NUMERICAL CONTROL AND COMPUTER AIDED MANUFACTURING

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Preface

It would not be incorrect to state that the present manufacturing era belongs to numerical control. With larger and larger proportion of manufacturing activity becoming involved in job or small batch production of a variety of components, often of complex shapes requiring high precision, the need for flexible automation has always been felt. Very high under-utilisation of machine tool capacity in conventional batch manufacture results in high costs and unpredictable delivery schedules. The operation of automatic machines under program control has brought in the real solution to these problems. With the revolution in electronics, control systems are now available with very high reliability, low costs and in smaller sizes, which has given a real stronghold to numerical control in manufacturing.

The need of this presentation was felt because information pertaining to this important area is available in a very scattered form. To train suitable personnel for the industry, it is essential that the subject should be given careful attention in engineering institutes. With this aim, we have been teaching this subject during the last 12 years in undergraduate and postgraduate classes and have also organized a number of short courses on Numerical Control Manufacturing and Computer Aided Manufacture for the teachers of various engineering institutes and senior personnel of industry. The present work is an outcome of this effort. It is hoped that engineering students, teachers and practising engineers will find this useful.

While preparing this material, it has been assumed that the reader has basic information of the various manufacturing processes, process planning and conventional machine tools. The work essentially discusses the what and why of NC in Chapter 1; while how the hardware of NC differs from the conventional is brought out in the second chapter. Chapters 3 to 5 expose the details of the main NC hardware. Chapters 6 and 7 deal with programming, i.e. manual part programming and computer aided part programming. Partial and complete examples have been given to enable proper understanding of programming techniques. An exhaustive bibliography and a list of various standards pertaining to NC have been given at the end which will be found useful.

Our training in various universities and industries in the UK has helped

considerably in this venture. The material contained in this work is not new since reading of various books listed in the bibliography, manufacturers' catalogues, standards, etc. has had to be done off and on while teaching this course, which has definitely influenced us. We acknowledge all these authors collectively, since individual acknowledgement is not possible. We would like to express our special acknowledgements to Prof. W B Heginbothom, formerly Professor and Head, Department of Production Engineering and Management, University of Nottingham and now Director General, Production Engineering Research Association, Melton Mowbray, Leicestershire, UK, who has been the source of inspiration to one of us (Tewari) and led him into the fascinating area of automation; to Prof. R Bell of the Department of Engineering Production, University of Technology, Loughborough, who had been the guide to our activities in numerical control right from the beginning in our Institute and has been providing us all help as a teacher and as a colleague, to Dr S Hinduja, Machine Tool Division, University of Manchester, Institute of Science and Technology, Manchester, UK, for providing software training and assistance in project activities; and to Mr W A Smith, also of UMIST, for planning, training and assistance in setting up our NC activities. We are also greatly indebted to those in the Indian Institute of Technology, Delhi, and the British Council, who were responsible for our training and experience in this area. Participation in the NC courses, organized by the Central Machine Tool Institute, Bangalore, by two of us (Rao and Tewari) had also been a useful experience and is gratefully acknowledged.

The most important acknowledgement and gratitude is due to our wives and children who missed us badly and had to bear the boredom during the period of preparation of this material and the training courses which kept us busy for weeks together. We express our sincere appreciation to our colleagues and friends in the Central Workshop and Mechanical Engineering Department of the Indian Institute of Technology, Delhi, for their cooperation in preparing this material.

No work can be said to be complete and without mistakes which is due to the limitations of our experience. We would be grateful to the readers if they will be kind enough to bring to our notice such shortcomings which, we are sure, will enable us to improve future editions.

T K Kundra
P N Rao
N K Tewari

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Introduction

1.1 THE PRODUCTION SPECTRUM

To stay in business, the main motive is profit. Generally speaking, profit, which is used as a parallel term to productivity in manufacturing, means a positive difference between output and input, measured in same units. Better services offered on schedule, reliable, improved and consistent quality of product also mean profit since these establish the prestige and hence a larger market. To increase productivity, therefore, one has to maximise the output while keeping the input as low as possible. To meet the objective of consistency of quality particularly required in accurate and complex components, calls for use of special purpose or automatic equipment. The cost of such equipment could only be met if the quantity of production and the production rate are very high—a kind of mass/continuous production. Thus if quantity, quality and delivery schedule are of prime importance, the answer is mass production.

However, the entire spectrum of production activities shows that hardly 15-20% of the demand desires the use of mass production. The remaining requirements can be met only by conventional means of job or batch production since not only is there a large variety of products but also the demand of the products is discontinuous, the batch sizes being small or medium. In such situations, functional type of production is a must which means the use of conventional standard equipment and manual skilled labour. This unfortunately results in poor consistency in quality and unpredictable delays in delivery schedules. Not only this, the machine utilisation time is too low (15-20%) besides the high waiting time and large amount of work in progress. All these factors result in high cost of production. If the situation demands accurate production of components as per schedule, this technology is quite unsuitable.

1.2 PROGRAMMED AUTOMATION

The situation referred to above is the one faced in industry where one-off jobs are very common, like the aircraft industry, ship building or any prototype manufacture. This is what happened around 1940, when the U.S. Air Force felt the need of an equipment which could ensure consistency in quality in production of complex components. This meant that human intervention is to be eliminated, i.e. the equipment needs to be automatic but since it has to deal with a variety of products, therefore it should also be flexible. These requirements are quite contrary to each other since automation has all along been thought to be special purpose. However, "Necessity is the mother of invention", and the concept of *flexible automation* took birth, which means that the system works automatically but on instructions which can be changed as desired. This is called *programmable automation.* In fact, even the conventional automatic equipment works on program—a physical one in the form of cams, etc. which are fixed programs. The use of such programs in batch production is economically prohibitive. The programs being referred to in flexible automation are the inexpensive ones—on paper tape or cassettes which can be read by the controller which in turn sends suitable signals to the machine unit to move automatically to manufacture the product. However, these machines would be too expensive, and therefore, to keep the machine hour costs low it would be necessary to keep them busy all the time. This has been possible since programs for various jobs could be prepared well ahead and used one after another on the machine to produce accurate components as per schedule. Further, very high consistency in quality in batches, produced at different times, can be ensured since the production no longer depends upon the skill of the operator but on a single program used again and again (in the conventional system, the operators also change and thus inconsistency is all the more difficult to ensure). Also, since the program is inexpensive, changes in product design from job to job can easily be catered in programmable automation, which is not easy and also time consuming in case of conventional batch production. Another aspect, that of inspection, should also be kept in mind. In conventional systems, the worker stops the machine frequently to take measurements and thereby slows down production. This would not happen in case of programmed automation. The loss of time due to setting of work, tools and preparation (reading of drawings, seeking instructions, etc.) which form an important time element in the conventional system, are eliminated to a large extent in programmable manufacture. All these factors result in high productivity in batch manufacture.

1.3 NUMERICAL CONTROL

Flexible automation, is implemented in machine tools in the form of digital control. The programs are in binary, in numerical form; strictly speaking alphanumeric. These instructions when read by the system, regulate the various slides of the machine tool to enable the tool/tools to shape the objects to required profiles by positional and/or continuous control. Such systems are known as numerical control (NC) systems. As would be obvious, special skill would be required for writing programs and maintenance of these machines. These were the main factors which delayed the quick acceptance of these systems but with the present advancement in technology, these factors are no longer that important. Computer-assisted programming using high level languages, manual data input system, computer numerical control systems and self diagnostics have made the systems so useful and easy to learn and maintain that there has been a phenomenal rise in manufacture of NC machines. The revolution in the electronic industry has not only brought down the cost of the control systems appreciably but also very largely miniaturised the controls. The use of microprocessors has brought a very significant increase in the reliability in present systems besides reducing costs tremendously and also increasing the versatility of the control systems. The latest systems are the interactive type in which the operator can carry on a dialogue with the system with the assistance of a key board and a VDU screen enabling him to enter and edit programs to deal with a variety of production, modifications in product design in case of prototypes, etc. while the manufacturing is in progress. In fact, this makes the automation really flexible.

1.3.1 Advantages of Numerical Control

The advantages of NC can be summarised as follows:

(i) Due to its flexibility, the machine utilisation is very high.

(ii) The lead time is very largely reduced, thereby prediction of the delivery schedule is more reliable.

(iii) Need of special purpose tooling, jigs and fixtures is mostly eliminated.

(iv) Consistency in quality is assured since the manufacture is automatic. This indirectly reduces the inspection costs.

(v) Handling time is very largely reduced since most of the operations can be carried out in minimum number of setups. With facility of automatic tool changing, pallet change and clamping and unclamping arrangement, the non-machining time is eliminated to maximum extent.

(vi) Since a single machining centre can carry many operations, large floor area is saved which otherwise would be required to install a number of conventional machines.

(vii) Since the input instruction can be easily modified, design changes in the products can easily be incorporated. This is very advantageous in prototype manufacture or in manufacture of similar parts in small batch sizes.

(viii) Operator's skill is no longer important since the accuracy is dependent on the program. This reduces scrap loss and rework.

(ix) Sudden change in demand can be easily handled because the system has in-built flexibility.

(x) Work-in-progress, handling time and errors due to a number of setups, as in conventional manufacture, are reduced to a very large extent when machining centres are used.

(xi) Since mostly all conditions are under control, the estimation of costs involved can be done quite accurately.

1.3.2 Demerits of Numerical Control

(i) NC essentially calls for very high investment. But this should be carefully considered in the light of numerous advantages and over a period of time.

(ii) Special skills in programming and maintenance are essential.

(iii) Redundancy in labour may be there. But this again needs careful consideration. When planning for NC, re-training of staff for newer requirements must be taken into account.

(iv) Down time of NC systems is very expensive. Therefore, it is very essential that the staff is adequately trained in operation and maintenance at the supplier's place before the machine is delivered.

1.4 CNC AND DNC

A brief mention about *computerised numerical control* (*CNC*) and *direct numerical control* (*DNC*) is desirable at this stage. This should not be confused with computer aided programming associated with NC. The latter is essentially off-line since the programs are prepared on the computer independent of the NC machine. The CNC system has a dedicated computer in it which controls the NC functions. In a conventional NC system the control is hardwired and therefore any modifications or addition in facility call for many changes in the controller which may or may not be possible due to limitations of basic configuration. Besides this, the tape needs to be loaded each time when the component needs to be reproduced. This results in loss of time and some times error in reading. If any change in instructions is desired, modifications and editing are not possible. As compared to this, in a CNC system, a bare minimum of electronic hardware is used while software is used for obtaining the basic functions. That is why it is sometimes termed as softwired control. This assists in adding extra facilities conveniently without much problem and cost. The system has the capability of entering the program through a tape or the keyboard which is then stored. Whenever any program is required to be run for manufacture of a component, it is called thereby saving time and eliminating errors due to tape reading. Further, editing of program is now much more convenient which is a very desirable operation in small batch or prototype manufacture. Any particular information or operation block can be called for display and/or use, i.e. the system has facilities for searching, etc. which the operator can perform on the machine during progress of work. Since these computers are dedicated type, they need comparatively much less storage and with the present costs and high reliability, CNC have become a reality in all NC work. Diagnostic software makes trouble shooting extremely easy on these systems.

The direct numerical control system refers to use of a large frame computer which not only performs other functions in the company but also controls a number of NC installations in the plant. This has come to be useful since in the present age of computer integrated manufacture and flexible manufacturing systems, centralised data handling and control is desirable. The main-frame computer stores programs and after processing sends the control signals to the respective NC systems. CNC systems can be easily adapted to a DNC set-up. Historically speaking, DNC systems came into existence earlier than CNC. Since a large memory system is required and substantial cabling work is involved in interlinking the NC machines to the computer, DNC system is expensive. Further, it necessitates that any new NC machines added to the installation must be compatible with the main computer. One of the other points to be considered is the down time when the main computer breaks down. This is one aspect when CNC—each NC machine with its own dedicated computer, a modular approach—is definitely advantageous.

1.5 CONCLUSION

The next few years are going to be years of very fast change. We have entered the era of flexible manufacturing systems wherein integration of a large number of manufacturing and handling facilities including robots is involved which necessarily involves program control with the help of computers. As expected, individual activities like Computer Aided Design and Computer Aided Process Planning are already on the process of being combined as Computer Integrated Manufacturing. Would it be inappropriate if *numerical* control is called *newmiracle* control?

2

Numerically Controlled Manufacturing

2.1 INTRODUCTION

Numerical control as mentioned earlier is a method of automation. The common household water cistern is a simple case of automation. Another common example is the thermostatic control of temperature of an electric iron or oven.

Consider the operation of the ball-vaive in the water cistern in Fig. 2.1. The water supply from the overhead mains gets cut off when the water level reaches a pre-decided position. The ball floating at this position actuates the linkage to close the valve. Similarly, at the desired temperature position, the electrical contact switch is actuated to stop the heating in an electric oven (Fig. 2.2). Thus, in both these cases the processes are automatically controlled by the information on POSITION. The master templates for copying lathes or milling machines, cams and guides for automatic machines have also been used for controlling the industrial processes automatically. All these mechanisms are set to several pre-determined positions.

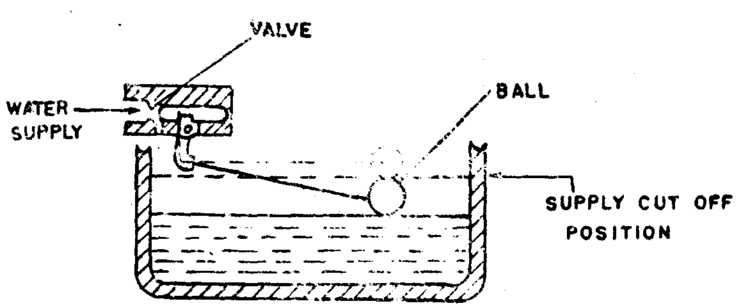

Fig. 2.1 Automatic control of water level in water cistern

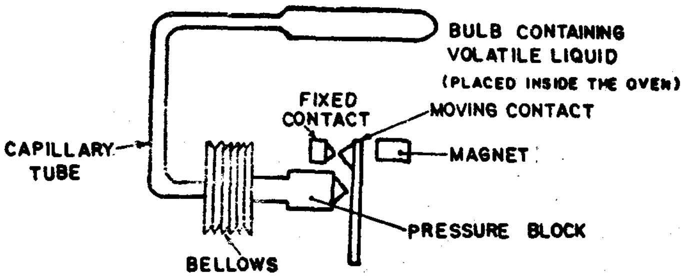

Fig. 2.2 The principle of automatic temperature control in an oven

The above mentioned processes can also be controlled by digits or numbers. Such a method is known as numerical control. In actual practice, in addition to the numbers, alphabetic characters and several symbols are also used. It is also implied that such a numerical control (mentioned as NC from now on) refers to the automatic control of machines (particularly the machines tools as far as this book is concerned). A NC machine is a combination of a machine tool and a control system. Original control systems were of the valve type but these were soon replaced by electronic controls which in turn were replaced by computer controls. The term NC, of course, continues to be used even for computerised numerical control (CNC) of machine tools. No doubt all these controls use several alphanumeric characters and symbols as mentioned earlier.

2.2 NC MANUFACTURING

In this section, various elements of NC manufacturing have been identified. A major part of the book has been devoted to the detailed discussion of these elements. One can easily pinpoint these elements on any NC manufacturing shop floor. The major ones are mentioned below.

2.2.1 Machine Tool and Control Unit

Every NC machine tool unlike its conventional counter-part is fitted with a machine control unit (MCU). The MCU may be housed in a separately standing cabinet like body; it may be mounted on the machine itself; or it could be like a pendant which could swing around (Figs. 2.3, 2.4). It is with this control unit that the path to be followed by the cutting tool, speeds and feeds, tool changes and several other functions of the machine tool can be controlled.

Though from outside, the NC machine tool does not look very different except that it appears bigger and without handwheels; its basic design is quite different from the similar conventional machine tool. Details of these fea-

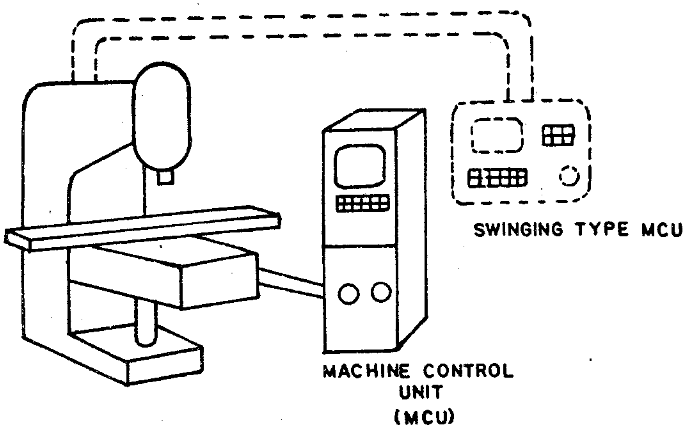

Fig. 2.3 Machine tool and control unit

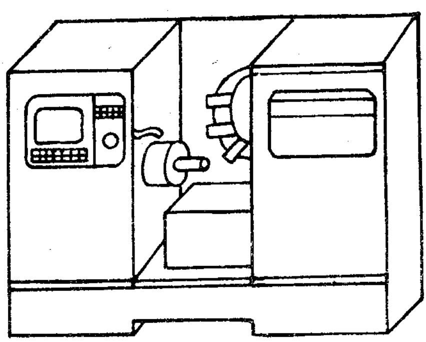

Fig. 2.4 Machine mounted MCU

tures and the MCU are presented later. The most important element of a NC manufacturing system is of course the part program (Fig. 2.5).

2.2.2 Part Program

These are number of sheets looking like computer print outs, containing number of lines/statements (called instructions). It is, therefore, the plan proposed for machining the part. It is written by keeping in view various standard words/codes and symbols. It is dependent on the machine tool hardware and the MCU and details on this programming shall be presented under *Manual Part Programming*. The programs could also be written in a higher level language, e.g. APT, UNIAPT, COMPACT etc. These programs have to be converted into the above mentioned machine tool level program with the help of processors. It is analogous to the practice by which computer programs written in FORTRAN language are converted into the relevant

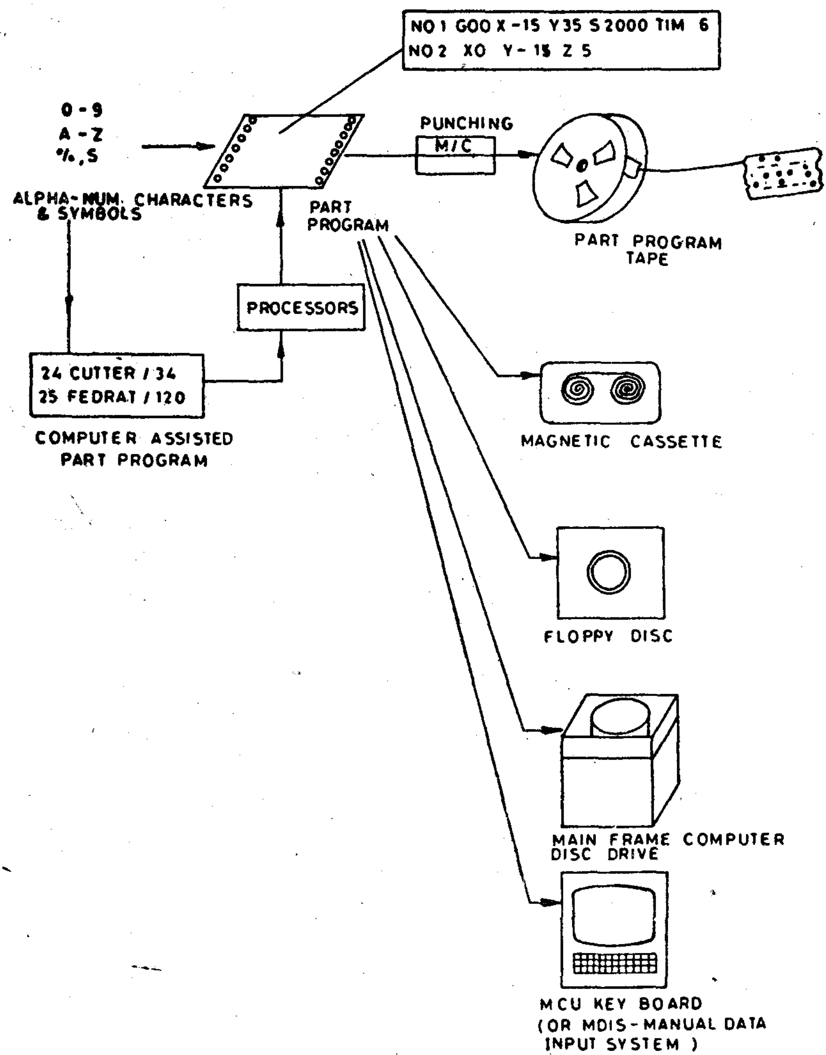

Fig. 2.5 Input media for MCU

computer machine language with the help of a suitable compiler. The programming done in a language like APT is mostly processed with the help of a computer and is therefore also known as computer aided programming.

NC Tape

The NC machine operator usually gets a roll containing a long strip of paper having punched holes. This is known as NC tape. It, in fact, contains the part program though in the form of holes. The tape is usually punched on a Teletype (a typing cum punching machine). A computer or a desk-top tape preparation system could also be used for the same purpose. The hole patterns on the tape follow the standard codes. The tape is commonly made of paper though other materials like mylar, reinforced paper, mylar-coated aluminium and some plastics are also in use. Instead of the above mentioned tape, the part program can also be written on magnetic cassettes, floppy discs or the main disc drive of the in-house computer. The keyboard of the MCU can also be manipulated to enter the program directly instead of using any of the input media mentioned above (Fig. 2.5).

2.2.3 NC Tooling

The operator gathers or is supplied with the relevant tooling for the part to be machined. The unique deviation of the NC tooling from the conventional one is that each cutting tool is set in a different adaptor (Fig. 2.6). NC tooling could thus be reasonably expensive. For long range objectives of maintaining the accuracy, and of course the convenience also, the tooling is usually stacked on a shelf or a trolley (Fig. 2.7). One major variation is that the tools are stored on a drum which is operationally an integral part of the machine tool itself (Fig. 2.8).

Tool off-set Sheet

This informs the operator about the deviation of the tool tip of the actually supplied tool from the one taken into account by the programmer. The programmer gets the information from the tool files which are updated now and then. In spite of the 'updating', the position of the tool tip when supplied to the operator may be different (than what is mentioned in the tool file) because of the wear, resharpening or setting of a new cutting tool due to breakage.

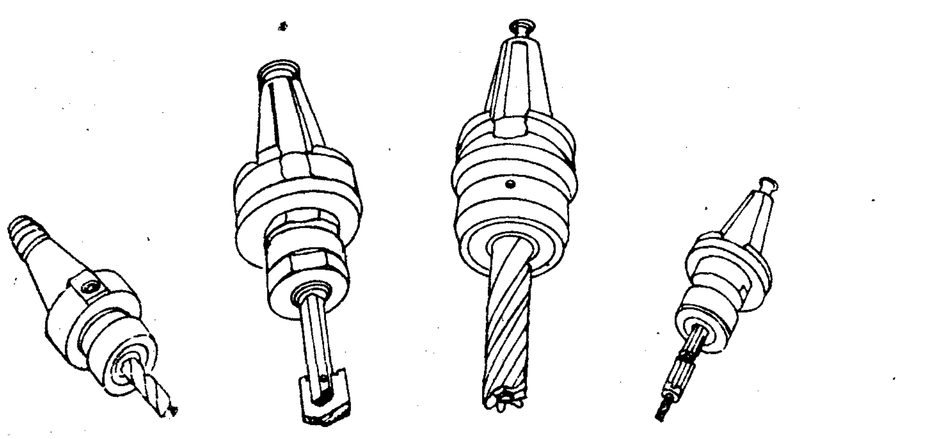

Fig. 2.6 NC tooling