who would actually use the system, and also that it was in a sense fulfilling its role as an educational institution by making the results of its research directly available to those who could make best use of them.

The initial overall coordination of the APT Project was the responsibility of the M.I.T. Servomechanisms Laboratory. A meeting at M.I.T. in May 1957 was attended by 21 representatives of fourteen different aircraft companies and plants, most of whom were experienced computer programmers. During the one week meeting the purpose and functioning of the automatic programming system which was to result from the joint effort were discussed and a design was formulated for what later became known as the 2D-APT II System. In the name the abbreviation 2D indicated that the part programming language was to be designed primarily for producing two-dimensional parts, and the abbreviation APT II indicated that the system is programmed in terms of three-dimensional space curves. (The next level of sophistication of APT systems, called an APT III system, is programmed in terms of entire regions of surfaces in three dimensions. Although research is still going on in APT III, programs are now under development for this type of system which will blend smoothly with the existing APT II system.)

Since almost all of the interested companies already had or planned soon to have an IBM 704 computer, the initial APT system was coded for that machine. Although it had originally been suggested that the most expeditious way to program the APT system would be to have all programmers work together under one roof at M.I.T., this was not feasible at that time. Therefore, programming conventions were established at the May 1957 meeting so that the large programming task could be performed by the individual programmers working at their own plants. The entire operation was carried out by mail and telephone correspondence, primarily through a series of progress reports from the individual companies and coordinator reports issued by the M.I.T. group. By early 1958, computer program card decks had been received from most of the

participating companies and M.I.T. then combined all of these various programs into one overall computer program. In April, 1958, the field trial version of the 2D-APT II Phase I system was shipped by M.I.T. to seventeen participating companies for shakedown tests. The field trial package included some 8,000 computer cards and about 200 pages of preliminary program documentation which had been prepared by the various individuals who wrote the programs. Operating and part programming instructions also were included, along with a few sample test parts for use in testing out the system.

Very early in the planning of the 2D-APT II system, it was decided that development should take place in successive phases. It was decided that the modified field trial version would be called the 2D-APT II Phase I system and would represent the first plateau or level of achievement which would be considered a completed APT system. During the field trial period a number of difficulties were uncovered, mostly clerical but some reflecting significant system inadequacies. As these difficulties were overcome and as a number of proposed Phase II features were added to the field trial system to make a more usable Phase I system, it developed that the resulting set of programs was capable of performing almost all basic three-dimensional work automatically. Therefore, the 2D-prefix was dropped midway in these developments and the name APT II Phase I was adopted. The contributions of many of the companies were not incorporated in the Phase I system, but were reserved for early developments in Phase II.

Since the primary aim of the MIT project is research in automatic programming rather than development, it was felt that after the Phase I system had been launched effectively, coordination of the joint effort should be taken over by an industry sponsored committee and the M.I.T. project would then revert to ordinary membership in the joint effort. The transfer of coordination responsibility from the M.I.T. project to the APT Project Coordinating Group, sponsored by the AIA, took place in June of 1958. The modification of the field trial programs into the Phase I system was shared between the coordinating group under the Chairmanship of Mr. O. Dale Smith, North American Aviation, Los Angeles, and the M.I.T. project. Also in order to insure that the future developments

were launched on a firm foundation, it was felt that a full set of documentation should be prepared describing not only the detailed functioning of the system but the philosophy and motivation behind various features of the system as well. This documentation task, of which this is one volume, has been performed primarily by the M.I.T. project, based upon the program writeups provided by the participating companies.

The APT II Phase I system was officially demonstrated to the public in a special conference for the popular and technical press held at M.I.T. on February 25, 1959, almost two years after the initial planning of the joint programming effort was begun. The conference was jointly sponsored by the Aircraft Industries Association, the Air Materiel Command, United States Air Force, and M.I.T. Although there was a tendency in the resulting coverage to state that the potential capabilities of the APT system were present capabilities of the Phase I system, the general technique, and the APT Project of the AIA which would carry forward its further development, were hailed as a significant achievement in increasing the productivity of numerical control. A number of the more technical publications properly credited the many other automatic programming systems which had been developed by various aircraft companies and users of numerical control as being quite comparable in many respects with the Phase I system, and pointed out that the real import of the APT Project developments would come in the further development of the system in later phases.

With this brief history of the APT Project completed, we now turn to a discussion of the APT Project itself, how it is presently organized, and what it can mean to the future development of improved production of complex parts through the combination of automatic programming and numerical control.

1D.2 Participation in the APT Project

The function, organization, and operation of the APT Project, as constituted by the Aircraft Industries Association, are spelled out in the APT Project Directive, a copy of which appears in an appendix to this volume. Quoting from that directive, "The objective of the APT Project is, through the pooling of resources and ideas to produce a universal automatic programming system to fully exploit the economic potentialities

of numerically controlled machines and equipment." The project itself
is made up of computer programmers from the participating organiza-
tions who have been assigned by their respective companies to work on
programming assignments which will further the objectives of the pro-
ject. "Any corporation, or division of a corporation (AIA member or
otherwise) is eligible to become a participant in the APT Project..."
contingent upon certain agreements which are essential to meeting the
objectives of the project. Overall coordination of the project is carried
out by the APT Project Coordinating Group, primarily through the acti-
vities of the APT Project Coordinator. Coordination within the project
is accomplished by progress reports from the participants to the Coor-
dinator, Coordinator reports, and group meetings as required, as well
as communications on an individual basis. The computer programs which
result from the combined efforts of all members of the APT Project are
available to all participants, programs and documentations being dis-
tributed by the Aircraft Industries Association at cost. Information is
also available at cost to non-participating organizations.

The organization of the APT Project is simple, but the tasks it
must perform are not. This means that a high level of understanding
and cooperative spirit is required from all participating organizations
and individuals if the project is to function smoothly and effectively.
There has probably never before been a cooperative effort of this type
which is comparable in size, scope, and extreme technical detail at
which compatibility must be maintained. There are many cooperative
ventures between companies and individuals, but those which become as
technical as the APT Project usually are considerably smaller in scope
and number of participants, whereas those which are of comparable size
usually do not have to function at a very detailed level. These points are
not mentioned here to bring foreboding to the minds of participants or
future participants, but to point out that because of its very nature,
membership in the APT Project cannot be taken lightly, but rather the
attitude of each participant must be to do as much as he can as well as
he can. Every participant must be an active participant.

Granted that in order for the APT Project to flourish, and in order
for it to be truly effective, it must have the full support of its members,
what does it mean to be an active participant? There are actually several

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levels or types of active participation, depending upon the size of an organization and its level of experience in computer programming or problems similar to the APT system. A large company with competent and experienced staffs in the computer programming and numerical control fields can obviously contribute considerably more than a small company which has only recently entered the field. Despite the large discrepancy in actual amount of contribution, however, the attitudes of these two companies can be very much the same. If the intent of the APT Project is properly understood by both of these companies, each will wish to contribute as much as it can in order to gain from the cooperative effort as much as it can. Before delving further into this subject of active participation, let us examine more closely the personnel of the APT Project.

In accordance with the APT Project Directive, each participating organization must agree to assign at least one full-time, competent computer programmer to work on the APT Project. Due to the complexity of the subject matter, this requirement should be interpreted as one full-time individual, not two half-time individuals. Experience has shown that the effectiveness of an individual drops off rapidly if extraneous work assignments are sandwiched in among APT activities. It should also be emphasized that this one individual is a minimum requirement, and any organization which intends to actively pursue the use of the APT system will find very quickly (as also has been verified by experience) that the assignment of additional personnel either on a full-time or part-time basis is very worthwhile. As will be discussed shortly, the assignment of a person to work on the APT Project does not mean that he is working on non-company assignments. This is further emphasized if we consider the probable breakdown of this individual's time as APT Project representative.

The APT representative is considered the authority on the APT system for his company, and even with minimum responsibilities this requires that the individual wear several hats. A reasonable estimate of his duties, as judged from past experience by the APT Project Coordinating Group, is that one quarter of his time will be spent in maintaining, updating, and checking out revisions to the APT system in use in the plant as information comes in from other parts of the APT Project.

Another quarter of his time is used in explaining the APT system to individuals and groups within his own organization and acting as general liaison within the organization concerning the APT system. In this respect he must consult with part programming groups to inform them of changes in the system and to obtain their suggestions for improvements, he must cooperate with training groups so that courses in using the system are kept up to date, and he may also be called upon to assist in keeping management informed concerning APT system operation. These duties as general APT representative leave the individual only half of his time to actually apply to the analysis, design, and programming of further additions to the APT system under a work assignment made by the APT Project Coordinating Group. Translating these duties into terms appropriate to some of the larger companies makes it clear why frequently a fairly large number of individual people will be assigned to APT Project work.

As to the matter of work assignments, whereby a participating organization makes further contributions to the APT Project, these also come in several categories. When an organization first joins the APT Project it is quite probable that the full capabilities of its assigned personnel will be consumed in merely catching up with the current status of the project and learning what is in the APT system and how to make it work properly. Some companies, especially those with previous experience in this field, will have certain pet problems that lie outside the scope of the current APT system and which they would like to work on as their contribution. The wording of the APT Project directive in this regard is that the project participant will "accept and execute mutually agreeable assignments from the Coordinating Group." Since one of the primary objectives of the APT Project is to extend and broaden the base of the APT system capabilities, almost any legitimate problem area which is related to current APT system capabilities is likely to be "mutually agreeable." Thus it is perfectly possible (and in practice usually the case) that the actual work assignment of a participating organization is in an area of their own choosing and the work itself is actually work which they would perform for their own purposes in any case. The advantage of performing these tasks through the medium of the APT Project is that frequently constructive suggestions can be made by other

project participants, and in most cases, if the problem area is reasonably closely related to the APT system proper, it will be found that by building on the existing capabilities of the system the work required to break into a new area is greatly reduced. It may also be that the desires of one participant when made known through a meeting to the other participants will be found to mesh well with other schemes of their own so that a subgroup effort can be started combining the best features of all approaches. In this way every participant is virtually guaranteed that he will gain more from the cooperative APT Project than he puts in.

There will probably always be a backlog of work assignments for the APT system which have been proposed, but for which no manpower is immediately available. From this pool of APT improvements waiting to be worked on, assignments can be made to new companies once their personnel are sufficiently steeped in the APT system to undertake a work assignment. Also the presence of such a backlog of work areas means that once a company completes one assignment there are others ready to be worked on. The APT system development has only begun and for the foreseeable near future there will continue to be work areas in which the effort expended will be a sound investment for any participants. It will be some time before further expansion of the system can be considered the addition of unnecessary frills. In particular a significant portion of work assignments will probably continue to be the revamping of existing system capabilities for greater efficiency as well as greater flexibility, as experience is gained with the system in actual operation.

The wide diversity of work assignments that has been indicated by the preceding paragraphs serves to point out once again the extreme complexity of the coordinating task in APT system development. In order to ease this problem, a sort of informal structure in addition to the APT Project Coordinating Group is presently in use. This internal structure consists of certain of the more experienced and larger companies taking over some of the coordination responsibilities for certain work areas. These sponsor companies assume the overall responsibility for coordinating the technical details of the various work assignments of other participants working within their areas. In this way no one individual need be cognizant of all the current problem details throughout

the entire effort.

This, then, completes the discussion of what active participation means. We have seen that participation by organizations can involve one man or many. Work assignments can range all the way from half an individual's time spent in learning how to use the system, as in the case of a newcomer small company, all the way to large companies which sponsor a work area and also have several individuals actively programming (some of them full time) on particular work assignments. The degree of participation is up to the individual company, but the general conclusion which may be drawn is that the greater the participation of a company, the more vitality it can contribute to the APT Project as a whole, and the more the APT Project will be able to serve the interests of all.

1E. PUTTING THE APT SYSTEM TO WORK

We have now considered the APT system in broad terms, what it is, why it is needed, how it works, and how the APT Project will maintain and expand it. One important topic still remains for discussion before this general introduction is considered complete. And that is how the APT system can be put to work. What are the economics of APT? How much investment must a company make before it can use the APT system in a production sense? How big a computer is required, how much computer time will APT applications consume? How does APT affect drafting practices and other phases of the production process? What savings can be made in tooling cost? How are part programmers to be trained? How many different types of parts can be economically produced through the APT system? How much savings can be expected in the part programming process? How much savings can be expected in machining time? How likely is it that a seemingly routine part would require specialized procedures to be handled by the APT system? In general, what are the economics of APT?

Everyone is well aware that economics involves considerably more than money or product. Associated and inextricably intertwined are numerous intangibles, some of which play important roles in economics. Numerous studies have been made and are still being

made on the economics of numerical control, including all of the various aspects from drafting and part programming practices through production and equipment maintenance. The present author does not feel qualified to write on the subject of the economics of numerical control, nor even the economics of APT, since it is impossible to talk of APT without numerical control or numerical control without a part programming scheme such as APT. It can be said, however, that because of its scope, the APT system compares favorably in overall economics with almost any existing automatic programming scheme, and almost definitely will out-perform other systems by a considerable factor in the very near future. In other words, even the initial APT system should be able to do at least as well and quite probably better than other present-day automatic programming systems, and because of its flexibility and capacity for growth (and because of the APT Project to insure that this growth actually takes place!), the economics of APT will almost certainly be considerably better than that shown by economic studies which have already been made.

Similar studies on APT itself must, of course, be made, and it is hoped that this section of this chapter can be replaced in the near future by a summary of definitive results on economic studies using APT, and that full data will be added to Chapter 5, which has been reserved for this purpose. It should be borne in mind, however, that even when studies of present APT systems are made, there still may be many intangibles which fall outside the scope of those studies. This is because the primary places where APT differs from systems now in use are those which will take time to become integrated into actual production procedures sufficiently to have an impact. It may be extremely hard to gage, for example, the economic effect of transferring certain aspects of the data processing from the drafting room to the part programmer's desk, and it may be some time before economic studies of real depth will be possible. Since this, however, is the true testing ground for any new technique, it is hoped that carefully executed economic studies will be made in order to provide answers for these questions.

1F. A GUIDE TO THE APT DOCUMENTATION

This volume is the first in a series of six describing the initial APT II Phase I system. In any undertaking as ambitious as the APT

Project, especially one which is intended to continue to expand and develop, adequate documentation is essential. Although a complete description of the documentation system is presented in a later chapter, we give here a brief outline of the sturcture and intent of the documentation to assist the reader.

Documents are aimed at three principal classes of readers. Of the original six volumes, Volume I is intended for the general reader who is interested in learning about the overall features of the APT system. Volume II is for the part programmer or user of the APT system. Volumes III to VI are intended for the computer programmer who is interested in the working details of the computer programs. It is intended that as the documentation is expanded and modified to keep up with the progress of the system itself, additional volumes will be added to these categories of reader interest, so that at all times documentation will be available describing the system from these three principal points of view. The breakdown is of course somewhat artificial since the reader who is interested in details of the working of the system can also benefit from the broader coverage aimed at the general reader, and parts at least of the more detailed documentation will be meaningful and enlightening to the general reader as well. It is hoped, however, that by following this procedure and showing the various features of the APT system and the APT concept from various viewpoints, the greatest clarity of presentation will result, so that as much of the know-how as possible is generally disseminated.

The following chapters of Volume I go into the workings of the APT language and system of computer programs in greater depth than the brief coverage presented in the early parts of Chapter I. Some possibilities of the future expansion of the system are also described, as well as a detailed description of the documentation system.

Volume II, the "APT Part Programmer's Manual," describes in detail the language facilities which are available in the APT system. Sample part programs are worked out completely to illustrate how the language is used, and a number of specialized part programming techniques are also illustrated.

Volume III, "Mathematics of the APT System," presents the general derivations of the mathematics and data processing techniques employed

in the design of the computer programs. The treatment of this volume is primarily at a philosophical and mathematical level, the intent being to provide as complete motivations as possible for the ways in which various operations are performed. Coding details are minimized and the emphasis is on the general overall techniques employed. It is hoped that by attempting to be explicit in the reasoning behind the various developments, a good foundation will be laid for improved methods for accomplishing the same tasks, and also for expansion into new areas.

Volume IV, "A Description of APT Computer Programs," contains detailed writeups of all the various computer programs which compose the APT system. Detailed flow diagrams are given and coding details are emphasized. The initial volume contains descriptions of how the system has been coded for the IBM 704 computer, and additional volumes parallel in structure will probably be required to document the equivalent programs coded for other computers.

Volume V, "Operators and Troubleshooters' Manual," contains information concerning operation of the system on the computer. It is hoped that as the APT system is put into routine use in more and more production facilities, the operating techniques for each of these procedures will be described in this volume. It is of course possible to operate the programs in many different ways setting up magnetic storage differently, using so-called off-line input techniques, and operating the programs either manually or automatically. By having representative writeups of the various possibilities, the user can choose that method most appropriate to his own installation. The troubleshooter portion of this volume concerns listings of diagnostic information printed out at the various error stops in the program. The check list will prove helpful to the operator during the running of the system as well as the computer programmer in off-line debugging procedures. Where the system is as complex as the APT system, especially if allowance is made for its future expansion, efficient procedures for system maintenance in terms of the programs, themselves, becomes increasingly important. It is hoped that as experience is gained with the system, this volume will grow in comprehensiveness and usefulness.

Volume VI, "Modification and Change Procedures," describes the various changes to the programs which must be made for the more

important standardized additions which are expected to be made to the system. Such things such as adding words to the vocabulary, inserting new surface types and other changes, which represent a horizontal rather than a vertical exapnsion of the system, are spelled out in great detail. Using this volume it is an easy matter for the individual user of the APT system to increase and mold its capabilities to suit his own needs. This volume also provides a useful adjunct to the earlier more descriptive volumes in that by collecting all of the aspects of the various programs concerned with one topic under one heading, it can be of great assistance to the computer programmer in obtaining an overall view of the entire collection of computer programs.

As new programs are added to the system and new facilities are thereby made possible, additions must be made to the APT documentation. In a system as large and complex as the APT system, especially when it is supported and made possible by a cooperative programming effort, carefully prepared and suitably organized documentation is an absolute necessity. The page numbering and section numbering system used in the APT documentation is purposely designed for easy alteration, and the Aircraft Industries Association will maintain the documentation in the future by reproducing and distributing additional material at cost. In general a minor alteration to the APT system will cause the changing or addition of a few pages to several of the documents, reflecting the various aspects of the change as appropriate to each volume. More major additions will call for the addition of entire sections or chapters to existing volumes; and in some cases, for example, in the case of a very large and complex type of surface calculation, it may be advisable to write a special volume on that single program, with the various chapters of the volume organized along the lines of the various volumes of the APT documentation itself.

The conclusion for this introductory chapter is most appropriately the following brief summary. The APT system concept provides the technical basis for the full exploitation of the possibilities of numerical control with automatic programming. The APT Project, being an organization of the actual users of the system, has both the technical capability and depth for bringing the present and future ideas which evolve from the APT system concept into practical fruition. The APT documentation

system, being organized in accordance with the various reader classifications, can provide the necessary cohesion to disseminate the knowledge and techniques developed in the APT Project to all those interested in numerical control.

CHAPTER 2

THE PART PROGRAMMING LANGUAGE

One of the most important features of the APT system is the English-like part programming language which permits the capabilities of the system to be brought to bear on the production of parts with an ease and directness which yield not only substantial savings in time and effort, but which also provide the best assurance that highly complicated tasks can be performed correctly and reliably by persons who are unfamiliar with the detailed mathematical problems involved. There are many reasons for choosing an English-like format for the part programming language, but they all boil down to one primary reason. The most natural way to describe the geometric and tool sequencing operations of part programming in a written language is to use English.

2A. THE ENGLISH-LIKE APT LANGUAGE

The present APT language is a restricted form of pidgin English in which words are abbreviated and unusual punctuation is employed, but in spite of these peculiarities, which were dictated by computer programming considerations, the general character of the language is that of English. Admittedly it is possible to obtain more condensed languages for part programming which could be made to perform the same tasks, but while these languages might be equally satisfactory for computer programmers or individuals with a natural aptitude for the thought processes involved in computer programming, they would be less easy to learn and less natural to apply for a majority of part programmers. Almost all part programming will be performed not by mathematicians or computer programmers, but by people who are skilled in the fields of tooling, planning, and metal cutting. The English format of the APT language will permit these people to employ the APT system as a valuable tool without undue effort, so that they can concentrate their efforts on those portions of the part programming problem which are not at present handled automatically by the APT system.

The combined facilities of the initial APT language provide the part programmer with an effective general purpose tool which is well suited to a wide variety of part programming problems. Since the APT system is capable, through the facility of the language, of shouldering most of the burden of the detailed aspects of part programming, the human is free to concentrate on the overall geometric planning and metal cutting aspects of the problem. It should be emphasized, however, that the initial version of the APT system represents only a first step in the continuing development of more and more comprehensive automatic programming techniques. Even though the initial system will handle a wide variety of problems with ease, there are many more problems which lie outside the scope of the initial system design. Also as the system is used, new methods will undoubtedly be found for doing some of the existing tasks more efficiently and effectively. The progressive expansion of the APT language and capabilities will have a profound influence on both the applicability of the automatic programming technique and the parts which may be produced through its use.

2B. FEATURES OF THE LANGUAGE

Although a complete understanding of the APT language can only be achieved by careful study of Volume II, The APT Part Programmer's Manual, an appreciation of its general characteristics can be gained by a brief description of the philosophy behind the design of the language and by reading a sample part program. The English-like words and statement format of the language make it easy to learn and to apply correctly. In fact it is necessary only that the part programmer learn the meaning of the words of the vocabulary plus a very few simple rules of punctuation and modifying power. Then if the rules are obeyed and if a statement makes good English sense it will be correctly interpreted by the APT system. This degree of flexibility has important consequences in the reliability of the overall application of the APT system since it permits each individual part programmer to choose a mode of expression which he himself prefers. Instead of being forced to conform to rules and procedures which are unnatural for him, he can exercise his freedom to choose part programming procedures which satisfy his own working

habits. In most cases there are many possible ways to program a given sequence of operations so that the part programmer can usually find a way to state a problem with a minimum of effort. With increased expansion of the language and APT system facilities, the flexibility in this respect will be increased many fold.

The primary philosophy which is represented by the APT language structure is that complicated parts are composed of a combination and interconnection of simple basic geometric shapes. Although the APT language is used to make parts by numerical control, the language itself is not numerical but rather is geometric in nature. Numbers appear only as necessary ingredients of certain geometric definitions, and almost all of the operations in the language use the English names for basic geometric shapes and relationships. Thus a line is called for by the word LINE, a circle by CIRCLE, a sphere by SPHERE, a hyperbolic paraboloid by HYP PAR, right by RGT, and tangent to by TAN TO. Virtually all operations and instructions are given in terms of general geometric elements of this type.

The basic framework underlying all geometric statements is a rectangular coordinate system, with X, Y, and Z axes, in which the APT system ultimately performs its calculations. In every part program certain geometric quantities must be specified using numerical parameters in terms of this coordinate system. Once a few geometric quantities have thus been defined in terms of the coordinate system, however, it is usually possible to construct the remaining curves, surfaces, and points implicitly using only the language facility to define them in terms of previously defined geometric quantities. Thus for instance a point may be defined by the intersection of (INT OF) two lines which have previously been defined, even though its numerical coordinates are not known by the part programmer. This point implicitly found in terms of two lines may in turn be used to assist in the construction of the definition of additional geometric quantities. For example, it might serve as the center for a circle. To assist in this process the APT language permits arbitrary symbolic names such as SIDE, LINE 3, CIR 2, to be assigned, so that once a geometric quantity has been defined it may be referenced in any succeeding statements merely by giving its

symbolic name. The ability to define geometric quantities implicitly in terms of previously defined quantities provides a very powerful part programming technique. For example, even restricting attention to the many forms for defining straight lines and circles, the part programmer is limited only by his knowledge of constructions with ruler and compass. The geometric features of the APT language can greatly reduce many of the tedious operations required for the careful drafting of parts to be produced by conventional means, since it is necessary in many cases only that the draftsmen provide a reasonably accurate sketch showing the relationship between the component shapes which compose a part. The APT system can itself perform the geometric constructions necessary to calculate the detailed relationships.

Tool shape and size as well as tolerances and feedrates are also specified by natural English-like statements. The APT system is capable of calculating tool center locations for a wide variety of tool shapes of arbitrary size. In addition to giving symbolic names to geometric quantities, the APT language permits synonym statements to be made so that symbolic names may be used for numerical parameters as well and can be changed throughout the part program merely by instructing the system to consider the given symbolic name synonymous with a specified number or other name. In this way for example, a part program may be written in which all tool size parameters are given symbolically so that by the alteration of only a few synonym statements the same part program can be run through the system several times to produce numerical control tapes appropriate for different sizes of cutter, automatically and without the introduction of errors which could arise were the part to be reprogrammed for each case. Control over the auxiliary functions of the machine tool such as starting and stopping, turning on and off of coolant flow, etc., are also handled by English-like statements.

The specification of the tool position with relation to the work piece and the path which it is to follow in space are given by additional English words from the APT vocabulary. For example, TL RGT or TL LFT specify that the tool is to be on the right or left hand side of a curve as it is traversed, and words such as GO RGT and GO LFT specify which

The author's name and organization should then be added to the list of authors which appears on page 0-4 of each volume.

The purpose of the list of authors is to provide a tabulation of the names and organizations of those individuals who have played a part in the actual writing of material that appears in the volume. The initials associated with full names in that list are used to tag portions of the table of contents and page corrections as described above.

It is quite obvious that the numbering system used in the APT documentation is the result of numerous compromises. Although it may leave considerable to be desired in terms of appearance, it is hoped that the system will serve its purpose and allow proper organization and authorship reference. It is hoped that full advantage will be taken of the flexibility of the documentation system so that the descriptive portion of the APT effort can be kept up to date with the functioning programs.

5D. PROCEDURES FOR DOCUMENT MODIFICATION

The original printing of the APT documentation has been carried out by M.I.T. with AMC sponsorship. Both bond and vellum reproducible copies of all documents have been printed. For active project participants a kit consisting of four copies of Volume I, two copies of Volume II, and one copy each of Volumes III, IV, V, and VI, in addition to one reproducible copy of each volume, have been supplied. In this way, an organization which actually plans to use the APT system has sufficient information to get underway, and also can reproduce as many copies of the various volumes as are required. Vellum masters for the various cover printings are also included so that the documents can be duplicated exactly if desired. It is also felt that the blank vellums of the covers may also be useful for memoranda or intermediate levels of documentation of more restricted scope. Non-participants are supplied single bond copies of the various documents.

Responsibility for maintenance of the APT documentation has been assumed by the Aircraft Industries Association and will include both bond and reproducible copies of correction material. This section should be replaced by a full description of the mechanical procedures for submitting information to AIA for printing and distribution, once these procedures have been established.

REMARK - ROCKER ARM CAM - PROGRAM NO. 1 - ROSS
REMARK - PRELIMINARY SPECIFICATIONS AND GEOMETRIC
           DEFINITIONS
           TL RAD/ +1.0, INCH
           TOLER/ +.005, INCH
           FEDRAT/ 80, IPM
           HEAD 1, MODE1, ON SPIN
           LOOK TN, TN CK PT/ 2.5, -5, 0
CIR 1   = CIRCLE/ WITH, CTR AT, 0, 0, 0, RADIUS, 6, INCH
CIR 2   = CIRCLE/ WITH, CTR AT, 5, 0, 0, RADIUS, 6, INCH
PNT A   = POINT/ Y SMALL, INT OF, CIR 1, WITH, CIR 2
LINE 1 = LINE/ THRU, PNT A, AT ANGL, 90, DEG
CIR 3   = CIRCLE/ WITH, CTR AT, PNT A, RADIUS, 2, INCH
PNT B   = POINT / Y SMALL, INT OF, LINE 1, WITH, CIR 3
CIR 4   = CIRCLE/ WITH, CTR AT, 0, 0, 0, RADIUS, 1, INCH
CIR 5   = CIRCLE/ WITH, CTR AT, 5, 0, 0, RADIUS, 1, INCH
CIR 6   = CIRCLE/ WITH, CTR AT, PNT B, RADIUS, 1, INCH
REMARK - START CUTTING OUTSIDE.
REMARK - INITIAL TOOL POSITION X = 2.5 INCH, Y = 5.0 INCH,
           Z = 5.0 INCH
SET PT = FROM, POINT/ 2.5, 5, 5
           ON KUL, GO TO/ 2.5, 5, 0
           IN DIR, VECTOR/ -1, 0, 0
LINE 2 = GO PAST, LINE/ RIGHT, TAN TO, CIR 4, RIGHT, TAN TO
           CIR 6
           WITH, TL RGT, GO LFT, ALONG/ LINE 2
           GO FWD, ALONG / CIR 6
           GO FWD, ALONG, LINE/ RIGHT, TAN TO, CIR 6, RIGHT
           TAN TO, CIR 5
           GO FWD, ALONG/ CIR 5
           GO FWD, ALONG, CIRCLE/ WITH, CTR AT, PNT A,
           RADIUS, 7, INCH
           GO FWD, ALONG/ CIR 4, UNTIL, TOOL, TAN, LINE 2
           OF KUL
           GO DLTA/ 0, 0, 5
           OF SPIN, GO TO/ SET PT
           STOP
REMARK - END OF OUTSIDE. TOOL SHOULD BE AT EXACT
           STARTING POINT

REMARK - CHANGE CUTTER. START CUTTING INSIDE
           TL DIA/ +2.0, INCH
           COR RAD/ +.25, INCH
           TOLER/ +.01, INCH
           GO TO/ 2.5, -5, 5
           FEDRAT/ 10, IPM
           ON KUL, ON SPIN, GO DLTA/ 0, 0, -4.5
           FEDRAT/ 80, IPM
PNT C   = POINT/ Y LARGE, INT OF, LINE 1, WITH, CIR 6
LINE 3 = LINE/ THRU, PNT C, AT ANGL, 0, DEG
           IN DIR, POINT/ PNT C
           GO TO/ LINE 3
CIR 7   = CIRCLE/ WITH, CTR AT, 0, 0, 0, RADIUS, +.5, INCH
CIR 8   = CIRCLE/ WITH, CTR AT, PNT B, RADIUS, +.5, INCH
           WITH, TL RGT, GO RGT, ALONG/ LINE 3
           GO RGT, ALONG, LINE/ LEFT, TAN TO, CIR 8, LEFT,
           TAN TO, CIR 7
CIR 9   = GO RGT, ALONG, CIRCLE/ WITH, CTR AT, PNT A,
           RADIUS, 6, INCH
CIR 10 = CIRCLE/ WITH, CTR AT, 5, 0, 0, RADIUS, +.5, INCH
           GO RGT, ALONG, LINE/ LEFT, TAN TO, CIR 10, LEFT,
           TAN TO, CIR 8.
           GO RGT, ALONG/ LINE 3, UNTIL, TOOL, ON, LINE 1
           IN DIR/ PNT A
           GO TO/ CIR 9
           GO DLTA/ 0, 0, 4.5
           OF KUL, OF SPIN, GO TO/ SET PT
           END, FINI
REMARK - END OF INSIDE. TOOL SHOULD BE AT EXACT
           STARTING POINT
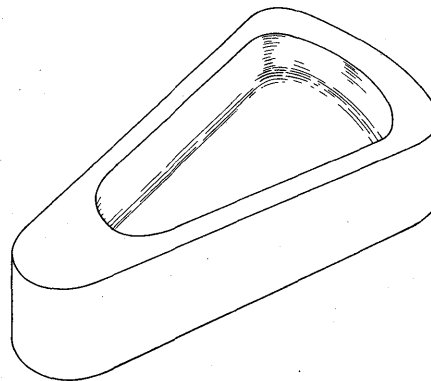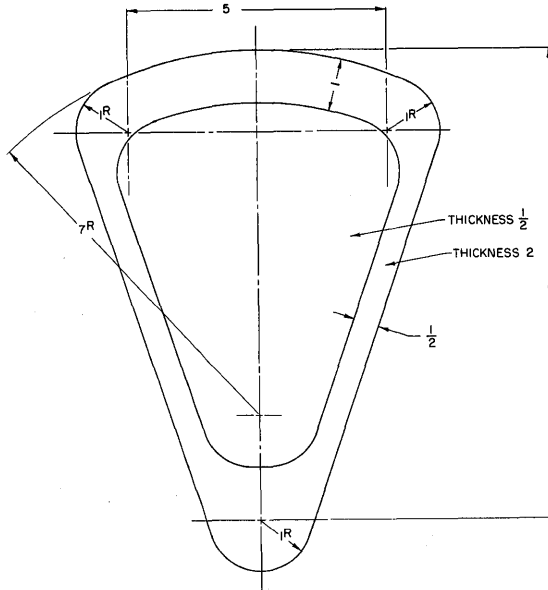
Fig. 2-7 Part Program and Specifications

the part is symmetrical, is sufficient for construction of part programs using the input language of the APT system. No mathematical calculations are required except for an occasional addition or subtraction of numbers.

A detailed derivation of part programs for producing the rocker arm cam are given in Volume II, The APT Part Programmer's Manual, but for introductory purposes, a completed part program is given here with the accompanying illustrations showing the geometric constructions. The point to be emphasized is that even with no preliminary discussion the reader will find that almost all of the statements in the APT language are immediately understandable to him. Certain abbreviations such as TL RAD for "tool radius", FEDRAT for "feedrate", CTR AT for "center at", etc., are easily understood. Most of the others such as TN CK PT represent less mnemonic features of the language which will rapidly be obsoleted as the system grows, since they represent operations which could be performed automatically by slightly more sophisticated data processing within the APT system. But until these techniques are actually incorporated into the system, the part programmer is required to indicate his preference by writing the appropriate statements.

We also should note the free use of symbolic names for geometric quantities. Many of these lines and circles have no relation to the finished part but are merely the results of simulated constructions with ruler and compass in order to locate implicitly defined points and lines. One final comment will facilitate the reading of the sample part program. The statements should be read down the major column, ignoring the symbolic names which are assigned on the left, until they are called for by subsequent statements.

CHAPTER 3

THE SYSTEM OF COMPUTER PROGRAMS

The complex data processing required to transform the instructions
for the production of a part from the English-like APT language into the
detailed numerically coded machine tool director control tape is carried
out by a collection of programs operating on a general purpose digital
computer. These computer programs have been coded for the IBM 704
computer, and could similarly be coded for any general purpose compu-
ter of sufficient capacity, but the particular computer used is not of
importance, since the APT system programs actually simulate a speci-
ally designed APT computer which is well suited to the part programming
task. In other words, the collection of computer programs which repre-
sent the APT system in effect transform the general purpose computer
into a special purpose computer which is particularly well adapted to the
part programming process. It accepts directly the APT language state-
ments as input and produces automatically the appropriate type of
numerically coded control tape. The user of the system need have no
knowledge of computer programming or any of the allied topics, since
the APT language, backed up and made meaningful by the capabilities of
the programs which simulate the APT computer, is sufficient for all of
the required part programming tasks. In this chapter we consider in
general terms the main portions of the simulated APT computer and how
they work together to accomplish the required data processing task.
More detailed information concerning the operation and design of these
programs may be found in other volumes of the APT documentation.

3A. PHASES OF APT SYSTEM OPERATION

The operation of the APT system breaks conveniently into three
principle phases, and these phases are reflected in the major computer
program sections, and therefore in the organization of the simulated
APT computer. Not only must the APT system bridge the gap between
the greatly different languages of the human part programmer and the
numerically controlled machine tool director, but in bridging the gap it

must perform many types of complicated data processing. In the <u>input</u> <u>translation phase</u>, operations are concerned primarily with the translation of the part programming problem from the human terms of statements in the APT language into the more detailed and restricted form required by the calculating routines of the system. In the <u>calculation</u> <u>phase</u>, the geometric and tool sequencing specifications are transformed into numerous incremental cutting tool motions so that the desired part will be produced to the required tolerance by means of short straight line cuts. The <u>post processing and output phase</u> is concerned with the problem of translating the sequence of tool centers calculated by the calculation phase into the required machine tool director language and making sure that the resulting tool path in space-time is within the dynamic capabilities of the machine tool control system. The separation of the data processing into these three phases permits the important and lengthy calculating part of the problem to be phrased in terms which are most appropriate to the computer, and yet flexibility is maintained at both the input and output ends, permitting the human part programmer great latitude in his choice of statements and also permitting the same basic APT system to service many different kinds of machine tool director systems.

The main programs which constitute the APT system are shown in Fig. 3-3. We now proceed to a brief description of the purpose of these various routines and how they are interconnected. The general features of each routine are also discussed since a true understanding of the system, including its present limitations as well as its capabilities, can best be achieved by considering the broad characteristics of the routines out of which the system is constructed.

3A.1 <u>The Input Translation Phase</u>

The operations of the input translation phase are accomplished by three main programs, the Input Translation Program (INTRAN), the Instruction Preprocessor Program (INSPRE), and the Definition Preprocessor Program (DEFPRE). These three programs perform the essentially distinct functions of preliminary recognition of APT statement structure, transformation of machining instructions into computer terms, and transformation of definitions of geometric shapes and quantities into

TRANSLATION
PHASE

INPUT TRANSLATION PROGRAM (INTRAN)

Translates APT statements by looking up words in appropriate "dictionaries" and placing dictionary entries in storage blocks.
Storage of translated words depends upon statement punctuation.
Establishes table of assigned symbolic names to be used as additional dictionary for subsequent statements.
Checks legality of spelling and statement format.

DIAGNOSTIC PROGRAM (DIGNXT)

Uses diagnostic print routine to control on-line and/or off-line printing of comments and core portions for diagnostic purposes in accordance with instructions from each program.

INSTRUCTION PREPROCESSOR PROGRAM (INSPRE)

Scans tables of translated words supplied by INTRAN and generates appropriate APT instructions for CONTRL. Some words call for several APT instructions and vice versa. Some instructions depend upon words from several APT statements.
Organization of INSPRE makes word sequence of little importance.
When geometric quantities are defined, INSPRE transfers control momentarily to DEFPRE to transform the data into canonical form. DEFPRE returns control specifying the location of the canonical form data.
Sequence of APT instructions stored as APT program for execution by CONTRL.

DEFINITION PREPROCESSOR PROGRAM (DEFPRE)

Transforms geometric definitions into canonical form.
Assigns starting address to each canonical form and stores for use by other programs.

TAPE STORAGE

Canonical forms of geometric elements of part shape

TAPE STORAGE

Motion, part surface, check surface and modifier instructions
Status modifiers
Parameters
X-codes

CONTROL ELEMENT PROGRAM (CONTRL)

Directs operation of ARELEM by executing instructions received from the translation phase.
Separates APT instructions received from INSPRE into classes and sets up arithmetic element for execution of each instruction as directed.
Determines legality of prefix of each class.

TAPE STORAGE
Feedrates
X-codes

CALCULATION
PHASE

LIBRARY OF SURFACE SOLUTIONS

Finds unit normals and directed distances on stored surfaces.

ARITHMETIC ELEMENT PROGRAM (ARELEM)

Performs elementary calculation of APT system, calculates cutter locations, and stores these cutter locations on tape for subsequent use by post-processor program.

TAPE STORAGE
Cutter locations

POST PROCESSING
and
OUTPUT PHASE

POST PROCESSOR PROGRAM

Prepares output of calculation phase for the numerical control director of the particular numerically-controlled machine tool.
Using X-codes, feedrates and coordinate data, the program slows down or speeds up cutter movements as cutter approaches or leaves corners.
Stores resulting command times, incremental distances, X-codes, commands and synchronization periods on tape.

TAPE STORAGE
Machine tool instructions

OUTPUT TRANSLATOR

Translates output of IBM 704 computer on tape suitable as an input to the numerical-control director of the particular machine tool to be controlled.
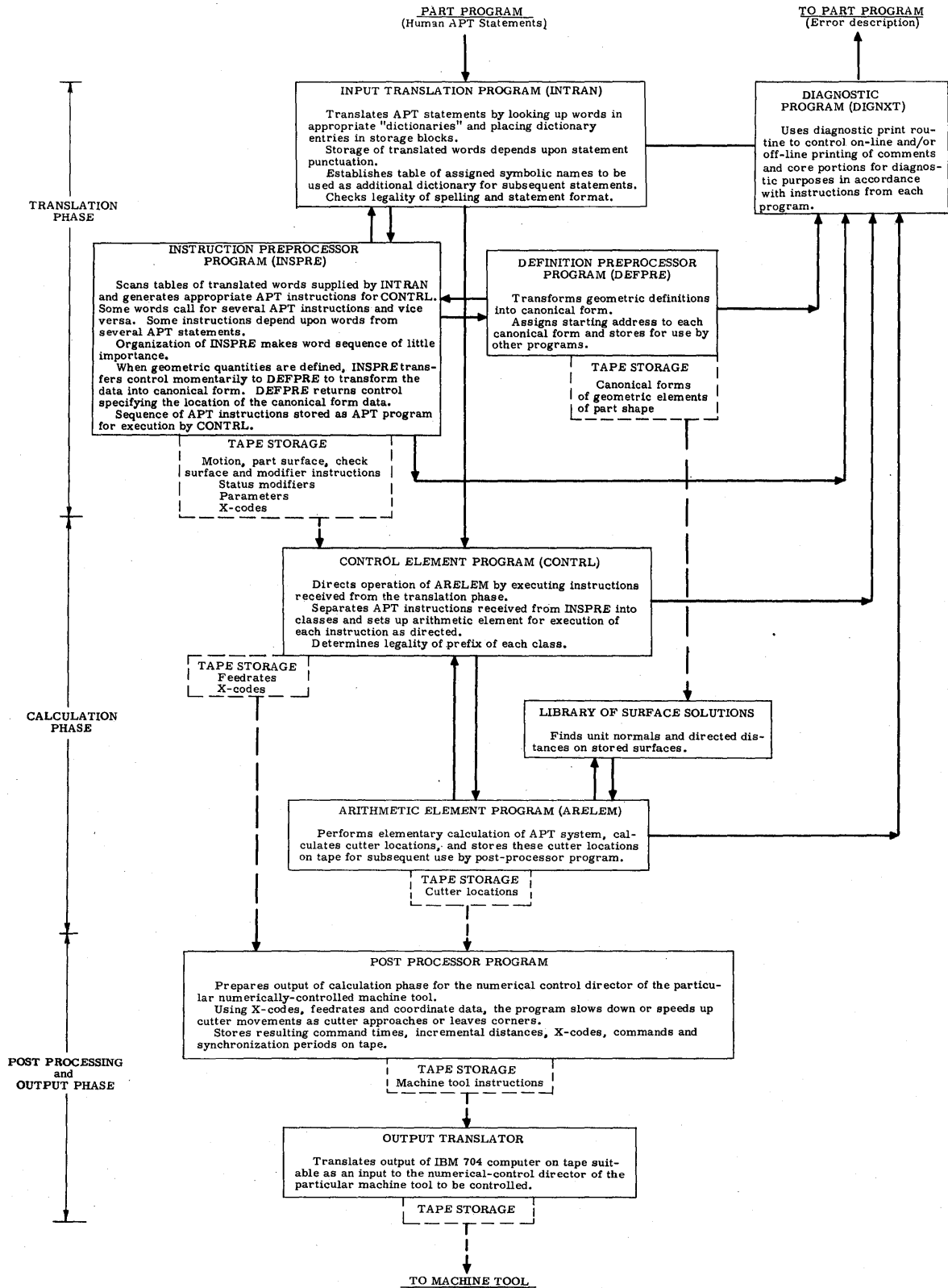
TAPE STORAGE

TO MACHINE TOOL

Fig. 3-3 APT System Programs

numerical forms which can be used by the calculating programs. Therefore, the input translation phase programs serve the important function of preparing the part program specifications written in English-like APT statements into computer terms which can be used by the programs of the calculation phase.

In operation, the Input-Translation Program examines the APT statements one at a time, looks up the words in a "dictionary" and sorts out various types of translated words into suitable categories. When it has completed its operation for one APT statement, it transfers control to the Instruction Preprocessor Program which then completes the translation of the meaning of the APT statement from human to computer terms. When necessary the Instruction Preprocessor Program calls upon the Definition Preprocessor Program to handle any numerical calculations required to transform geometric data from the form given by the human part programmer into the fixed canonical form required by the calculation programs. The resulting output of the input translation phase, therefore, is a sequence of numerically coded instructions in computer terminology, called the translated APT program, and a sequence of canonical form data for any geometric elements of the part shape which have been defined in the APT statement. The input translation phase continues with an interplay between INTRAN and INSPRE, with INSPRE calling upon DEFPRE when necessary, until all of the statements in the part program have been processed and the translated part program block and the canonical form block contain the complete information for the production of the part. When the Instruction Preprocessor recognizes the end of the part program, it transfers control to the next set of programs which constitute the calculation phase.

3A.2 The Calculation Phase

The operations of the calculation phase are carried out by the Control Element Program (CONTRL) and the Arithmetic Element Program (ARELEM), making use of additional routines from the Library of Surface Solutions as required. Just as an ordinary general purpose computer contains a control element which directs the operations of the various portions of the computer, and an arithmetic element which

actually carries out addition, subtraction, and other mathematical and logical operations, the simulated APT computer accomplishes its calculation task by an interplay between the Control Element Program and the Arithmetic Element Program.

The Arithmetic Element Program is a generalized program which is capable of moving a cutting tool of arbitrary shape along the curve, in three-dimensional space, defined by the intersection of any two surfaces. This generalized program is particularized to solve any specific problem of this type by the action of the Control Element Program. The Control Element Program connects to the Arithmetic Element Program appropriate routines from the Library of Surface Solutions for the two surfaces and cutter shape, and a third surface which indicates the end of the curve segment, after which the operation of the Arithmetic Element Program is fully automatic. The Control Element Program is again called upon to set up the next curve when the end of one curve segment is reached. This action is very similar to that found in the general purpose computer in which the control element sets up the interconnections required to specify the location of two numbers which are to be added together and then instructs the arithmetic element to perform the addition. The arithmetic element performs its task automatically and once the addition is complete it again calls upon the control element for the next instruction. As will be described in more detail in a later section, this construction of the Arithmetic Element Program so that it is independent of the particular surfaces involved is one of the most important features of the APT system since it gives the system essentially unlimited capabilities. The operation of the Arithmetic Element Program results in the calculation of a sequence of cutter location coordinates which, when connected by straight lines, will cause the cutting tool to machine the specified curve to the required tolerance. The Control Element intersperses among these cutter locations the appropriate feedrate and special machine tool director function codes, so that the output of the calculation phase is a sequence of machine tool director instructions in computer terminology and format.

3A. 3 The Postprocessing and Output Phase

It is the task of the postprocessing and output phase to perform yet another language translation to transform the machine tool director information from computer terminology into the particular numerical codes required by any one of a number of machine tool director systems. For each type of director system, there is a Postprocessor Program and an Output Translator Program which are especially written to match the characteristics of the machine tool director system. The Postprocessing Program checks the successive cutter locations and the feedrate specified by the programmer to make sure that the resulting broken line path in space will be within the dynamic capabilities of the machine control unit. If the Postprocessor Program discovers that excessive overshoot will occur at corners, it automatically modifies the output data to slow the machine tool down, overriding the programmed feedrate, so that the machined part will meet the specified tolerance. Some Postprocessors also interpolate additional cutter locations between those calculated by the calculation phase if they are required by the director system. Once the postprocessing operations are complete, the Output Translation Program transforms resulting data into the particular binary coded numerical format which will be acceptable to the machine control unit. The final conversion of this information into punched paper tape is performed by auxiliary equipment, and not by the computer programs.

3B. MAIN PROGRAMS OF THE APT SYSTEM

The APT system is composed of a number of main program sections, each with a characteristic job to do. In this section we introduce these main programs by name, and describe in general terms what they do and how their individual actions interrelate to perform the overall automatic programming function.

3B. 1 The Input Translation Program

In order to simplify the distribution of the computer programming load among the cooperating companies in the Joint Effort, the input translation phase of the APT system operation was broken into three

main functions carried out by the INTRAN, INSPRE, and DEFPRE programs. An additional benefit of this approach is that the resulting translation system is inherently easy to modify and adapt to new circumstances. Only relatively simple linkage is involved between the programs, and each performs its task in its own manner. Input to the Input Translation Program consists of the alphabetic and numeric characters of the APT statements which comprise the part program on punched cards. Output of the program consists primarily of two tables, the translated modifier table, and the translated parameter table. The translated modifier table contains the dictionary entries which are to be processed primarily (although not exclusively) by INSPRE, and the translated parameter table contains similar information which is to be processed primarily (although not exclusively) by DEFPRE. The translated modifier and parameter tables are constructed in a very straight forward manner by INTRAN. The program examines each word or combination of letters appearing between punctuation characters and scans through several dictionaries until the word is found. If the word is not found, the program calls for a descriptive printout by the diagnostic program, but continues to search for further errors. In most cases, however, the word will be found in a dictionary, in which case the "translated" version associated with that word in the dictionary is stored in the appropriate table. At the end of the operation of INTRAN the translated modifier and translated parameter tables contain the same information that appeared on the original APT statement card, but in computer terminology. Numerical information from the punched card is translated into the computer's number system and stored in one of the tables just as though it were an ordinary word. The dictionary entries corresponding to words in the APT vocabulary are usually skeleton versions of the corresponding APT instructions which the Control Element Program will execute. In this way the operation of the Instruction Preprocessor Program is simplified, since it is necessary only for it to complete the skeleton instruction to finish the translation phase. When the Input Translation Program has translated all of the words in an APT statement into computer terms, and constructed the translated modifier and translated parameter tables, it transfers control to the Instruction Preprocessor Program.

3B.2 The Instruction Preprocessor Program

It is the job of the Instruction Preprocessor to complete the translation of the part program from APT statements into a sequence of coded information in computer terms which will be understandable to the Control Element Program. There are many facets to the operation of the Instruction Preprocessor. In general the completion of the translation consists of recognizing words or word combinations in the translated modifier table and setting up portions of the Instruction Preprocessor Program so that the appropriate APT instructions, understandable to the Control Element Program, will be generated. The operations are performed in this sequence rather than on a word by word basis for two principle reasons. One reason is that since the translation into computer terminology is not one-to-one, it would not be possible to perform all necessary operations in one step since some of the required information is contained in different portions of the APT statement and sometimes in other APT statements. The other reason is that by setting routines to generate the appropriate instructions and then generating all instructions at the same time, the particular sequence of words in the APT statement is in general not of importance, since the required sequence is built into the order in which the generating routines are executed. Thus, considerable flexibility in the input language is made possible with essentially no increased complexity in the APT system.

The construction of the translated version of words stored in the dictionaries of INTRAN is such that it is not necessary for INSPRE to examine them in detail since entire classes of words can be processed in the same fashion. Whenever a word is encountered which calls for a definition of a geometric quantity such as a point, circle, ellipse, etc., the Instruction Preprocessor Program transfers control momentarily to the Definition Preprocessing Program which takes over the preprocessing of the remainder of the entries in the translated parameter table. When it has stored the data in the required canonical form it returns control to INSPRE along with the location at which the data has been stored. This information may be used to complete an APT instruction which is being generated as a result of the current APT statement, and in addition it may be passed back to the Input Translation Program for

insertion into the variable dictionary of symbolic names so that later APT statements can refer to the data merely by name.

The Instruction Preprocessor also controls the termination of the translation phase of APT system operation. When the word FINI is encountered, the Instruction Preprocessor knows that the part program is complete. If no catastrophic errors have been discovered (and reported by use of the Diagnostic Program), then the Instruction Preprocessor will automatically cause the translation phase to be terminated, and will transfer control to the Control Element Program.

3B.3 The Definition Preprocessing Program

The Definition Preprocessing Program is actually a collection of specialized routines which transform specifications for geometric quantities into the fixed canonical form required by the subprograms of the Library of Surface Solutions. For each geometric quantity which is included in the vocabulary of the APT system, there are many possible ways of specifying sufficient conditions to define the quantity uniquely. For example, a circle may be specified by center and radius, or passing through three points, or tangent to two lines with a specified radius, etc. In order to provide flexibility in the part programming language, and in order to minimize the number of operations which the part programmer must perform, the APT system is designed to permit many possible definition forms to be used for each type of geometric quantity. In this way, no matter how the part programmer thinks of a geometric quantity he can usually find a simple means for expressing the specifications directly in the APT language. The canonical form of the data (the center and radius for a circle) is chosen to be that form which will result in the most efficient calculations in later parts of the APT system. Therefore, the Definition Preprocessing Programs transform data from any one of many possible forms into the single canonical form for the particular type of geometric quantity.

In the initial APT system the organization of the Definition Preprocessing Program is that of a library of subroutines and a dispatcher which selects the appropriate routines depending upon the format of words, found in the translated parameter table, and the name of the geometric quantity, found in the translated modifier table. Once the

data from the translated parameter table has been transformed into the canonical form, the results are stored in sequence in the canonical form block of storage. In some cases the canonical form data is actually stored in the sequence of APT instructions generated by the Instruction Preprocessor rather than in the canonical form block in order to increase the capacity of the system. Once the data has been stored, the Definition Preprocessor returns control to the Instruction Preprocessor along with the location at which the canonical form data has been stored.

3B.4 The Control Element Program

When the translation phase of operation of the APT system is completed the calculation phase begins. The first program which operates is the Control Element Program whose functions are to set up the connection of appropriate routines from the Library of Surface Solutions to the Arithmetic Element Program, set up various modes of operation of the Arithmetic Element Program, and then initiate its operation. The Control Element Program obtains its instructions by interpreting the sequence of APT instructions in the translated part program which has been generated by the Instruction Preprocessor. The instructions are examined one by one and the meaning of various portions of the instruction word are determined by the settings of other portions. The meaning of APT instructions as they are executed by the Control Element Program is considerably different from the meaning of the words in the APT statement which led to their generation by the Instruction Preprocessor. Rather than geometric quantities and logical instructions, the translated APT instructions are concerned with setting address locations, transferring blocks of data, setting indicator digits in control words, and various other detailed operations which are concerned directly with the manner in which the other programs of the calculation phase are constructed. Many operations which have greatly different meaning in terms of geometric operations are efficiently handled in exactly the same routine fashion by the Control Element Program. When all of the various interconnections and set up operations called for by the APT instructions have been completed, the Control Element encounters an instruction which causes control to be transferred to the Arithmetic Element Program so that a segment of calculations can be executed. The logical decisions

necessary to insure that all setting operations are done in the appropriate sequence before calculations begin, are carried out by the Instruction Preprocessor. By the time the Control Element Program gets into operation it can proceed automatically and at high speed on a single sequence of well-defined tasks, without considering possible alternatives.

3B.5 The Library of Surface Solutions

Before describing the operation of the Arithmetic Element Program we first consider the construction of the Library of Surface Solutions. The APT system is actually a three-dimensional program so that even two-dimensional quantities are stored as three-dimensional surfaces. For example, a line is actually stored in canonical form as a plane; a circle is stored as a cylinder, etc. For each type of surface the Library of Surface Solutions contains two general subroutines called the normal vector program and the directed distance program. Normal vectors and directed distances are two fundamental properties of all surfaces.
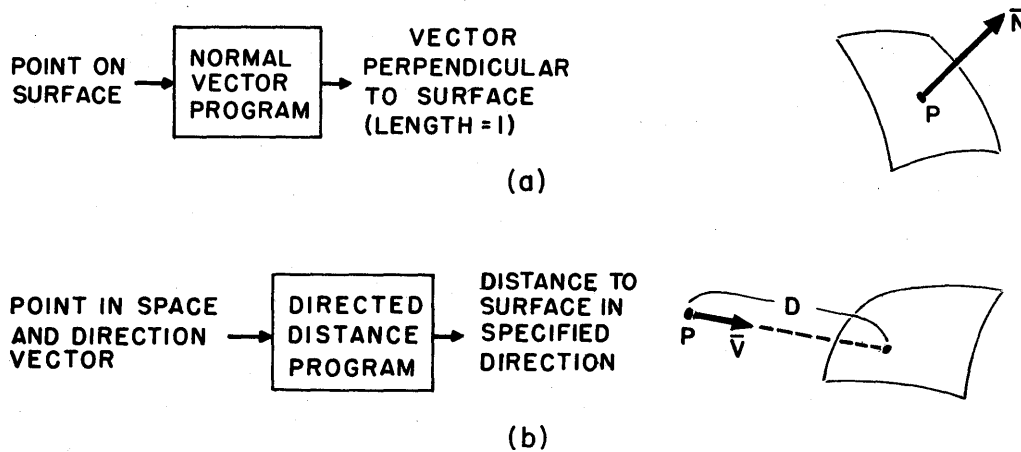

(a)

(b)

Fig. 3-11 Normal Vector and Directed Distance

As shown in Fig. 3-11a, for a given surface specified by a set of data in canonical form, the normal vector subroutine calculates a vector of length one, perpendicular to the surface at any specified point. As shown in Fig. 3-11b, the directed distance program calculates the distance from

a specified point to the surface in a specified direction.

Although the various normal vector and directed distance subroutines are written in different ways depending upon the equations for the various surface types, they all have a common input format. Therefore, the linkage between the Arithmetic Element Program and any one of the subroutines can be handled in a standardized fashion by the Control Element Program. In order to add new surfaces to the APT system, it is necessary merely to observe these linkage conventions and write the appropriate normal vector and directed distance subroutines. It is quite probable that in the near future a general purpose iterative subroutine will be written which will calculate normal vector and directed distances for any surface, given an additional subroutine to calculate points on the surface. In general, however, for surfaces which are to be used frequently, greater computing efficiency can be achieved by writing special purpose subroutines which can take advantage of the particular characteristics of the surface equations.

3B.6 The Arithmetic Element Program

The central program in the APT system, the one for which all of the other programs are either preparation or conclusion, is the Arithmetic Element Program. It is here that the many factors of geometry, tool shape and size, and tolerance are taken together to produce incremental motions of the cutting tool which will result in the machining of the desired part to specified tolerance. The intersection of two three-dimensional surfaces is a three-dimensional space curve. The Arithmetic Element Program performs the calculations necessary to move a cutter of arbitrary shape along a space curve so defined, automatically supplying the appropriate offset with respect to one or both of the surfaces. The calculations are performed entirely in terms of normal vectors and directed distances, so that as long as these quantities can be calculated by routines in the Library of Surface Solutions, the surfaces involved are completely arbitrary. It is this feature which gives the APT system its great capability for expansion. In order to cut an entirely new class of space curves it is necessary only to add the appropriate normal vector and directed distance subroutines to the Library of Surface Solutions. The difficult part of the calculating program has been solved once

and for all in the systematized solution of the Arithmetic Element Program. This is not meant to imply that the present Arithmetic Element Program cannot be improved upon, since plans are already underway for more refined calculations than those of the initial system, but the comtemplated changes are for the improvement of overall system performance and do not depend upon particular surface characteristics.

How does the Arithmetic Element Program perform its task? How is it possible to write a routine to calculate motions over surfaces without regard to those surfaces? The answer lies in the word "approximation". The entire numerically controlled machining operation is, of course, one of approximation. Desired curves are always approximated by sequences of more elementary curves. The fact that approximations are used makes possible the systematized solution of the Arithmetic Element Program, since one generalized routine can be written which will satisfactorily approximate the solution to an entire class of problems. By careful derivation, it is possible to reduce the variability among the various problems which are to be solved so that the primary skeleton solution, which is common to all problems, contains almost all of the difficult aspects of each problem, and only simple details need to be filled in to solve any individual problem. In the case of the systematized solution of the Arithmetic Element Program, the detailed operations are embodied in the necessary connections to the normal vector and directed distance subroutines.

As shown in Fig. 3-14, the calculating procedure of the Arithmetic Program involves two principle iterations in its innermost calculating loop. Motion along a curve in space, defined by the intersection of the part surface and the driving surface, is accomplished in a step-by-step manner. The length of each step is determined by the required tolerance and the curvatures of the two surfaces. The point of calculation shown in Fig. 3-14 is essentially used to scout out the conditions along the desired curve. Before a stepping of the tool control point itself is made, the point of calculation is moved out along the tangent to the curve by an amount determined by the curvatures, and then the point of calculation is forced back to the curve by a zigzag iteration, jumping back and forth between the part and driving surfaces. When the point of calculation has

converged back to the curve, then the normal vector and directed distance programs for the surfaces are interrogated to determine the surface conditions at that point. Then with sufficient knowledge about the surfaces,
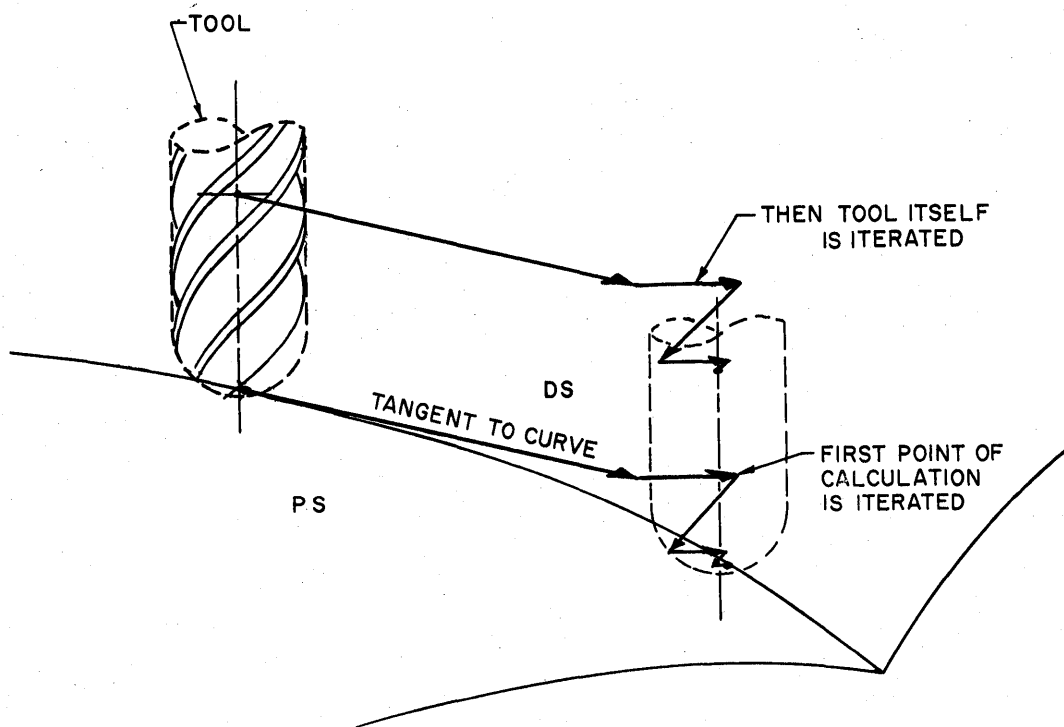
Fig. 3-14 Basic Calculation Iterations

the tool itself is stepped forward and another zigzag iteration is performed, this time bouncing the tool shape alternately between the driving and part surfaces. The tool shape itself is determined in a manner very similar to the directed distance by the so-called directed cutter radius routine. In this way many different shapes of tool can also be accommodated by the Arithmetic Element Program. When a stabilized tool position is found, the coordinates of the tool control point are stored away for the later postprocessing programs and the sequence is repeated again for the next step along the curve. The actual motion of the cutting tool will be straight lines connecting these stored points.

Needless to say the description of the preceding paragraph is greatly simplified, but in essence the operation of the Arithmetic Element Program consists of the calculation of each incremental tool motion as

3-14

described above. It is necessary, however, for the program to check when motion along one space curve should be terminated in order to begin the cutting of another curve segment. For this purpose another set of routines are incorporated called the check surface calculation. The termination of the cutting of one space curve is specified by the check surface. It is possible, depending upon the conditions of the "corner" between successive space curves, that the tool should move until it just touches the check surface or until it has passed through the check surface and is touching on the other side with the trailing side of the tool as illustrated in Fig. 3-15. Once the Arithmetic Element Program detects that the appropriate condition has been met, it transfers control back to the Control Element Program so that the necessary subroutine connections, etc., for machining the next curve can be set up.
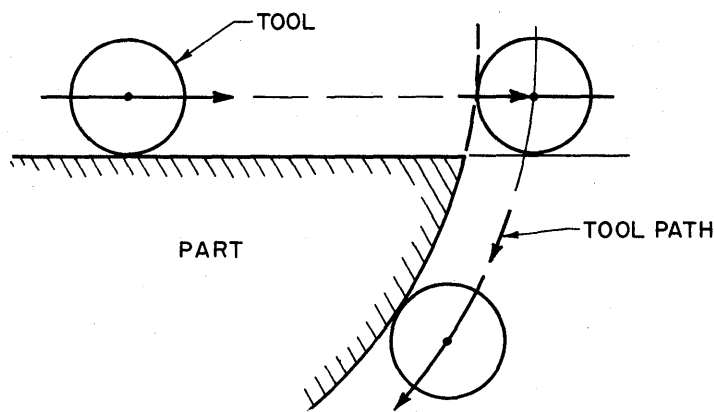
Fig. 3-15 Illustration of Tool PAST

The machining of an entire part proceeds automatically with the transfer of control back and forth between the Control Element Program and the Arithmetic Element Program until the Control Element Program encounters instructions stating that the part is completed. At this point, the Control Element Program transfers control to the appropriate Post-processing and Output Programs, and the third phase of APT system operation takes over.

3B.7 Postprocessing and Output

The output from the calculation phase is a magnetic tape storage block containing the sequence of tool center locations as calculated by

the Arithmetic Element Program. Interspersed among these tool centers are special instructions concerning feedrates and control of auxiliary functions which have been inserted at the appropriate time by the Control Element Program. This sequence of data constitutes the input to the postprocessing and output phase. For each type of numerical control director system there is a different Postprocessing Program and associated Output Program which transform the data into a numerically coded control program suitable for input to the director system.

The tool centers which have been calculated by the Arithmetic Element Program satisfy the mathematical tolerance conditions specified by the part programmer in the APT language program, but may not be directly suitable for particular types of machine tool directors. Similarly the feedrate information specified by the part programmer may be excessive so that the task of the Postprocessing Program is to insure that suitable tool center locations and feedrates are generated so that the part can actually be produced to the required tolerance specifications. All machine tool control systems are servomechanisms controlling massive members of the machine tool itself. Any such control system has performance limitations, and if an attempt is made to turn a corner at too high a speed, overshoot will result which could damage the part or the machine tool itself. The dynamic characteristics of the machine tool and director system are represented in the Postprocessing Program by a set of equations and conditions. Each pair of incremental tool motions must be checked against these criteria, and feedrates must be modified if necessary. Most directors also have a limitation on the amount of acceleration or deceleration which can take place within a given interval. Therefore, it is sometimes necessary for the Postprocessing Program to interpolate additional tool center points when modifying feedrates. In general, the operation of the Postprocessing Program is to tailor the output of the calculation phase so that the resulting instructions are acceptable to the director characteristics.

For any director system, the Output Program has the intricate but straightforward task of scaling and transforming the numerical output of the Postprocessing Program into the particular numerically coded language of the machine tool director. Since most directors have a

punched tape input, whereas the IBM 704 computer produces punched cards, the Output Program actually translates the information into a form acceptable to a card-to-tape converter, and the actual conversion process is carried out off-line and not on the computer.

3B. 8 The Diagnostic Program

Although many of the individual steps are simple, the overall data processing task performed by the APT system is one of great complexity. There are many possible sources of error and an important adjunct to the system is the Diagnostic Program which reports error information in easy-to-read form. The Diagnostic Program itself is a generalized computer output program which is capable of collecting numbers and data from arbitrary locations in the computer, printing these out in various formats along with descriptive English or APT language statements. The control routine for the Diagnostic Program in any particular application is located within the source program in which the error occurs. When difficulty is encountered, control is transferred to the Diagnostic Program which then interprets the instructions specified in the source program, collects the appropriate data, arranges it for readable format, and incorporates appropriate labelling information and comments.

Although present use of the Diagnostic Program is relatively limited, it is planned that the same set of instructions will cause the Diagnostic Program to produce three separate outputs, one for the part programmer, one for the computer programmer, and one for the computer operator. The computer operator printout will be quite limited and will consist primarily of instructions concerning the next operating step printed on the on-line printer of the computer. Therefore, if the program should stop when an error occurs, the diagnostic printout will instruct the operator what action to take next. The part programmer's printout will be restricted to information which is directly in English or in APT language format which will be immediately understandable to the part programmer. For any detailed information concerning the internal workings of the APT system, the printed comment will suggest that the part programmer consult with the computer programmer. The computer programmer's printout will be the most elaborate and will contain detailed information at the computer coding level when necessary to assist in uncovering the source of difficulty.

CHAPTER 4

FUTURE DEVELOPMENTS

The preceding chapters have described the language and programs of the initial version of the APT II system. From the beginning it has been recognized that the development of APT systems through the Joint Effort would be a continuing evolutionary process in which the capacity of the system would be increased within certain areas of capability, with occasional revolutionary innovations opening new areas of work. In this chapter a few of the highlights of projected future expansion are described to provide an indication of the potential of the APT system. No claim to completeness is made, and the sequence in which topics are discussed is not intended to imply any sort of priority, since in fact it is possible that future developments will take an entirely different course than that which is outlined here. One firm prediction is possible, however, based upon past performance of individuals and techniques. The APT system will expand both in technical capabilities and philosophical outlook, and will be an effective force in increasing our productive capability and efficiency.

Future developments of APT system capabilities may be divided into several categories. Some will be the routine refinements associated with any experimental development, while others will represent technical advances of startling implications. Some will be made merely for the sake of data processing efficiency, while others will automatize entire new classes of operations. In general the modifications and alterations to the APT system will range over the entire spectrum from the mundane to the spectacular. The potential is there--in the APT system structure and in the APT Joint Effort- in the machines and in the men--for as much or as little development of automatic production techniques as the industrial community desires to support. Progress will probably be sporadic, and at times possibly even discouraging. But with a growing body of technical experience and competent personnel schooled in the stimulating atmosphere of far-reaching developments, the long term trend can only be upward.

4A. REFINEMENT OF EXISTING TECHNIQUES

The initial version of the APT II system is capable of producing a great variety of complex parts in two or three dimensions using several machine tool director systems. It is, however, only an initial system and extensive additions, improvements, and refinements can be made to do still more jobs better. As mentioned previously, the system is purposely designed so that new surface types can be added at will merely by inserting the appropriate normal vector and directed distance subroutines. There are already a number of such new surface routines which are virtually ready for inclusion into the system, including surfaces specified by an arbitrary mesh of points in three-dimensional space and surfaces described by sequences of conic sections which are suitable for handling complex air-foil shapes. If it is recalled that any two surfaces can be intersected to give a space curve, it is clear that with the addition of these routines, and others of a similar nature, very intricate curved parts in space can automatically be made by the APT system.

In addition to entirely new surface types, plans are already under way towards increasing the number of ways in which surfaces can be specified. The expansion of this definition preprocessing capability is of the utmost importance to the usefulness of the system, since the more definition preprocessing facilities which are available the less mental translation is required of the part programmer and the more efficiently he can use the system. These changes will also, of course, call for a corresponding increase in the language capability of the APT system.

New tool shapes can easily be incorporated into the system if the appropriate directed cutter radius routines are written. Post processing and output programs will also be written to permit the use of the APT system with many new machine tool director systems. Some of these director systems may call for changes in the calculating programs, in order to take full advantage of more complex interpolation features of the directors, or because the directors control angular rather than linear variables. The present APT system calculates for tool motion in the three cartesian coordinate directions X, Y, and Z, whereas certain spar mills and lathes will involve angular control instead. Similarly,

five axis control will be added in which the cutting tool can be tilted through two angles simultaneously with other motions.

Although the initial APT II system contains an elaborate diagnostic program for reporting information to the part programmer, the computer programmer, and the computer operator, space limitations in the computer have made it necessary to use the program in only the most limited fashion. A highly important development in establishing the usefulness and efficiency of the APT system will be the incorporation of complete control programs for reporting and diagnosing difficulties with the system. With increased experience with the system in operation, the diagnostic information should become successively more pertinent and helpful. In this way the learning curve of experience gained from the use of the system in many installations can be made common to all users so that maximum utilization of the system capabilities can be made to everyone.

In addition to refinements which add to the initial system capabilities there are many places in the programs of the system which can be improved. Certain geometric combinations can cause iterations not to converge or to converge extremely slowly, and improved calculating techniques are already well along in development. Efficiency in operating the system can also be improved by further experience. Another characteristic of the system programs which is of fundamental importance, but not apparent on the surface, is that a great many of the routines contain parameters or criteria which are intimately related to the calculating speed, since they affect the number of iterations which are performed at various places. Some of these parameters also affect the precision at which answers are calculated. Since it is impossible to determine analytically the optimum settings for these numerous parameters and criteria, system performance must be "tuned up" experimentally to determine the optimum balance between acceptable precision and maximum computation speed. Sometimes the changing of a single parameter by only a relatively small amount can double the calculating speed of the system without noticeably affecting the precision of results. Since most of these parameters have been set conservatively to ensure correct system operation initially, considerable improvement in computing speed

can be anticipated as more appropriate settings are found from experience.

4B. ADDITIONAL CAPABILITIES

A number of very useful techniques were purposely omitted from the initial APT system in order to conserve manpower. Completion of the initial system to the point where it can be placed into routine operation will make it feasible to turn attention to these additional capabilities which will greatly ease the part programmer's burden. One of the most important of these is the ability to transform from one coordinate system to another, since very frequently the coordinate system in which the original data for a part is presented is different from the coordinate system of the machine tool itself. There is some question concerning the point in the data processing at which transformation of coordinates should take place. Should it be at the very beginning between the reading of numbers from part program cards and input to the Definition Preprocessing Programs? Should it be after the definition preprocessing has been completed and before the canonical form data is stored for the calculating programs? Should it follow the operation of the Arithmetic Element Program before the postprocessing and output phase begins? These are important questions, since the usefulness of the coordinate transformation will depend strongly upon where it is applied. It seems probable, however, that it will be possible to incorporate a coordinate transformation scheme which can be applied at almost any selected point in the data processing procedure by taking advantage of the possibilities of introducing modifiers into the language which specify the range of applicabilty of the coordinate transformation instruction. If this is done, then once again the part programmer will be able to apply a powerful technique at the appropriate point without any pretranslation on his own part.

A large number of the parts which are scheduled to be made using the APT II system are essentially two-dimensional parts but frequently they include a number of three-dimensional characteristics. An example of this which occurs quite frequently is a pocket of a forging which must be cleaned out and which has a sloping and contoured bottom. If the sides

of this pocket become shallower than the radius of the tool which is used to cut out the pocket, then a problem arises which the present system is incapable of handling. The difficulty is that since the top of the work piece is lower than the corner radius of the cutting tool, the effective tool diameter is less than the actual tool diameter and appropriate compensation must be made. It appears that in order to solve this problem a limiting surface as shown in Fig. 4-5 must be introduced so that
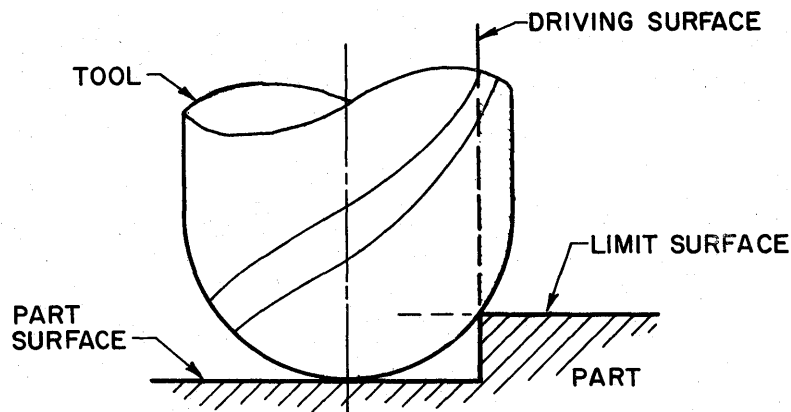
Fig. 4-5 The Limit Surface

the Arithmetic Element Program calculations must be modified to treat three surfaces, the part surface, the driving surface, and the limiting surface, in determining the appropriate tool position. These modifications are due for early inclusion in the APT system as well as a number of other limited three-dimensional techniques.

Quite frequently parts which are made by numerical control are actually machined twice, first with a rough cut using coarse tolerance to remove most of the material, and then with a finished cut to high tolerance and possibly lower feedrates to obtain the desired finish. Since the geometry for these two operations usually remains the same, it would be very desirable to be able to write one part program concerned essentially with the geometry and be able to use it more than once, changing tooling and feedrate instructions. For this purpose, logical instructions must be

4-5

added to the APT language vocabulary instructing the APT system to transfer control to a specified instruction. In this way one set of tooling information can be programmed followed by the geometric program and then a "jump instruction" can transfer control back to the beginning of the geometric program, but with different tooling instructions. Logical instructions of this type will also find additional uses in providing increased flexibility in the part programming language.

The definition preprocessing phase of APT system operation can also be improved by permitting definitions within definitions to be made. With this facility it would be possible for the part programmer to construct a geometric definition as he thinks it through without requiring that he first prepare all preliminary defintions and then use these preliminary definitions for the final geometric definition. The efficiency and reliability of an experienced part programmer can be greatly enhanced by such techniques. Accompanying such a change in the part programming language would be the ability to extract or reference a geometric definition which is embedded in another geometric definition. For example, it should be possible to call for the third point used in the definition of the circle whose symbolic name is CIR 3. *

Another addition which is urgently needed is the ability to automatically clean out pockets even though it may not be done in the most efficient manner. A rudimentary routine of this type for flat bottom pockets is quite easy to achieve and increased flexibility in this respect will be given by logical instructions of the type described previously. Associated with this problem is the idea of a decision surface, as distinct from an ordinary check surface. Recall that a check surface is always used in the Arithmetic Element Program calculations to determine the end point of one curve segment and the beginning of the next. The decision surface on the other hand would be supplied with a variable threshold distance so that as long as the tool is far away from the surface, one set of instructions is executed, whereas when the tool gets within a certain distance of the decision surface control is transferred to a different set of APT instructions. By programming suitable combinations of decision surface instructions with ordinary part programs, the automatic clean out of pockets of many shapes and with curved bottoms can

be accomplished.

An important addition to the facilities of the APT language will be the introduction of a macro-instruction facility. It will be possible to define an arbitrary symbolic name to stand for an entire APT program including the provision for substituting arbitrary symbolic names or numbers for quantities appearing in that program. In this way, for example, an extended sequence of machine tool director instructions calling for stopping and starting of various pieces of equipment, intermixed with the appropriate delays, can be set up with appropriate settings for a particular machine tool and then the entire complicated operation can be obtained in any part program merely by writing the single word calling for that program. Similarly, entire procedures concerned with definition preprocessing or geometric constructions can be made into a subroutine and called for by single macro-instruction. For example, the perpendicular bisector of a line between two points can be constructed by elementary geometry using a ruler and compass. An APT program for accomplishing the same result could be written using variable names for the two points and a single macro-instruction defined so that the perpendicular bisector for any two points could be obtained immediately merely by writing down the appropriate point information after the macro-instruction name. The generality of the macro-instruction concept makes possible almost unlimited variation in the APT language itself, since the exploitation of this facility depends only upon the ingenuity of the part programmer. It also will have important consequences in permitting individual installations to modify the APT system to suit their needs or to build in standard operating procedures reliably. For example, a set of instructions for a uniform method for beginning the cutting of a part could be written once and for all by the supervisor of a part programming section, and all part programmers instructed to start each part program by using one macro-instruction. In this way checking procedures and correct operation procedures can be automatically obtained without fear that an individual part programmer will forget and omit an essential step. Efforts will be made to also insure that all of the criteria and parameters which determine APT system performance are given names in the APT vocabulary so that they

can be changed from within an APT part program itself rather than requiring computer programming.

4C.   REGION PROGRAMMING

One of the most important extensions of the APT II system will be the inclusion of APT III capabilities. Recall that APT II means a system which is programmed in terms of space curves, whereas APT III refers to a system which is programmed in terms of entire regions of surfaces in three-dimensional space. Whereas it is indeed true that a surface region can be programmed in the APT II system by a succession of appropriately spaced curves, in an APT III system all that is required is the definition of the region, and the many repetitive passes of the tool are automatically calculated. Since many of the parts to be produced by numerical control are sculptured parts composed of curved surfaces, the addition of an APT III capability is of great importance.

The addition of an APT III capability calls for changes to the Arithmetic Element calculating routines. Also, the language translation portions of the system must be added to, since new terminology must be introduced for the purpose of defining regions and how they are to be cut. Experimental APT III Arithmetic Element procedures have been under development and test for some time, and a complete initial system based upon this research which will blend smoothly with the current APT II system is presently being written.

An important aspect of region programming using an APT III Arithmetic Element Program is that once the problem has been stated, the part programmer has no control over the actual tool path. Since the method does ensure that the tool path will result in the machining of the surface of the specified tolerance, in most cases the use of an APT III Arithmetic Element will be acceptable. In other cases, however, the part programmer may wish to have more control over the final surface finish, so that it seems likely that even with a full APT III capability it will be desirable to have some other means for conveniently program-ming regions in which the responsibility for placing individual passes of the tool rests with the part programmer. In this case what is desired is a semi-automatic means for successively modifying a collection of APT II

instructions to produce a sequence of related curved paths without having to specifically write out the instructions for each curve. This feature can be provided by means of macro-instructions and logical instructions of the type referred to previously. If instructions are added to the vocabulary for modifying individual numbers or parameters, then these instructions can be successively applied, through the use of a logical program, to a macro-instruction which includes all of the APT II part program for the general curve. By modifying surface parameters in this way, any curve may be distorted and shifted to yield sequential passes suitable to the regions involved.

In addition to features which pertain directly to region programming, the addition of APT III capabilities will make possible a number of additional system refinements. For example, a combination of region programming and three-dimensional part specification could lead to automatic calculation of feedrate on the basis of the volume of metal removed. In this case the geometry of the blank out of which the part is to be produced, whether it is a forging or a slab of metal, would be described by one set of instructions and the desired finished part by another set of instructions. It would then be possible for the system to compute the volume of metal removed as the cutter progresses and by taking account of the type of material, the cutting tool and other relevant factors, the feedrate could be manipulated to achieve a type of optimum cutting efficiency.

In general, APT III offers many possibilities but still contains many problem areas for which detailed solutions have not yet been derived. In addition to those previously mentioned, others which will need early solution are fairing or blending between surfaces, various types of finish control through the generalization of mathematical tolerance, automatic sequencing of multiple regions, and in addition a whole list of complex problems concerned with the verbal description of intricate relationships between surfaces in three-dimensional space. Although there are proposed methods for the solution of most of these problems much work remains to be done in the development and testing of techniques suitable for actual production use.

4D. INTEGRATION OF APT WITH OTHER SYSTEMS

It was recognized from the beginning that as the APT system grew in capability and performance, it would also grow in size. Therefore, an important part of the system is the Group Control Program which is now nearing completion. The Group Control Program is a program-handling program which automatically shuttles sections of programs and data between the very large capacity but slow speed storage of the computer and the moderate capacity high speed storage. The Group Control Program permits an arbitrarily large system of computer programs to be operated on a computer of limited storage capacity, automatically and with good computing efficiency. Not only will the Group Control Program be a necessary part of an operating APT system once the projected expansion of surface types and vocabulary take place, but the Group Control Program also makes possible the integration of the APT system with other automatic programming systems designed for computer programming. Many of these systems are in fact larger than the present APT system, and taken in combination they would exceed the high speed storage capacity of any existing computer. The Group Control Program makes it possible, however, to consider combining these systems into an integrated whole which will permit essentially unlimited flexibility in the APT system.

Even when the system is greatly expanded there will always be certain important part programming problems which lie outside the scope of the existing system. There will always be some part which is vital to the success of an important project and yet which is too complex for the APT system to handle or which contains features which would require drastic revision of the system. If it were possible to go conveniently from APT language to basic machine language or to a mathematical automatic programming language, then even these parts could be said to lie within the scope of the system. To be sure it would be necessary that the part programmer in this case be a computer programmer as well, but still these important jobs could be accomplished.

Another desirable feature of the combination of the APT system with other automatic programming systems is that the modification of the APT system itself, which is of course done by computer programming, would be greatly facilitated. It is hoped that this kind of multiple system operation will be a reality within the near future.

CHAPTER 5

THE APT DOCUMENTATION

5.A   PURPOSE

The purpose of the APT documentation is to provide complete information concerning the design, operation and use of the APT system. In any endeavor as large as the APT Project, in which many people are involved in the performance of a very complicated task, it is essential that good communications be maintained.   Day-to-day communications as necessary are maintained among the project members by letters, phone calls, project reports, coordinator reports, and periodic group meetings.   Once a given development has been completed, however, another extremely important communication problem arises.   In order for the new development to be used properly or modified to satisfy slightly different conditions, it is necessary that complete information be written down in an orderly fashion, or else the person wishing to use or modify the new development must obtain the information directly from the originator.   Over a period of time the APT Project would become chaotic and unable to fulfill its mission without a complete and adequate set of documentation, maintained insofar as it is possible to correspond to the current state of the APT programs.

The original APT documentation consisting of six separate volumes aimed at three general classes of readers have been written primarily by members of the M.I.T. project based in part upon information supplied by other members of the APT Project. In many respects, however, these original documents are obsolete so that changes, additions, and modifications are required.   Since it will always be necessary to alter the documentation to match program changes, the documentation system has been designed from the beginning for expansion and modification.   The required changes are to be written by the appropriate members of the APT Project, and will be distributed at cost by the Technical Services of the Aircraft Industries Association as part of its support to the project.   It is anticipated that as the APT system comes into more general use, the necessity for up-to-date documentation, being more

acute, will shorten the time lag between modification of the program and modification of the corresponding documents.

With reference to modifying the APT documents, it should be pointed out that the various volumes are intended to serve different purposes, as outlined in Chapter 1. Thus, the addition of a major feature to the system of programs might call for additions to all six of the existing documents in order that the various aspects of the new item may be referenced from the appropriate points of view. This approach of making additions in the proper places to various volumes is preferable to the treatment of new material as separate entire volumes, since then the new features are placed in proper context with the remainder of the system. It should be remembered that there will always be new people just learning about the system from the beginning, even after it has been in development for some time, so that the organization of the overall documentation system will still be valid even in the future. If, on the other hand, a new development is quite large but of a very restricted nature, then treatment of the new material in a separate volume would probably be most appropriate. General rules for adding to the documentation cannot be made explicitly here but in summary it should be mentioned that the organization of the original documentation has been carefully worked out to meet the various needs of the present and future users of the APT system, and these considerations will continue to apply, and perhaps will be even more important, as the system grows in comprehensiveness. The goal should be to express the maximum amount of information and know-how in the most easily understood form. If this can be accomplished in good measure, the documentation will serve its purpose well.

5B. NUMBERING SYSTEMS

Since the programs of the APT system are scheduled to be in a continual state of flux, many revisions and additions to the documentation will be required. For this reason, a numbering system has been devised which will allow for arbitrary changes in the documentation organization and still maintain sufficient structure to assist the reader in using the documentation.

5B.1 Section Numbering Systems

The numbering system for text is based upon each book being

divided into chapters and each chapter into sections, subsections, and paragraphs as necessary. Firm conventions are established only to a certain point. Notation used in headings of a finer structure may be completely arbitrary and is left to the discretion of the writer of the section. Chapters within a volume are numbered decimally: 1, 2, 3, ... Sections within a chapter are denoted by capital letters preceded by the chapter number. Thus, the sections of Chapter 6 are 6A., 6B., 6C., ... Section titles are in all capital letters, set off from the text starting at the left margin. Subsections within a section are denoted by a section number followed by a decimal integer. Thus the subsections of Section 6A. would be 6A.1, 6A.2, 6A.3, ... Subsection titles are underlined, upper and lower case, set off from the text starting at the left margin. Internal headings within a subsection are numbered in decimal, set off from the text starting at the left margin. Internal headings within a subsection are numbered in decimals set off from the text, indented from the margin in upper and lower case. Subinternal headings within an internal an internal heading receive lower case letters, upper and lower case underlined, and are incorporated as the beginning of the paragraph of text. Examples are shown in Fig. 5-4.

5B.2 Page and Figure Numbering System

Page, figure, and table numbers consist of the chapter number followed by a dash and the respective page in the chapter. For example, 6-5 is the number of the fifth page in Chapter 6. Page numbers should be centered at the bottom of the page to permit the reproduction of the final copy on either one or two sides of the page. Figure numbers should be the same as the page number on which the figure appears. For example, Fig. 6-5 appears on page 6-5. When more than one figure appears on a page lower case letters are appended. For example, Fig. 6-5a, Fig. 6-5b, ...

5C. INSERTION OF NEW MATERIAL

In the future it is most likely that a programmer adding to the documentation will be given a section number under which his writing is to be inserted. If he considers his own writing as a complete report of his subject, then the subsection headings may be considered chapters

CHAPTER 6

TITLE OF CHAPTER

Author Name
Organization Name

6A.   SECTION HEADING

    x   x
                 Text
x   x

6A.1 <u>Subsection Heading</u>

    x   x
                 Text
x   x

    1.   Internal Heading

       x   x
               Text
x   x

       a.   <u>Sub-Internal Heading</u>.   x   x
               Text
x   x

       b.   <u>Sub-Internal Heading</u>.   x   x
               Text
x   x

    2.   Internal Heading

       x   x
               Text
x   x

6A.1.1 <u>Subsection Heading</u>

    x   x
                 Text
x   x

6A.2 <u>Subsection Heading</u>

    x   x
                 Text
x   x

Fig. 5-4 Example of APT Documentation Format
("Text" may be <u>many</u> paragraphs.)

within that report, and internal and subinternal headings should be used at his discretion whenever necessary. In the event that appendices are required, in order to present detailed information outside of the main flow of the descriptive text, these appendices should be treated as subsections but followed by, for example, 6A.7 (Appendix 1), followed by the title of the appendix. Authorship for chapters, sections, and other major pieces of writing should be included as shown in Fig. 5-4. Most of the original documentation gives this author information by initials in the table of contents, but does not give it at the beginning of each chapter (except in Volume IV), since entire volumes have been written by individuals. In the future, however, authorship for sections which are added should be acknowledged.

The insertion of new subsections, pages, or figures require only the addition of a period and a number to the preceding number letter combination, e.g.,

	Existing	Additions	Further Additions	
Subsections:	6B.1	6B.1.1	6B.1.1.1	etc.
	6B.2	6B.1.2	6B.1.1.2	
Pgs. or Figs.::	6-5	6-5.1	6-5.1,1	etc.
	6-6	6-5.2	6-5.1.2	

To prevent ambiguity the following procedure is used for the insertion of complete new sections:

6A.	6A(1).	6A(1.1).	etc.
6B.	6A(2).	6A(1.2).	

Whenever a modification is made to the documentation, the authorship and date of that modification should be made clear. If an entire section is added so that authorship is shown in the section heading, this is sufficient. If an individual page is changed, however, then the initials of the author and the date of the change should be typed below the page number at the bottom of the page. For example,

6-5.1.2
O.D.S. 6/26/59

The author's name and organization should then be added to the list of authors which appears on page 0-4 of each volume.

The purpose of the list of authors is to provide a tabulation of the names and organizations of those individuals who have played a part in the actual writing of material that appears in the volume. The initials associated with full names in that list are used to tag portions of the table of contents and page corrections as described above.

It is quite obvious that the numbering system used in the APT documentation is the result of numerous compromises. Although it may leave considerable to be desired in terms of appearance, it is hoped that the system will serve its purpose and allow proper organization and authorship reference. It is hoped that full advantage will be taken of the flexibility of the documentation system so that the descriptive portion of the APT effort can be kept up to date with the functioning programs.

5D. PROCEDURES FOR DOCUMENT MODIFICATION

The original printing of the APT documentation has been carried out by M.I.T. with AMC sponsorship. Both bond and vellum reproducible copies of all documents have been printed. For active project participants a kit consisting of four copies of Volume I, two copies of Volume II, and one copy each of Volumes III, IV, V, and VI, in addition to one reproducible copy of each volume, have been supplied. In this way, an organization which actually plans to use the APT system has sufficient information to get underway, and also can reproduce as many copies of the various volumes as are required. Vellum masters for the various cover printings are also included so that the documents can be duplicated exactly if desired. It is also felt that the blank vellums of the covers may also be useful for memoranda or intermediate levels of documentation of more restricted scope. Non-participants are supplied single bond copies of the various documents.

Responsibility for maintenance of the APT documentation has been assumed by the Aircraft Industries Association and will include both bond and reproducible copies of correction material. This section should be replaced by a full description of the mechanical procedures for submitting information to AIA for printing and distribution, once these procedures have been established.

CHAPTER 6

(APPENDIX)

APT PROJECT PROCEDURES

6A. DIRECTIVE

The following APT Project Directive was approved by the Numerical Control Panel of the Aircraft Industries Association in its Atlanta meeting, March 16 to 18, 1959.

APT PROJECT DIRECTIVE

1. FUNCTION

1.1 Authority: The APT Project is established by the Numerical Control Panel within the authority granted by the Airframe Manufacturing Equipment Committee. The APT Project Coordinating Group is responsible to the Numerical Control Panel for meeting the requirements of provisions following herein.

1.2 Objective: The objective of the APT Project is, through the pooling of resources and ideas to produce a universal automatic programming system to fully exploit the economic potentialities of numerically controlled machines and equipment.

1.3 Scope: The APT Project shall concern itself with operations at the working level relative to the most effective use of digital computers, by means of the APT data processing system, to translate product design intent into the control media for numerically controlled machines and equipment.

2. ORGANIZATION

2.1 APT Project: The APT Project shall be national in nature and composed of participants as defined in paragraph 2.4, Project Participants.

2.2 APT Project Coordinating Group: The APT Project Coordinating Group shall consist of AIA member company representatives, shall be appointed by the Numerical Control Panel, and shall be responsible for:

2.2.1 Formulating official policies affecting the APT Project.

2.2.2 Establishing the status of the various organizations receiving information concerning the Project and maintaining up-to-date distribution lists of the various categories of recipients.

2.2.3 Organizing meetings as authorized in Paragraph 3.4, Meetings.

2.3 **APT Project Coordinator:** The APT Project Coordinator shall be a representative of an AIA member company, and shall be appointed by the Numerical Control Panel. The Coordinator shall:

2.3.1 Serve as chairman of and coordinate the activities of the APT Project Coordinating Group, as defined in Paragraph 2.2, APT Project Coordinating Group.

2.3.2 Act as the centralized source of information about the APT Project and the official spokesman of the Coordinating Group.

2.3.3 Act as consultant and technical advisor to all participants and/or organizations attempting to install the APT system.

2.3.4 Act as the executor of policy decisions of the Coordinating Group; in particular this includes:

2.3.4.1 Delegating work to the various participants in the Project, and ensuring that participants working on interconnecting assignments have sufficient information to guarantee compatability.

2.3.4.2 Establishing the merit of the various proposals for modification of the APT Program and arbitrating conflicting proposals or conflicting methods of accomplishing any one accepted proposal.

2.3.4.3 Preparing periodic written status reports sufficient to ensure the general dissemination of up-to-date information concerning the Project and cooperating with AIA in reproduction and distribution.

2.3.5 Maintain and cooperate with AIA in the distribution of up-to-date information concerning technical details of the APT Program Deck; in particular, this includes:

2.3.5.1 Maintaining up-to-date master decks of the various computer routines involved, one copy of each being stored in a place secure from accident.

2.3.5.2 Providing a copy of the complete master deck to an agency designated by AIA for reproduction and mailing to authorized organizations, and assisting AIA in establishing billing rates and reimbursement rates.

2.3.5.3 Providing copies of "corrections or additions" to master decks to an agency designated by AIA for reproduction and mailing to authorized organizations.

2.3.5.4 Providing "change memos" announcing official changes to the APT Program Deck, to an agency designated by AIA for reproduction and mailing to authorized organizations.

2.3.6 The Coordinator shall not be obliged to troubleshoot specific APT part programs for any organization, incur travel expenses in his capacity as consultant and technical advisor, nor be held responsible for errors in the APT Program Deck. He shall be responsible to accumulate data provided by participants and exercise normal and reasonable diligence to assure the completeness and accuracy of released information.

2.4 Project Participants: Any corporation, or division of a corporation (AIA member or otherwise) is eligible to become a participant in the APT Project upon written application to the APT Project Coordinating Group by a corporation executive, contingent upon agreement to the following:

2.4.1 The corporation executive must assign the services of a competent computer programmer, on a full-time basis. The computer programmer shall be the authorized APT Project representative for his company and will accept and execute mutually agreeable assignments from the Coordinating Group.

2.4.2 The computer programmer shall submit, at a frequency established by the Coordinating Group, reports containing any plans and proposals for new work, progress on existing work assignments, and any comments or suggestions concerning the Project.

2.4.3 The computer programmer shall assist the Coordinating Group in establishing methods for incorporating the results of a work assignment into the overall APT System, including suitable system testing procedures.

2.4.4 The computer porgrammer shall provide modifications and additions to the existing system documentation, as required by the Coordinating Group.

2.4.5 To reimburse AIA for the cost of material received as defined under 3.5.1.

2.4.6 Project participation may be terminated by written notification where, in the opinion of the Coordinating Group, the participating organization fails to meet the requirements of Section 2.4.

3. OPERATION

3.1 Policy Matters: Policy relating to AIA administration and project organization, function or procedure, shall be referred to the Numerical Control Panel.

3.2 Technical Matters: Matters relating to technical aspects of the

APT Project, exclusive of policy as stated in Paragraph 3.1, are the responsibility of the Coordinating Group.

3.3 **Directive Amendment:** This Directive may be amended only by the Numerical Control Panel.

3.4 **Meetings:**

    3.4.1 **Frequency:** Meetings of participants may be called by the Coordinating Group through AIA as required.

    3.4.2 **Representation:** It is the responsibility of the officially assigned computer programmer to attend meetings called by the Coordinating Group, or to designate a qualified alternate to attend.

    3.4.3 **Outside Representation:** Non-participating organizations may be invited through AIA to attend meetings for a specified purpose.

3.5 **Distribution of Information:**

    3.5.1 **To Participants:**

    All APT Project documentation, computer programs and informational releases will be distributed at cost to participating organizations by AIA.

    3.5.2 **To Non-Participants:**

    Revisions to the M.I.T., APT documentation as released by the Coordinating Group, will be available at cost through AIA.

6B. AIA SERVICES

This section should be replaced by a description of the services and conventions which will be observed by the Aircraft Industries Association providing support to the APT Project. Services to be performed and the cost of those services to the project participants, or organizations on the information distribution list, should be described, once they have been determined.

CHAPTER 7
(APPENDIX)

COMPUTER PROGRAMMERS OF THE APT PROJECT

AUSTIN, Len S.	McDonnell Aircraft, St. Louis
BATES, Edgar A.	Convair, San Diego
BLASSINGAME, Forrest L.	Martin Company, Denver
BUCKNAM, J. S.	Chance Vought, Dallas
BYRNE, Ruckman G.	Convair-Astronautics, San Diego
CAIN, George, Jr.	Lockheed, Marietta
CAMPBELL, Richard	Chance Vought, Dallas
CASTLE, E. L.	Chance Vought, Dallas
CELLERS, John	Douglas, Long Beach
CLINE, Jack L.	Martin Company, Baltimore
CORLEY, Charles F.	North American Aviation, Los Angeles
CRIBBS, Hal	Convair, San Diego
DAVIDSON, Tom	Marquardt Aircraft Company, Van Nuys
FELDMANN, Clarence G.	Servo Lab, M.I.T., Cambridge
FOLKNER, Charles A.	Convair, San Diego
GABBARD, J. L., Jr.	Union Carbide Nuclear Co., Oak Ridge
GODDARD, Homer D.	Douglas, Long Beach
GRAY, Jerrold H.	Boeing, Wichita
HALLMAN, Charles	Martin Company, Baltimore
HARNQUIST, Kenneth	Douglas, Long Beach
HOWARD, Tom B.	Northrop Aircraft, Hawthorne
JOHNSON, Robert A.	I.B.M., White Plains
KAYNOR, K. W.	United Aircraft, Hartford
KNOWLES, Eugene D.	Boeing, Seattle
KNOWLES, Henry	Martin Company, Baltimore
LEMAY, Arch	Boeing, Renton
LEVITT, Richard H.	United Aircraft, Hartford
McAVINN, David F.	Servo Lab, M.I.T., Cambridge
McKINLEY, W. K.	Boeing, Seattle
McWHORTER, B. J.	Convair, Ft. Worth
NANCE, Charles	Douglas, Santa Monica
NOBLES, H. D.	Convair, Fort Worth
PETERS, E. A.	North American Aviation, Columbus
PHERIGO, John B., Jr.	Northrop, Hawthorne
PINTER, H.	Boeing, Seattle
POPLE, Harry E., Jr.	Servo Lab, M.I.T., Cambridge
RIED-GREEN, Kieth	Martin Company, Denver
ROBERTSON, W. P.	Northrop, Hawthorne
ROBINSON, Charles E.	United Aircraft, Hartford
ROSS, Douglas T.	Servo Lab., M.I.T., Cambridge
SCHMIDT, Raymond M.	Bell Aircraft, Buffalo
SCHNEIDER, Milt	Republic Aviation, Farmingdale
SCHWIND, C. H.	Chance Vought, Dallas
SENNEVILLE, Leo A.	North American Aviation, Rocketdyne
SHAFER, Harry	Convair, San Diego

COMPUTER PROGRAMMERS (continued)

SMITH, O. Dale	North American Aviation, Los Angeles
STRELLA, John	Republic Aviation, Farmingdale
SUTTON, George	North American Aviation, Los Angeles
SWIFT, Charles	Convair, San Diego
TREXLER, Richard L.	Martin Company, Baltimore
WALTER, Whit	North American Aviation, Los Angeles
WENKER, Jerome R.	Servo Lab, M.I.T., Cambridge
WHITE, Lester C.	Lockheed, Marietta
WILSON, Howard B.	Martin, Denver
WYATT, J.	Convair, Fort Worth