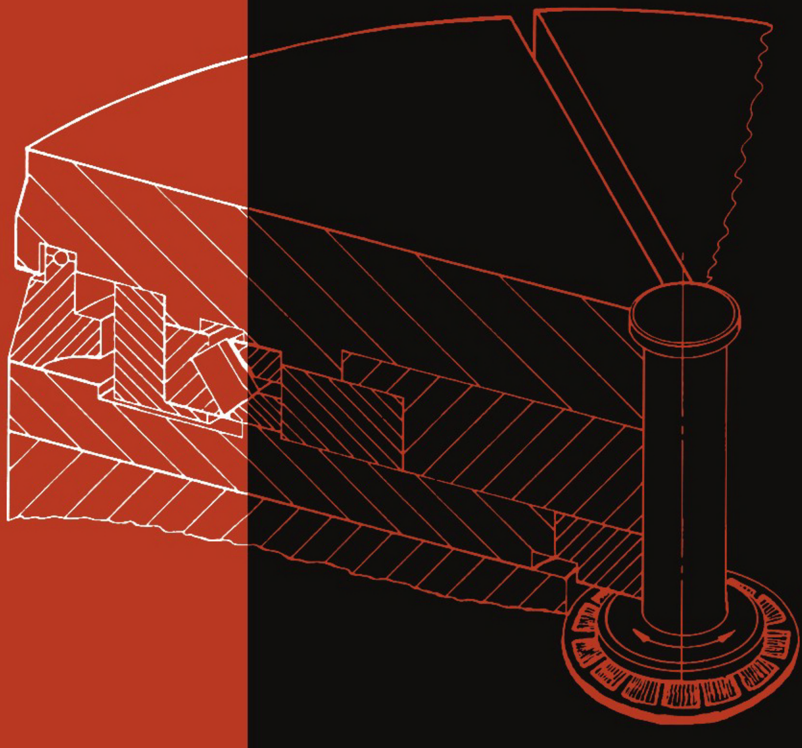
CNC MACHINING TECHNOLOGY

1 Design, Development and CIM Strategies



GRAHAM T. SMITH

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CNC Machining Technology

Volume I

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Graham T. Smith
Technology Research Centre, Southampton Institute,
City Campus, East Park Terrace, Southampton SO9 4WW,
UK

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To my grandfather
Mr T.W. Chandler
who encouraged me
to take an interest
in all things

ΣΟΦΟΣ ΑΝΗΡ Ο ΕΞ ΙΔΙΑΣ
ΠΕΙΡΑΣ ΔΙΔΑΣΚΟΜΕΝΟΣ
ΣΟΦΟΤΑΤΟΣ ΔΕ Ο ΕΚ
ΤΗΣ ΤΩΝ ΑΛΛΩΝ

Translation:

A wise man learns from
experience and an even
wiser man from the
experience of others

PLATO 428–348 BC

Contents

Preface

Each volume in this series of three attempts to explain the design of turning and machining centres and how they are operated through part programming languages. Furthermore, a discussion about how such stand-alone machine tools can be networked into flexible manufacturing systems is given along with the problems relating to such interfacing. These volumes were written as a companion book to the successful *Advanced Machining – The Handbook of Cutting Technology* published jointly by IFS and Springer Verlag in 1989. The individual volumes look at interrelated aspects of using turning and machining centres:

Volume I considers the design, construction and building of turning and machining centres, then goes on to consider how these individual machine tools can be networked together providing the desired communication protocols for flexible manufacturing systems, leading to a complete Computerised Integrated Manufacturing system. This latter philosophy is discussed in terms of a case study on the most automated factory in Europe, ironically manufacturing turning and machining centres. Finally, mention is made of the efforts given to ensure significant advances in both ultra high-speed machining design and submicron operation, which is sure to have a major impact on general turning and machining centres in the future.

Volume II discusses the crucial point of ancillary activities associated with these machine tools, such as the cutting tool technology decisions that must be made in order to ensure that each machine is fully tooled-up and optimised efficiently. A brief review is also given on cutting tool materials development and tooling geometry considerations. Modular quick-change tooling is reviewed together with both tool and workpiece monitoring systems. A discussion follows on tool management, which becomes a major activity when a considerable tooling inventory exists within a manufacturing facility. Cutting fluids are an important complement to cutting tools, as they not only extend tool life but additionally enhance the workpiece machined surfaces; therefore it is important to choose the correct cutting fluid and handle it in the approriate manner to obtain maximum benefit from its usage. Workholding technology is an expensive burden that requires careful consideration to achieve an economic optimisation, particularly in a larger scale automated facility such as in an F.M.S. environment and a range of workholding strategies and techniques are reviewed.

Volume III is a highly focused text that discusses how a part program is generated – after a general discussion about controllers. Consideration is given to the fundamentals of CNC programming and this becomes a major part of the volume with a structured development of how to build programs and where and when the "word address", "blueprint/conversational" and "parametric" programs are utilised. High speed machining fundamentals are considered along with the problems of servo-lag and gain for both milling and turning operations. A section is devoted to "Reverse Engineering" using digitising/scanning techniques – allowing replicas to be used to generate part programs, as these techniques are becoming popular of late. Finally a discussion ensues on the design of CAD/CAM systems and how they might be used for multiple-axis machining, through a direct numerical control link.

Graham T. Smith
West End
Southampton
January 1993

Chapter 1
The Development and Design of CNC Machine Tools

1.1 Historical Perspective – the Early Development of Numerically Controlled Machine Tools

The highly sophisticated CNC machine tools of today, in the vast and diverse range found throughout the field of manufacturing processing, started from very humble beginnings in a number of the major industrialized countries. Some of the earliest research and development work in this field was completed in the USA and a mention will be made of the UK's contribution to this numerical control development.

A major problem occurred just after the Second World War, in that progress in all areas of military and commercial development had been so rapid that the levels of automation and accuracy required by the modern industrialized world could not be attained from the labour intensive machines in use at that time. The question was how to overcome the disadvantages of conventional plant and current manning levels. It is generally acknowledged that the earliest work into numerical control was the study commissioned in 1947 by the US government. The study's conclusion was that the metal cutting industry throughout the entire country could not cope with the demands of the American Air Force, let alone the rest of industry! As a direct result of the survey, the US Air Force contracted the Parsons Corporation to see if they could develop a flexible, dynamic, manufacturing system which would maximise productivity. The Massachusetts Institute of Technology (MIT) was sub-contracted into this research and development by the Parsons Corporation, during the period 1949–1951, and jointly they developed the first control system which could be adapted to a wide range of machine tools. The Cincinnati Machine Tool Company converted one of their standard 28 inch "Hydro-Tel" milling machines to a three-axis "automatic" milling machine for this contract, having removed the contouring equipment. This machine made use of a servo-mechanism for the drive system on the axes, which controlled the table positioning, cross-slide and spindle head. The machine can be classified as the first truly three axis continuous path machine tool and it was able to generate a required shape, or curve, by simultaneous slideway motions, if necessary.

At about the same time as these American advances in machine tool control were taking place, Alfred Herbert Limited in the United Kingdom had their first NC machine tool operating, although Ferranti Limited produced a more reliable continuous path control system which became available in 1956. Over the next few years in both the USA and Europe, further development work occurred. These early numerical control developments were principally for the aerospace industry, where it was necessary to cut complex geometric shapes such as airframe components and turbine blades. In parallel with this development of sophisticated control systems for aerospace requirements, a point-to-point controller was developed for more general machining applications. These less sophisticated point-to-point machines were considerably cheaper than their more complex continuous path cousins and were used when only positional accuracy was necessary. As an example of point-to-point motion on a machine tool for drilling operations, the typical movement might be: fast traverse of the workpiece under the drill's spindle and after drilling the hole, another rapid move takes place to the next hole's position – after retraction of the drill, of course. The rapid motion of the slideways could be achieved by each axis in a sequential and independent manner, or simultaneously, if a separate control was utilised for each axis. The former method of table travel was less costly, whereas the latter was faster in operation. With these early point-to-point machines the path taken between two points was generally unimportant, but it was essential to avoid any backlash in the system to obtain the required degree of positional accuracy and so it was necessary that the approach direction to the next point was always the same. The earliest examples of these cheaper point-to-point machines usually did not use recirculating ball screws; this meant that the motions would be sluggish, and slideways would inevitably suffer from backlash, but more will be said about this topic later in the chapter.

The early NC machines were, in the main, based upon a modified milling machine, with this concept of control being utilised on turning, punching, grinding and a whole host of other machine tools later. Towards the end of the 1950s, hydrostatic slideways were often incorporated for machine tools of higher precision, which to some extent overcame the stiction problem associated with conventional slideway response, whilst the technique of averaging-out slideway inaccuracy brought about a much increased precision in the machine tool and improved their control characteristics.

The concept of the "machining centre" was the product of this early work, as it allowed the machine to manufacture a range of components using a wide variety of machining processes at a single set-up, without transfer of workpieces to other machine tools. A machining centre differed conceptually in its design from that of a milling machine, in that the cutting tools could be changed automatically by the transfer mechanism, or selector, from the magazine to spindle, or vice versa. In this manner, the automatic tool changing feature enabled the machining centre to productively and efficiently machine a range of components, by replacing old tools for new, or preselecting the next cutter whilst the current machining process is in cycle.

In the mid 1960s, a UK company, Molins, introduced their unique "System 24" which was meant to represent the ability of a system to machine for 24 hours per day. It could be thought of as a "machining complex" which allowed a series of NC single-purpose machine tools to be linked by a computerised conveyor system. This conveyor allowed the workpieces to be palletised and then directed to each machine tool as necessary. This was an early, but admirable, attempt at a form of Flexible Manufacturing System concept, but was unfortunately doomed to failure. Its principal weakness was that only a small proportion of component varieties could be machined at any instant and that even fewer workpieces required the same operations to be performed on them. These factors meant that the utilisation level was low, coupled to the fact that the machine tools were expensive and allowed frequent production "bottlenecks" of work-in-progress to arise, which further slowed down the whole operation.

The early to mid-1970s was a time of revolutionary advancement in the area of machine tool controller development, when the term computerised numerical control (CNC) became a reality. This "new" breed of controllers gave a company the ability to change workpiece geometries, together with programs, easily with the minimum of development and lead time, allowing it to be economically viable to machine small batches, or even one-offs successfully. The dream of allowing a computerised numerical controller the flexibility and ease of program editing in a production environment became a reality when two related factors occurred. These were:

the development of integrated circuits, which reduced electronic circuit size, giving better maintenance and allowing more standardisation of design;

that general purpose computers were reduced in size coupled to the fact that their cost of production had fallen considerably.

The multiple benefits of cheaper electronics with greater reliability have resulted in the CNC fitted to the machine tools of today, with their power and sophistication progressing considerably in the last few years, allowing an almost artificial intelligence (AI) to the latest systems. Over the years, the machine tool builders have produced a large diversity in the range of applications of CNC and just some of these developments will be reviewed in Volume III.

With any capital cost item, such as a CNC machine tool, it is necessary for a company to undergo a feasibility study in order to ascertain whether the purchase of new plant is necessary and can be justified over a relatively short pay-back period. These thoughts and other crucial decisions will be the subject of the next section which is concerned with the economic justification for CNC.

1.2 The Economics of CNC

1.2.1 The Importance of a Feasibility Study

It is normal for a company to embark on a feasibility study prior to the purchase of any capital equipment such as a CNC machine tool. This study fulfils many functions, such as determining the capacity and power required together with its configuration – horizontal/vertical spindle for a machining centre, or flat, or slant bed for a turning centre. Many other features must also be detailed in the study, encompassing such factors as the number of axes required and whether the machine tool should be loaded manually, by robot, or using pallets. An exhaustive list is drawn up of all the relevant points to be noted and others that at first glance seem rather esoteric, but will affect the ability of the company to manufacture its products. It has been shown time and again that many mistakes have been made in the past when companies rush into the purchase of new equipment without considering all of the problems, not only of the machine tool itself, but of the manning and training requirements together with its effect on the rest of the shop's productive capability. Often the fact that an advanced, highly productive machine is now present in the shop could affect the harmonious flow of production, causing bottlenecks later, when the purpose of purchasing the machine was to overcome those problems at an earlier production stage. Machine tools have even been purchased in the past without due regard for the components they must manufacture, or without correct assessment of future work. This latter point is not often considered, as many companies are all too concerned with today's production problems rather than those of the future. Taking this theme a little further, in a volatile market a feasibility study should perceive not only the short and medium term productivity goals, but also the long term ones, as it is often the long term trends of productive capability which are the most important if a company is to amortise their costs. When highly sophisticated plant such as an FMS is required, it can be several years from its original conception before this is a reality on the shop floor, and a company's production demands may have changed considerably in the mean time. If, for any reason, the wrong machine/s has/have been purchased, or more likely, something has been overlooked during the feasibility study, then the "knock-on effect" of this poor judgement is that it will have cost the company dearly and, at the very least, any future study will be looked on by the upper management with disdain and scepticism.

A company should plan and discuss their products and systems to be implemented in the future with an eye on the production equipment of the present. This is very relevant, as any responsible production engineering company will invest in manufacturing equipment which has reached a reliable level of maturity, yet at the same time allow for further growth over a foreseeable time, and in such a manner, maintain and strengthen the competitiveness of the enterprise. Fig. 1.1 graphically illustrates the relationship between product maturity and level of utilisation of production technology today. In recent years, the labour overheads have reached almost the same level as the direct labour costs and this has meant that methods employed using conventional production have clearly slipped into an "ageing phase". This is also true, to a certain extent, for NC technology, as this has shifted from maturity to a particular level of ageing and in the medium term, will offer no further competitive opportunities. Obviously, planned investments must embrace the growth area technologies

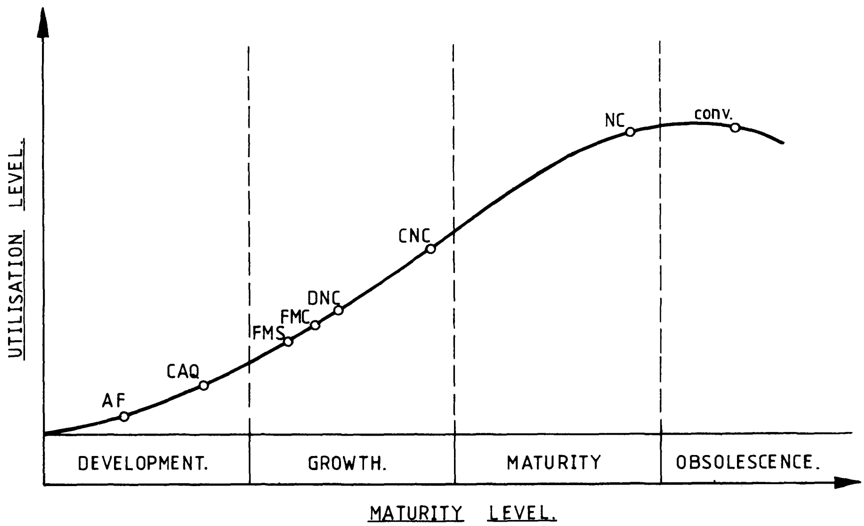


Fig. 1.1. The degree of maturity and utilisation of manufacturing techniques currently on offer. conv., conventional manufacture; NC, numerical controlled manufacture; CNC, computerised NC manufacture; DNC, distributed numerical control (note: not direct numerical control in this context); FMC, flexible manufacturing cell; FMS, flexible manufacturing system; CAQ, computer-integrated quality control; AF, automated factory. [Courtesy of Scharmann Machine Ltd.]

(Fig. 1.1), but these sophisticated technologies – although they create conditions for optimum utilisation of the plant – mean that capital equipment is more costly to purchase. Whenever high cost equipment is purchased it is usually the intention of a company to maximise their financial outlay by reducing the pay-back period to a minimum, using second and possibly a third shift. This strategy has the effect of lowering the hourly machine rate drastically, or to put it another way, these systems are over-compensated by more intensive utilisation, so that despite the higher amount invested, a better utilisation and in most cases higher machine performance will achieve a reduction in costs.

In the high technology-orientated former West Germany, a recent survey concluded that only about 12% of the machine tools installed were less than 5 years old. That is to say, many conventional machines are still actually in use and must be supplemented, or replaced in successive small steps by replacement and/or expansion investments. Continuing this theme, of current average age of the machine tool compared with its utilisation level, it can be seen (Fig. 1.2) that it is precisely in this area that the largest amount of manoeuvring space for entrepreneurial decisions occurs. In the early 1980s, a review regarding machine tool utilisation was conducted and the results showed that on average only approximately 700–800 hours per annum were spent actually doing "cutting" work. If one refers this to the theoretically available annual loading time for the machine tool of 364 × 24 hours per day, this time will represent approximately 8% and this is shown in Fig. 1.2. This graph also attempts to show the individual blocks of time which cannot be used for actual production and it illustrates just how little influence any small idle time improvements

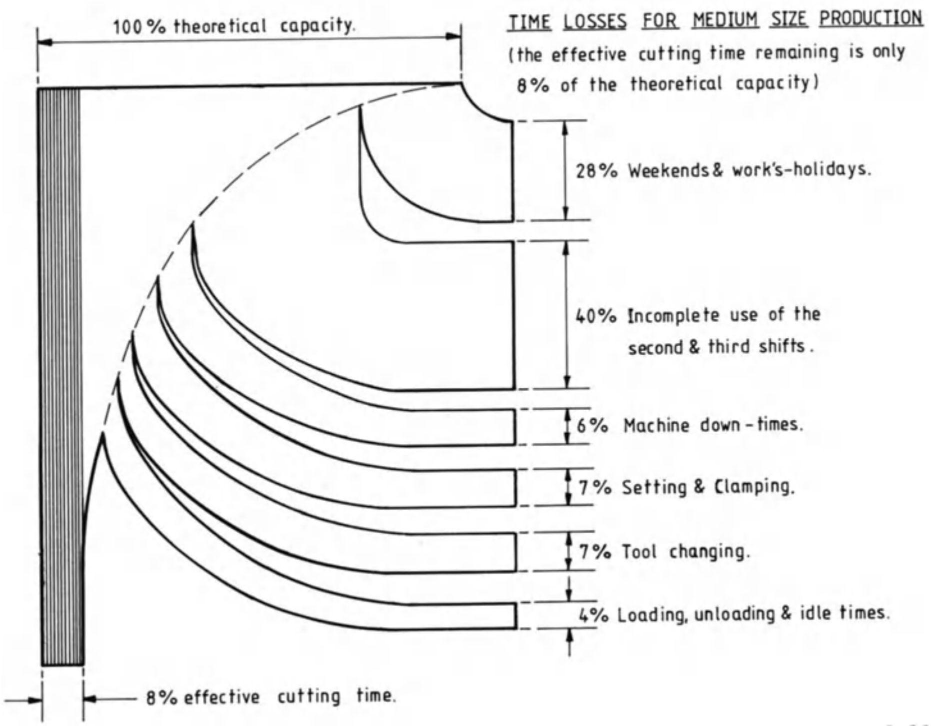


Fig. 1.2. Time loss constituents in medium batch manufacture. [Courtesy of Scharmann Machine Ltd.]

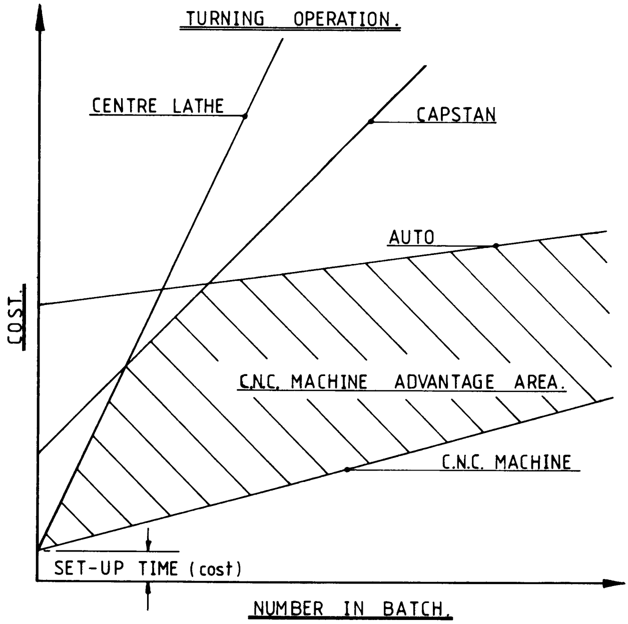


Fig. 1.3. Cost comparison against batch size. This shows clearly the advantage of using a CNC machine.

will achieve on the machine, when compared with the enormous potential of incomplete utilisation. Obviously, improvements during the last 20 years in the cutting capability of machine tools and their performance have shown increases averaging 500% and further drastic savings of time have been achieved in the area of idle times – where higher rapid traverse rates and automatic tool and workpiece-changing equipment have been developed. It nevertheless remains a fact, that even though these are impressive productivity gains, they are a "drop in the ocean" when seen from the overall view of the plant utilisation throughout the year.

So far we have been concerned with the likely problems that face a company embarked on a feasibility study for the purchase of new equipment. Let us now discuss the advantages to be gained from the purchase of the "correct" plant. One of the main purposes in using a CNC machine tool is to increase the productive throughput with this equipment – but this, as Fig. 1.2 has shown, can only be effective when the other time-loss constituents have been minimised. Although high volume production can occur using CNC equipment, it is not alone in this area and under certain conditions can be surpassed by using more conventional technologies, such as, single and multi-spindle lathes, or plug board machine tools, as illustrated in Fig. 1.3. However, even here most of these controllers are now being sold with CNC. The major feature of a CNC machine tool is its ability to cut down drastically the lead times for similar components manufactured by a different plant (as depicted in Fig. 1.4) and this has meant that an economic batch size is one! Even complex double-curvature component geometries can be quickly and successfully programmed by a trained employee using on- or off-line programming methods, but more will be said about this in Volume III. The real advance in machine tool design and monitoring systems has meant that accuracy and repeatability of a component's dimensional characteristics can be confidently predicted, thus time and again uniform work results.

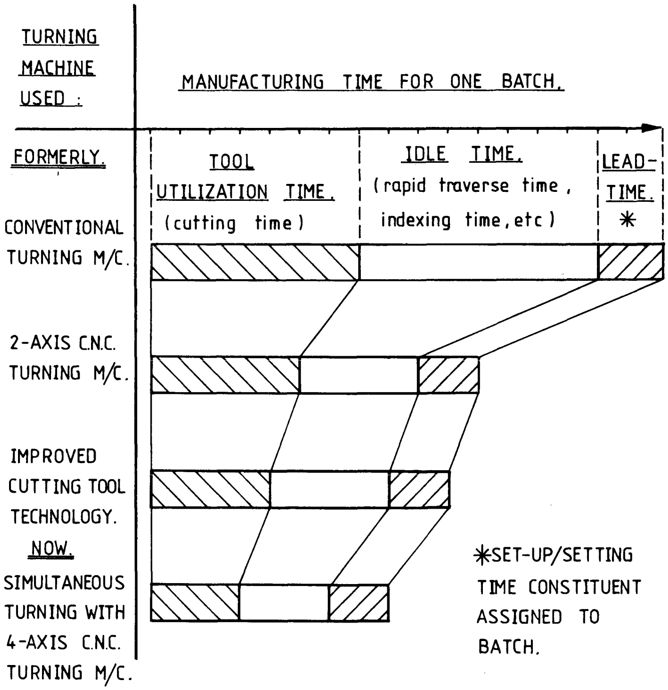


Fig. 1.4. To illustrate how cycle times have reduced with advancing CNC turning technology. [Courtesy of Gildemeister (UK) Ltd.]

This repeatability has the added bonus of reducing inspection, assembly and fitting costs by the virtual elimination of re-work and scrap. Storage of the part program and its retrieval also has the effect of decreasing the lead times over the more conventional manufacturing methods still further. As a consequence of this feature, the skill level is retained by the company and does not leave when the employee moves on, or retires. Other indirect, but crucial advantages accrue through the application of CNC technology and include: the precise processing of changes to the part with the minimum of disruption of production, improved planning and scheduling results, repeat orders are easily undertaken, plus many more attractive benefits. The results of these improvements of reduced tooling requirements and inventories together with the administration benefits can be summarised graphically by the simple profit and loss statement against time, shown in Fig. 1.5. Any machine tool is only making money when it is cutting material (Fig. 1.6) and it is important to maximise this fact by improving the machine's utilisation over second/third shifts and by other non-productive machining time advances, as clearly indicated in Fig. 1.2.

This section has tried to show that positive advantages occur when a company embraces the current CNC technology, but only, hopefully, after an exhaustive feasibility study. Let us now consider how and why CNC machine tools are designed and constructed and then go on to look at their systems of machine control.

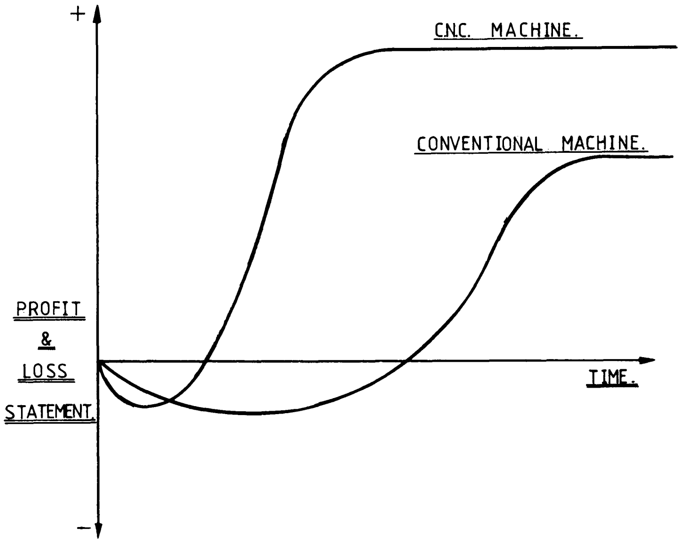


Fig. 1.5. Tooling lead-in time for a new product. NB: There is a definite period of loss before the product reaches the market and using CNC the "cross-over" comes sooner and profit is higher.

1.3 The Design and Construction of CNC Machine Tools

With the development of CNC machine tools from the earlier NC machines, this meant that they were able to impart a degree of flexibility into programming and more particularly editing. These controllers mean that program input and editing has drastically reduced lead-times, making the acceptance of CNC technology to a whole host of machine tools a more attractive proposition. Together with the great advances in CNC electronic developments, the major machine tool casting designs have also been rationalised and in many cases designed around "modular concepts". More will be said on this topic later in this chapter.

1.3.1 Developments in the Design and Cast Structure of the Machine Tool

The structure of a machine tool must fulfil several requirements if it is to allow an accurate and efficient cutting action to take place. The primary requirements for any CNC machine are that the structure should be: torsionally rigid, thermally stable and have adequate vibration damping capacity, in conjunction with precision and accuracy to the moving elements. Torsional rigidity is required to overcome the flexures that result from forces generated by the cutting action. The structure must be thermally stable to overcome the heat generated – not so much by the cutting action, but more particularly as a result of heat generated by bearings, motors and ballscrews, which might otherwise distort the structure through differential expansion/contraction. This factor of thermal drift is becoming a major problem for machine tools when used close to their process capability and in themselves can be the cause of scrap occurring. Any machine tool must dampen the vibrations set up by the cutting action quickly,

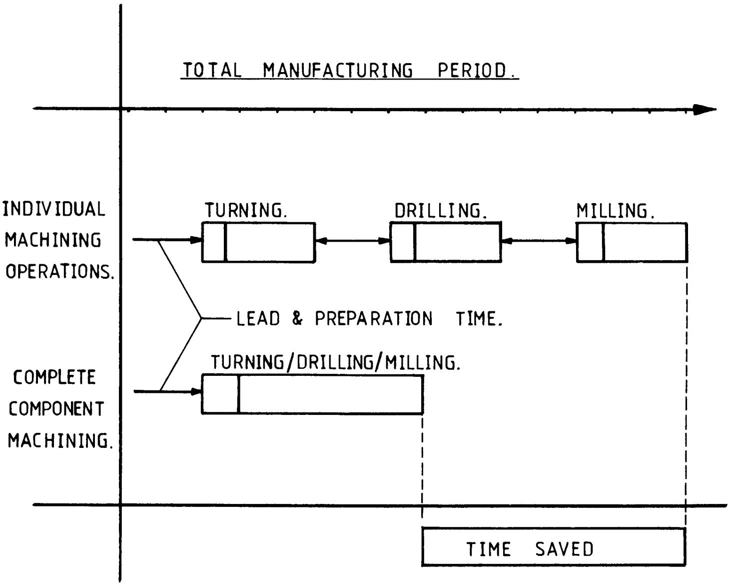


Fig. 1.6. The turning centre with driven tooling considerably reduces work-in-progress, compared with conventional manufacturing methods. [Courtesy of Gildemeister (UK) Ltd.]

otherwise they will have a disastrous effect on the tool life and on the workpiece surface finish generated.

The secondary requirements of the machine tool structure are that the workpiece and tooling are easily accessible to the operator, so that care is taken by the designers to allow ease of access to a machine, which in turn reduces operator fatigue, a major factor attributed to scrap workpieces. Until recently, all of the larger parts of a machine tool's structure were built using cast iron, although some companies have produced partially steel fabricated (welded) with cast iron assemblies fitted into them. Some years ago concrete was employed instead of the welded bases; but although it has been shown to give excellent results, only a few companies have chosen this route. In fact several machine tool builders having tried the welded/cast structures for a number of years, have reverted back to their original cast iron castings because of their superior ability to dampen the tendency for self-exciting vibrations which can attend the machining operation. It should be stated that all machine tool elements have both static and dynamic vibrations present, but the cast iron structures have shown superior vibration damping capacity to the partially welded and cast versions and are less prone to flex under the higher forces generated by the latest cutting tool materials and higher powered drive motors used of late. The very latest material to be used is "Granitan" which is a mixture of crushed granite and a thermosetting mixture to cure and bond it together; this is cold-set and has very high thermal stability, whilst offering much greater damping capacity over cast iron.

If vibration were the only problem when machining then this could easily be remedied, but, the cutting action induces high forces within the cast structure and if it is not robust enough to withstand them, then it may twist and distort slightly promoting poor geometrical and dimensional characteristics to the workpiece. In order to minimise the torsional and distortion problem, a rib, or box-like structure is usually

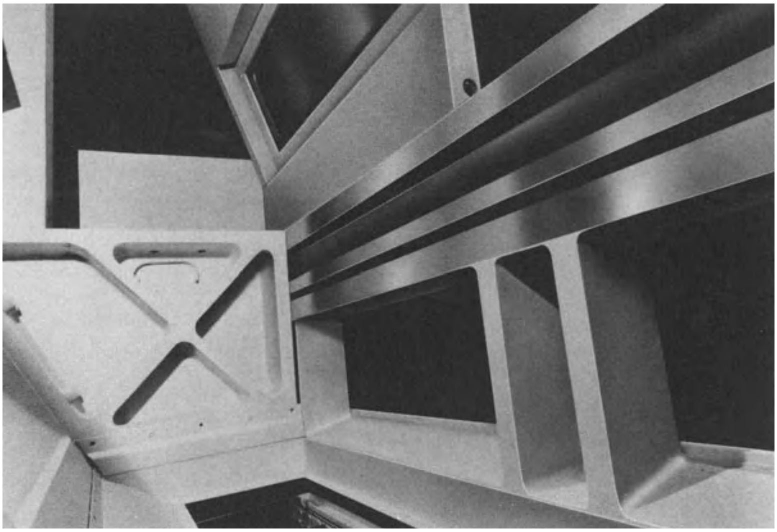


Fig. 1.7. The rib and boxlike construction of the castings. [Courtesy of Cincinnati Milacron.]

employed on the casting as shown in Fig. 1.7. With the advent of unattended machining which CNC allows, the structure of machine tools could be radically changed giving better access and easier swarf removal. Typically, the slant bed on turning centres has evolved which allows for these problems to be more-or-less overcome and is considered superior to the flat bed construction found on conventional lathes. When the lathe bed is slanted, tooling can be more easily reached by the operator, as is true in the case for the workpiece. Swarf build-up has always been a problem area when cutting certain materials and this has been completely overcome in turning using a vertical bed – which is often protected completely by shrouds from the swarf. When cutting long, stringy materials, the use of chip breakers allows the swarf to drop freely away from the cutting region to the bottom of the bed where it is disposed of efficiently.

Recently, many machine tool structures have become rationalised designs and are based upon the "modular concept" philosophy. This "modular" design (Fig. 1.8) allows the machine tool builder the opportunity to standardise certain features over a range of machine tools, benefiting the manufacturer and consumer alike in reducing the development and purchase costs whilst allowing more attention to be given to each "module" in the machine. The same column, or table, may be common to a variety of machines and this trend may be seen across the whole product range of a machine tool company in certain instances. A typical modular concept philosophy can be appreciated throughout the design of the major component parts shown in Fig. 1.9.

A critically important feature of any CNC machine tool is the accuracy/precision of the bedways which provide a datum from where all subsequent workpiece accuracy emanates. This feature must be rigorously assessed as, if inaccuracies are present in the base casting, as other axes are added this accumulation will compound the problem of workpiece inaccuracy. Fig. 1.10 shows nicely the slant bed Z axis, with the X axis assembly mounted in-situ and it can be appreciated that a single large casting is used for the bed with the bearing areas spaced widely apart for extra stability to minimise flexure – which is an important feature to note when purchasing a new CNC

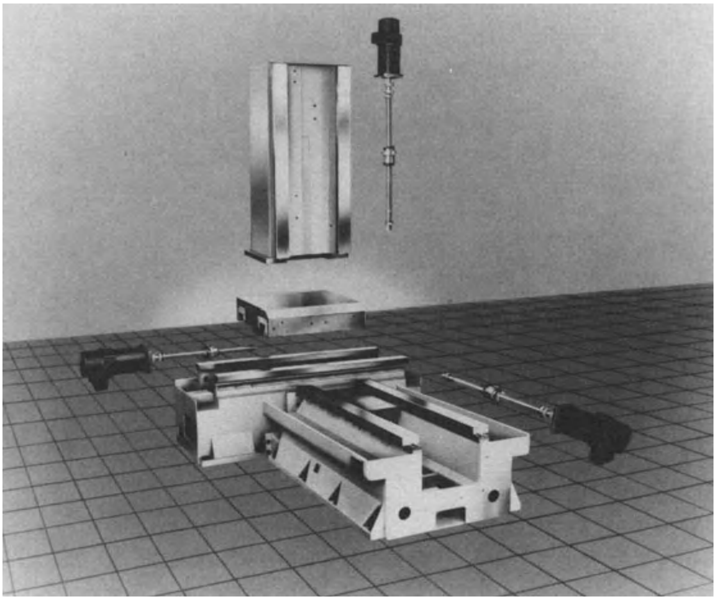


Fig. 1.8. The modular construction of machining centres. [Courtesy of Cincinnati Milacron.]

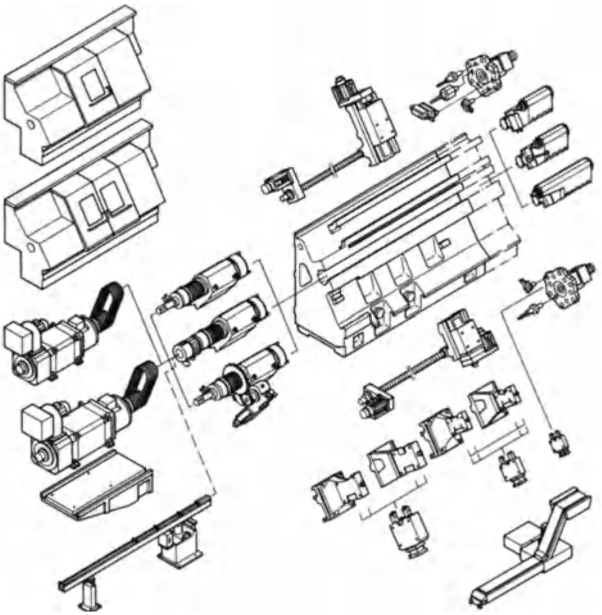


Fig. 1.9. The optional equipment and modular concept for a turning centre. [Courtesy of Gildemeister (UK) Ltd.]

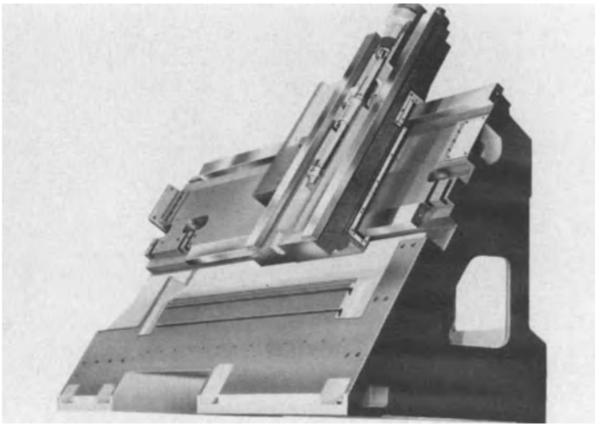


Fig. 1.10. Partial assembly of a turning centre's slideways. [Courtesy of Cincinnati Milacron.]

machine tool. Bedways have always been hardened in the past by using an induction hardening technique, or similar methods, but a more common feature now is to bolt fully hardened steel "ways" directly onto the casting. In particular, in recent years, the major advancements have been in increasing slideway response and overcoming the stiction problem which is present in most conventional bedway designs. As rapid speeds on machine tools have increased to 30 m/min recently, it was imperative that stiction was minimised by reducing the coefficient of friction levels considerably. Slideways are often given treatment such as "stick-free" coating – typically "Turcite". This minimises the "stick-slip" effect and has tended to be used on the lighter cast machine tool structures. When heavy workpiece loads are to be coped with, then hydrostatic slideways are the only choice, as these "oiled" solutions are the only viable alternative on extra large machine tools. With many of the machine tools carrying intermediate loads, a different solution is on offer to the machine tool designer and this utilises the so-called "frictionless" systems. A typical linear bearing assembly has a combination of either rollers or needle rollers assembled into hardened guides and bolted onto the casting and these run the whole length of the axis travel. When the axis travel is particularly long or loads are higher, then the "Tychoway" system might be used (Fig. 1.11). This assembly is in the form of continuous rollers which are situated in the moving members and they bear onto the fixed member either directly, when the surface is hardened, or onto a hardened strip let into the casting's bearing faces.

1.3.2 The Recirculating Ballscrew

Almost without exception, when the machine tool's slideway requires motion, this is transmitted via an assembly known as a "recirculating ballscrew". Fig. 1.12 shows a partially cut-away diagram of just one type of ballscrew assembly mechanism. The assembly shown in Fig. 1.12 has the flanged nut attached to the moving member and the screw to the "fixed" casting. Thus any rotational movement of the screw will displace the moving member's slideway in the desired direction. These recirculating ballscrew designs can have ball cages of internal or external return, but all of them are based upon the Ogival or "Gothic arch" principle. This geometry ensures that a point

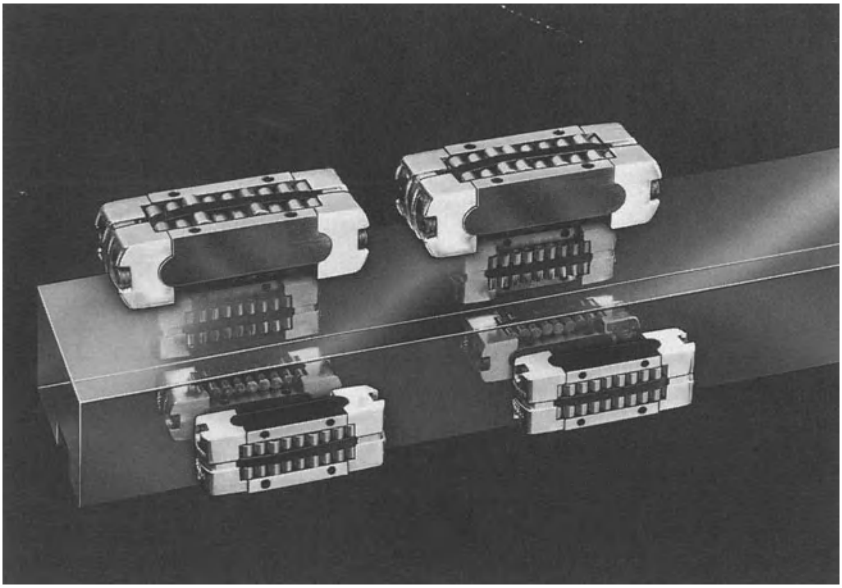


Fig. 1.11. "Tychoways" situated strategically along the hardened way of a machine tool for efficient transmission of loads and motions. [Courtesy of Cincinnati Milacron.]

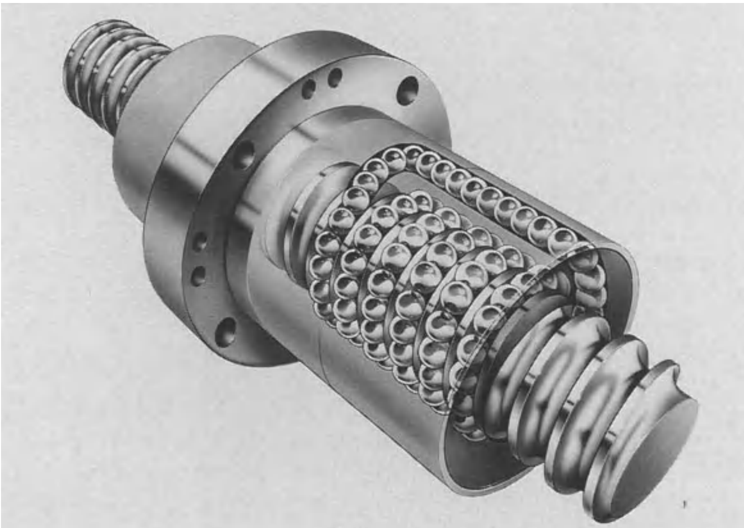


Fig. 1.12. A typical arrangement of a recirculating ballscrew assembly for efficient transmission of motion of slideways without "backlash". [Courtesy of Cincinnati Milacron.]

contact occurs between the ball, its nut and the screw, giving low friction with over 90% efficiencies. With the ultra-fast "rapid" motions of some of the latest CNC machine tools being around 30 m/min, some ballscrew assembles are of the two-start Ogival type and are needed to cope with such high translations of motion. As expected, the accuracies of such ballscrews are high, in the region of 0.005 mm over 300 mm being possible and on large machines these ballscrews may be of considerable length with high values of stiffness, up to 2000 N/μm.

The traditional Acme thread used on conventional machine tools has efficiencies ranging from 20% to 30%, but although this is significant, it is not the main reason why ballscrew assemblies have superseded them. The real reason for their universal acceptance by machine tool builders, is that they can be pre-loaded in-situ and in such a manner overcome any backlash which might otherwise be present in "normal" thread assemblies. Ballscrew assemblies vary in their method of achieving zero-backlash and are available as either single, or twin-nut designs with such features as vernier adjustments in the more expensive designs for accurate pre-loading level adjustments. These vernier systems can be precisely set to the required pre-load level, whereas the other ballscrew systems require a ground spacer to be fitted between the two flanged nuts. These hardened and ground ballscrew assemblies require little, if any maintenance during their working lives once "torqued-up" and set. Every ballscrew, however accurately ground it is, will have errors in its pitch present. This inaccuracy is removed upon laser calibration at the final assembly stage when alignment errors are assessed and these pitch errors are fed into the machine control unit at precisely displaced intervals (Fig. 1.13). This means that despite pitch inaccuracies occurring, the controller adjusts – in other words, compensates for – the slideway position to eliminate this error and move the axis to the command position given by the CNC program.

1.3.3 Drive Motor Advances

Complementary and in situ with the ballscrews are the main motor drives which are usually of several types:

stepper motors (these will be discussed in section 1.4.1)
DC motors
AC motors
digital drives

The power of DC motors has increased the metal cutting capability of CNC machine tools in a similar manner to that of advances in the cutting tool materials available and their geometries over the last few years. In 1900 a turning operation on a bar of steel 100 mm in diameter and 500 mm long would have taken about 105 min. By 1970, owing mainly to cutting tool improvements, the time taken to machine a bar of the same dimensions was down to 1.2 min. Today, a time of half the 1970 value is possible, with the added bonus that if a facing-off operation is required on a bar, a constant surface speed could be used. With DC motors, the trend at present is to use Thyristor/Triac controls to be fitted to machine tools. Asynchronous motors with variac controls which were fitted to the older machine tools could only achieve a speed range of 1:4. By using gearboxes the range could be enlarged to over 10 speed ranges in a geometric progression. The problem with the older system was that even with the highest speed selected, the range was not great enough to optimise the new speeds required by the latest cutting tools and to obtain a constant surface speed requirement. DC motors allow the advantages of higher speeds available with a better ratio between the lowest and highest speeds and this simplifies the gearbox requirements, whilst their high torque characteristics enable them to turn large diameter bars at low surface speeds.

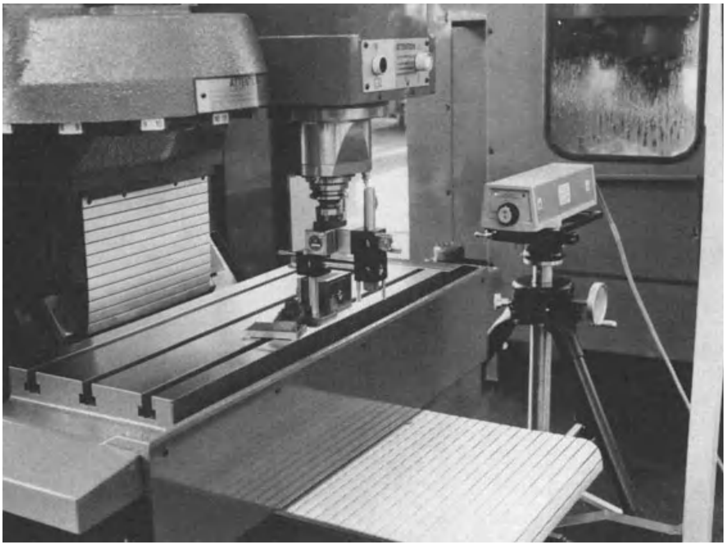
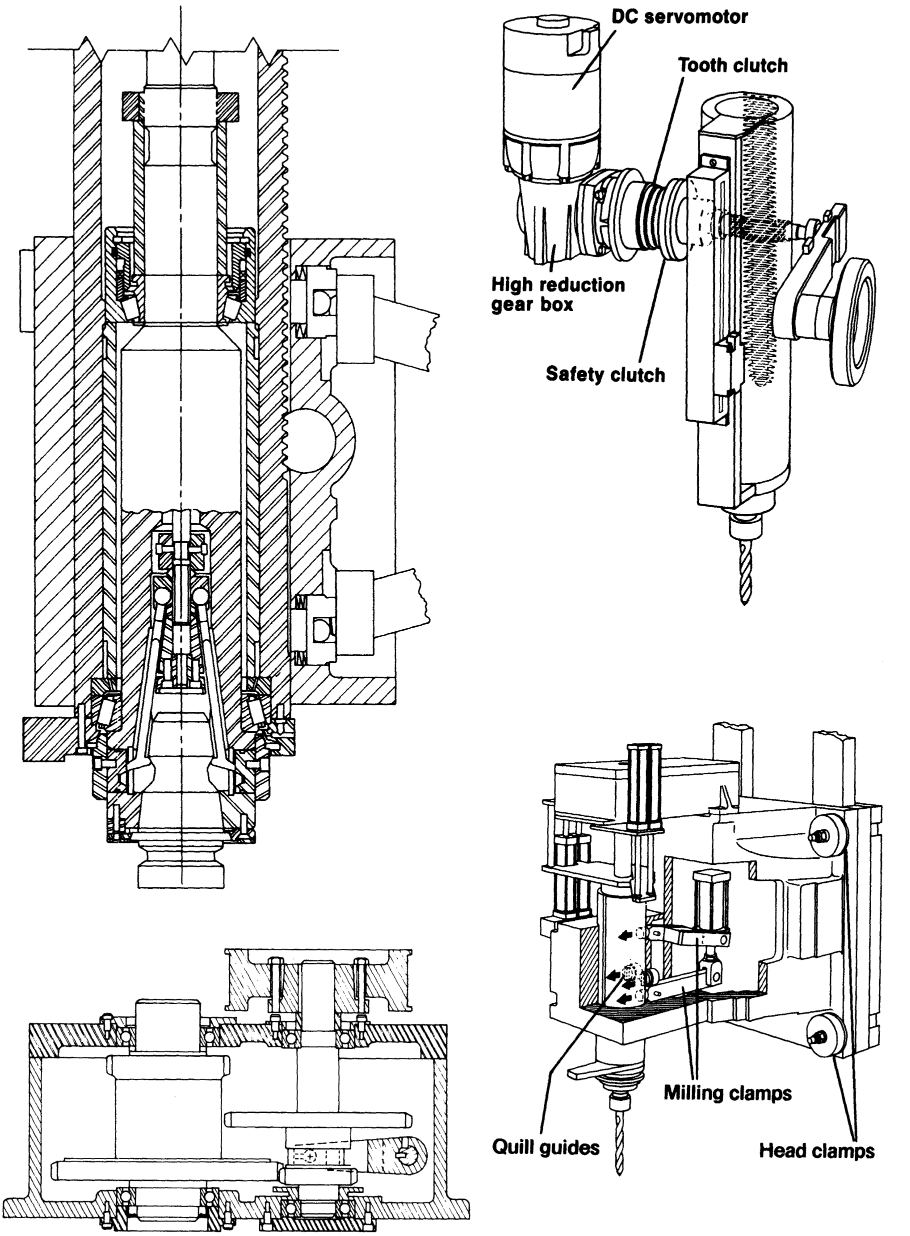


Fig. 1.13. The final test area, prior to alignment testing (laser calibration assessment). Each machine tool is run continuously to check both electrical and mechanical performance before acceptance. [Courtesy of Bridgeport Machine Tools.]

Metal removal rates under constant conditions of cutting speed, depth of cut and feedrate, will keep the cutting forces constant, so that when the bar diameter is increased the torque increases accordingly – hence the need for the high torque at low speed. Rapid advances have occurred with high-power control technology and this has meant that a reappraisal of DC motors for CNC machine tools has taken place.

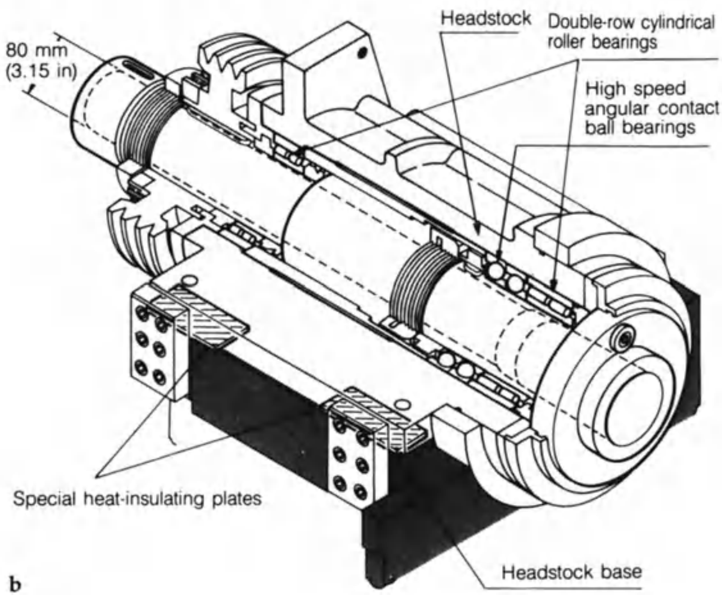
The advantages of using AC induction motors over other types is that they tend to be more reliable and easily maintained, yet are less costly than most other motors. Obtaining rotation reversal of direction is simple with these three-phase AC motors and it is possible using pole-change motors to obtain four speeds in arithmetic progression such as: 350, 700, 1400, and 2800 rev/min, or similar. AC motors are not usually used for driving the main spindle directly – apart from the pole-change motors, as expensive and specialised electrical equipment is needed to provide high power with accurate stepless variable speeds. Whenever there is a need to drive the main spindle directly, it is usual to utilise a mechanical variable speed unit in order to obtain spindle speed variation. By 1984, it became possible to produce speed control and variation of AC motors, by frequency variation of the electrical supply; this resulted in a more general adoption of the AC induction motor by industry.

Recently, digital drives have become an important addition to machine tools, particularly with the advent of machines requiring ultra-high speed spindle rotations and more importantly rapid feedrates in two, or three dimensions. Such drives have very fast response times and are ideal for minimising the "servo-lag" problems associated with high speed cutting operations, "data-starvation" – causing problems on part geometries and the tendency for cutter vibration, together with improved cutter accelerations/decelerations. However, this will be discussed in more detail in the following chapters.



a

Fig. 1.14. **a** A typical spindle system for a machining centre. (i) A large diameter spindle rides in tapered roller bearings in a quill which is chrome plated and ground for smooth motion and long wear. Tapered roller bearings have 6 times more stiffness than ball bearings to provide a net 50% increase in milling rigidity. At speeds above 1400 r.p.m., the bearing preload is automatically reduced by 30% to assure cool operation and long life. (ii), (iii) Quill guides provide accurate z-axis tracking. Milling clamps are automatically energised during the milling cycle. (iv) The DC spindle drive motor is blower cooled. Filters are easily inspected.



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b The construction of a turning centre headstock. The headstock is designed to minimise the effects of thermal distortion in order to provide high accuracy over extended periods of continuous operation. The symmetrical spindle housing is separated from the machine bed by a special insulation plate so that any heat generated by operation will not displace the spindle centre. In order to supply the rigidity required for heavy duty cutting, the spindle is supported by double row cylindrical roller bearings and combined angular contact ball bearings at the front, and double row cylindrical roller bearings at the rear. [**a** Courtesy of DSG/Monarch; **b** Courtesy of Yamazaki Mazak Corporation.]

1.3.4 Headstock and Main Spindle Design

Probably the most important element in the complex build-up of CNC machine tools is the main spindle on a machining centre or CNC mill, or the headstock on a turning centre or lathe. The crucial element of its design and subsequent assembly directly affects the workpiece quality. Fig. 1.14a shows a simplified diagram of a typical machining centre spindle system, illustrating the attendant shafts, bearings and gears, being of robust construction. Often the main spindle is refrigerated or the oil supply is kept at constant temperature in order to minimise the effects of thermal expansion. Figure 1.14b shows a typical advanced turning centre headstock spindle assembly with its sophisticated arrangement of bearings and heat resistant material strategically positioned to act as a "heat sink" to minimise the thermal growth and possible distortion of the headstock assembly. If any growth due to thermal effects occurs in the headstock its design should allow it to "grow" axially, thus minimising the effect on workpiece accuracy.

1.3.5 Auxiliary Equipment Fitted to Turning Centres

An important element on any turning centre when turning between centres, is the design and adaptability of the tailstock and the ability to remove it from the cutting zone when it is not required. Tailstocks tend to be of either the solid, partially programmable, or fully programmable varieties, with increasing versatility being with the latter type. If tailstocks are of the solid casting type then their use is rather limited to supporting the workpiece only and some simple machining operations during the CNC program, whereas the partially programmable type can be "latched-up" to the centre-line for work support between centres, or used for drilling etc., if mechanically attached to the cross-slide, which is a provision most machine tool companies offer. Figure 1.15 shows a partially programmable tailstock in the "latch-up" position supporting a workpiece whilst locked in position on the lathe bed. By far the most universal variety is the fully programmable tailstock which offers all the features of the partially programmable version, but in addition has a continuous feed control of the barrel enabling a range of hole generating processes to be achieved totally independent of the cross-slide operation. The barrel's oil pressure can be adjusted by a hydraulic restrictor to give a variation in clamping force to the component; this is necessary because small diameter work would distort or deflect otherwise.

The problem of rough turning operations is the nature and volume of swarf generated during cutting the workpieces under production conditions. The former problem of continuous swarf can be minimised by using chip-breakers on the cutting tools (more will be said on this topic in chapter 2) whereas the volume of swarf would build up to unacceptable levels and interfere with the cutting process if not removed. By supplying a swarf conveyor on a turning centre, the swarf can be deposited in a container well away from the cutting region. There are several varieties of design of swarf conveyors, ranging from the most common chain-type to the rotating spiral

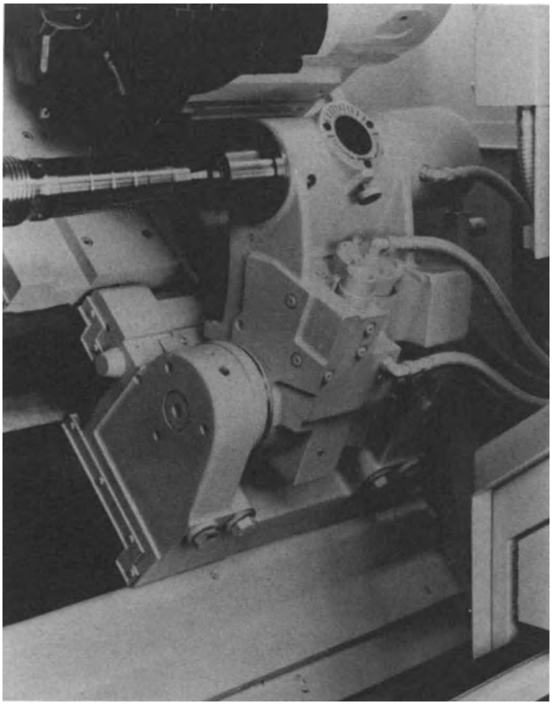


Fig. 1.15. A partially programmable tailstock supporting a long workpiece in the "latch-up" position. It can be "latched-down" (lowered) when not required. [Courtesy of Cincinnati Milacron.]

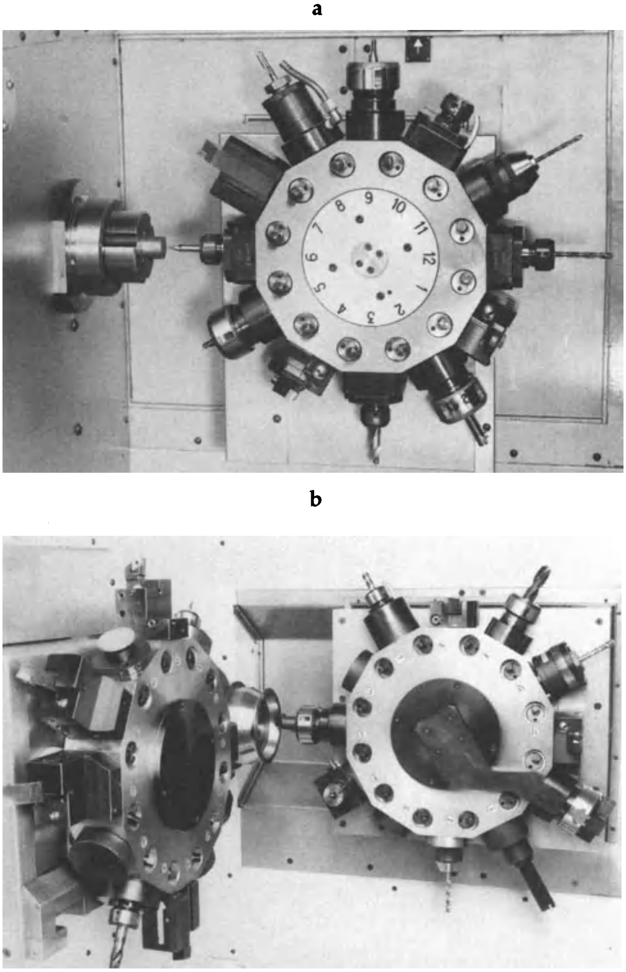
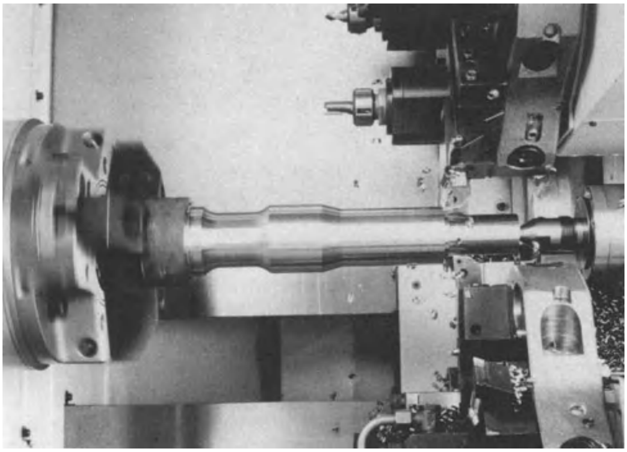


Fig. 1.16. Turret configurations. **a** 2-axis, driven/conventional tooling. **b** 4-axis, twin turret with driven/conventional tooling. [Courtesy of Gildemeister (UK) Ltd.]

versions, but they all achieve the desired effect of removing unwanted swarf from the machine.

Automatic and programmable tool changing mechanisms are an essential feature on any turning centre and usually of the indexable turret variety typified by Fig. 1.16. The two-axis version is normally a single type whilst the four-axis configuration has the ability to machine several features on the same component, typically roughing and finishing operations – known as "balanced turning" (Fig. 1.17a), or individual features on the same component such as turning and boring (Fig. 1.17b), or to machine dimensions on separate components, when an auxiliary spindle is present. To give the turning centre even more versatility it is possible for most machine tool companies to offer machines with a "driven/live spindle" to most, or all, of the turret positions if required. This allows the programmer to specify drilling or milling operations on the component using a rotating tool station (Fig. 1.18). This useful feature of powered tooling requires at the very least, some form of indexing control to the headstock a



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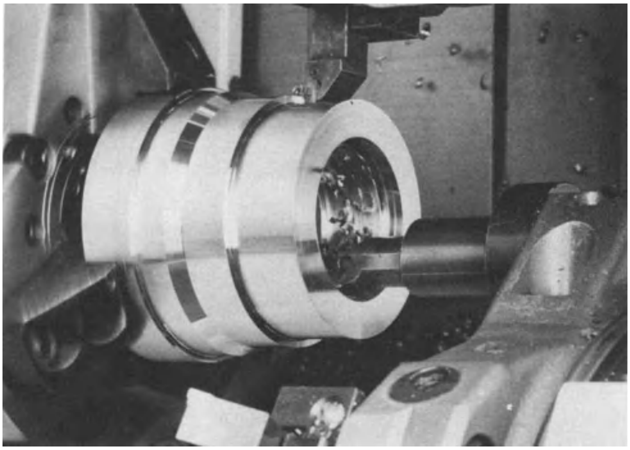


Fig. 1.17. **a** "Balanced turning" produces fast stock removal, or different features to be machined simultaneously. **b** Twin turrets allow versatility, i.e. to turn and bore simultaneously. [Courtesy of Gildemeister (UK) Ltd.]

spindle, allowing such features as: flats, slots, and splines, etc., to be machined on prismatic parts. The indexing "C-axis" will clamp the headstock spindle at the required angle via a "shot-pin" which positively locates into an index plate slot, then the feature to be milled, drilled, or tapped etc., can be accomplished with a degree of accuracy and constraint.

For completely universal machining capabilities on a turning centre using the so-called "one-hit" cutting capabilities in just one set-up, the machine tool needs to be equipped with a fully programmable "C-axis" control to the headstock spindle coupled to a "driven tooling" facility (Fig. 1.19). By using such a combination of full "C-axis" control and "live tooling", this will, in one sense, negate the need for using, say, a machining centre to complete the part. "One-hit machining" has several major economic benefits:

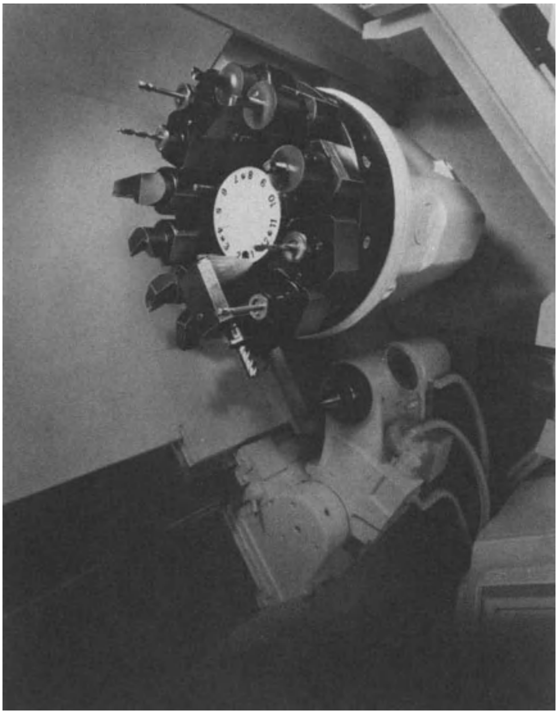
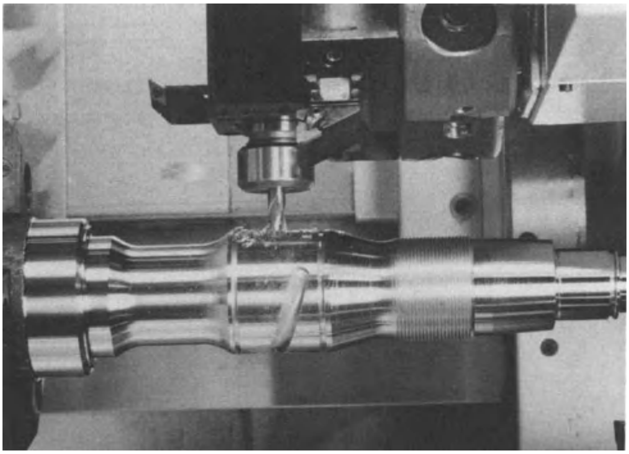


Fig. 1.18. A "driven tooling" facility will increase a turning centre's versatility to machine a range of prismatic parts. [Courtesy of Cincinnati Milacron.]

it reduces capital outlay on a second machine tool
it significantly cuts down work-in-progress times
it increases the range of component parts to be machined by the turning centre
it improves the overall machine tool efficiency by increasing the productive cutting time
higher quality parts result as the turning centre completes the parts at one set-up on the machine
it uses less floor space, therefore only one machine tool is necessary, rather than two

NB: Although a turning centre with "driven tooling" has such versatility and the ability to cut a large universal range of products, it is not cheap to purchase initially but has the advantage that its pay-back period is considerably reduced and offers better utilisation than the more "simple" turning centres. Figure 1.20 shows just some of a whole host of cutting tool configurations of the "live tooling" variety which can be held in the tool turret and this increases the machining capabilities of turning centres considerably.

Obviously a turning centre is only making money as it cuts metal; this means that delays in the supply of workpiece material will have serious consequences on the efficiency and overall productive capability of the machine tool. To minimise any non-productive time that would otherwise accrue, automatic bar-feeders housing wrought bars can be supplied to the machine (Fig. 1.21) and these feed lengths of material



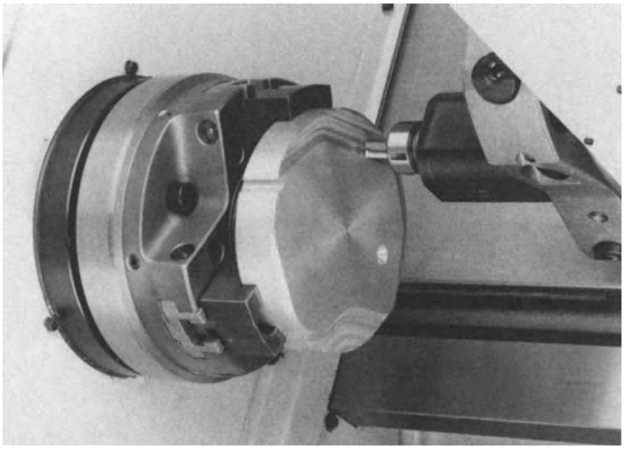


Fig. 1.19. To show just some of the cutting capabilities when a fully programmable "C-axis" headstock spindle, utilising a "driven tooling" facility is available. [Courtesy of Gildemeister (UK) Ltd.]

through the headstock spindle for the manufacture of parts. Some bar-feeders are of quite sophisticated design with "silent-running" capabilities; these also allow new lengths of bar stock to replenish the bar-feeder when the previous one has been consumed. When automatic bar length loading accessories are present, then an untended machining condition is possible with large batch runs.

When it is necessary to machine either long workpieces or those requiring support whilst either centre-drilling or boring, then a very useful accessory is the programmable steady. The programmable steady (Fig. 1.22) supports the part in order to eliminate the effects of the cutting force and its subsequent displacement of the work during machining operations – this would be a particular problem whenever it is necessary to completely machine a long, thin bar along its entire length. Steadies are usually of two types, those:

with a separate motion along the bedway of the turning centre,
fixed onto the turning centre turret (as shown in Fig. 1.22).

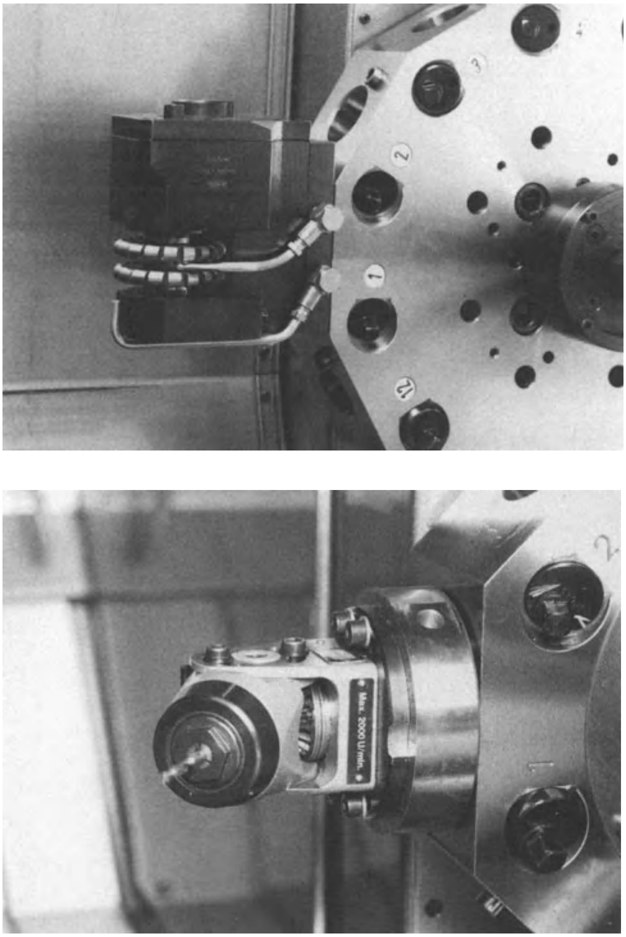


Fig. 1.20. "Driven tooling" configurations can be quite sophisticated, ranging from (*above*) straddle milling to (*below*) adjustable angled heads on a turning centre turrets. [Courtesy Gildemeister (UK) Ltd.]

In either case, the rolling element supports are positioned on adjustable fingers which automatically open, or close, according to the diameter to be supported.

In order to minimise the damage to the completed workpiece an automatic part-catcher is a useful addition to a turning centre. Part-catchers come in a variety of designs and have different methods for catching the workpieces. As the surface finish is often a criterion used in assessing the part quality, then any damage to its surface once machined will obviously affect the quality attributes on the drawing and may lead to the workpiece being scrapped. Therefore the part-catcher should collect the workpiece and deposit it into a receptacle and avoid damage to the finished part by gently guiding the components to their respective parts bins.

To complete this over-simplified and brief view of just some of the auxiliary equipment offered by machine tool companies on turning centres, it is worth returning once again to some other interesting tooling configurations available today. Fig. 1.23 illustrates a synchronised dual turret mechanism that has been partially cut away to

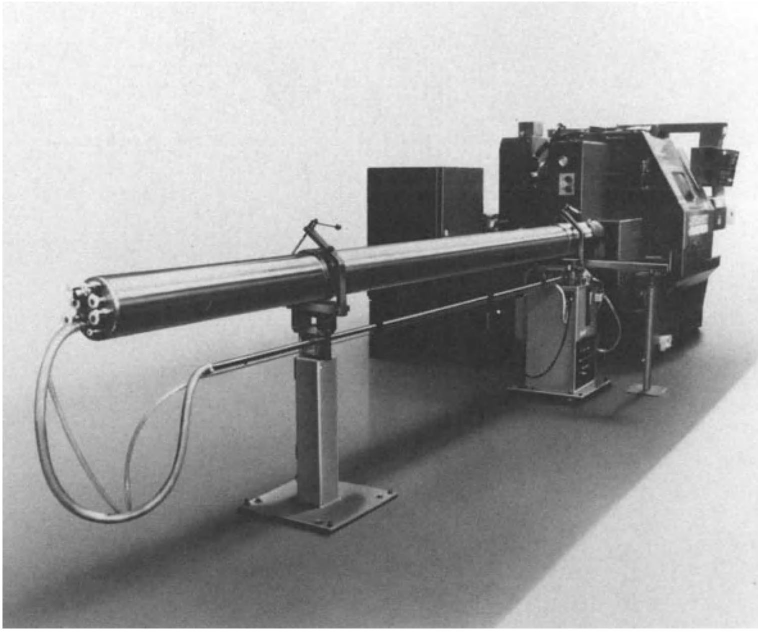


Fig. 1.21. A "silent running" automatic bar-feeder for uninterrupted production of parts. [Courtesy of Cincinnati Milacron.]

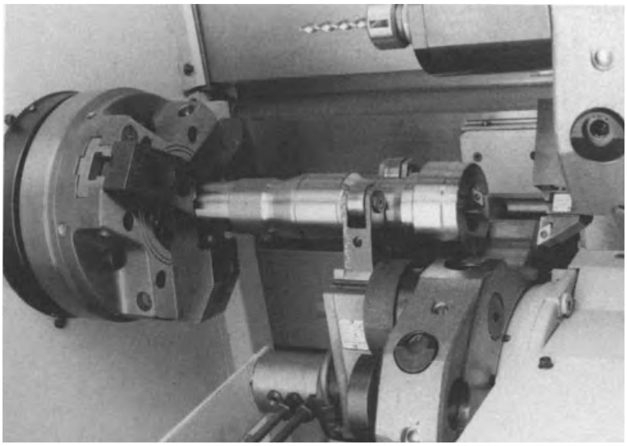


Fig. 1.22. A programmable steady for long workpiece support. [Courtesy of Gildemeister (UK) Ltd.]

show the internal constructional details of its assembly. As can be appreciated from the photograph, the external tooling is held in the lower drum turret whereas the internal tooling is located on the larger turret. This design considerably increases the versatility and range of cutting tools available for component production. The final tool holding mechanism, shown in Fig. 1.24, utilises an automatic tool delivery system to the turning centre via a gantry robot. This type of tooling arrangement decreases

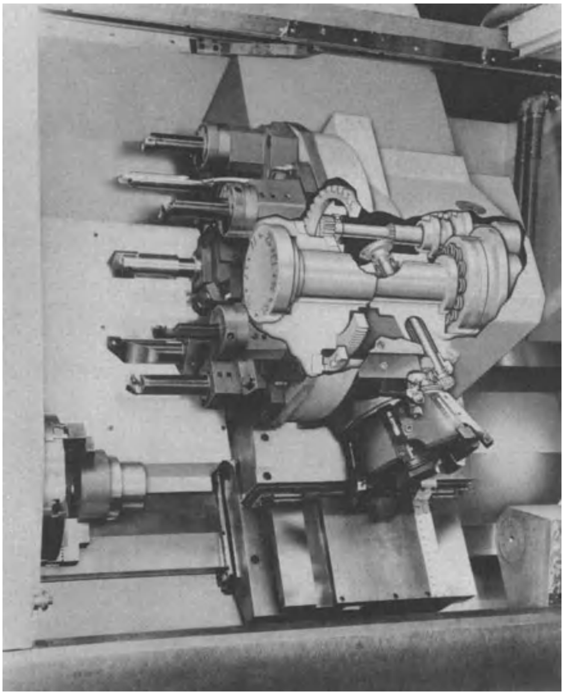


Fig. 1.23. Synchronised dual turret mechanism. [Courtesy of Cincinnati Milacron.]

the amount of tooling held on the turning centre at any instant and allows "sister-tooling" concept (this means a duplication of much-used tooling) to be incorporated, whilst a large tool library is held in the buffer-store of a chain-type holder. The versatility of tooling configurations is increased phenomenally by such mechanisms and they are often incorporated into Flexible Manufacturing Systems, but are not unusual in the larger "stand-alone" turning centre applications and auxiliary equipment.

1.3.6 Tooling Mechanisms and Auxiliary Equipment Used on Machining Centres

As with turning centre tool-carrying configurations, machining centres are just as diverse, ranging from relatively simple geneva-mechanisms for turret indexing with a small tooling complement, to highly complex and sophisticated tool storage and delivery methods. Typical of the drum-type of tooling carousels is the one shown in Fig. 1.25, where a large machining centre is fitted with twin rotary carousels holding a considerable tooling inventory. The tool transfer mechanism is situated above the machine's horizontal spindle and can extract tools from both magazines by pre-selecting the next tool to be used whilst cutting continues. These tool magazines are bi-directional, meaning that the quickest time for indexing the carousel results from it taking the shortest route to the tool-change position. Tool pre-selection in such a manner means that the non-productive idle-times are reduced to a minimum. A different approach to tool storage is shown in Fig. 1.26, where the chain-type of

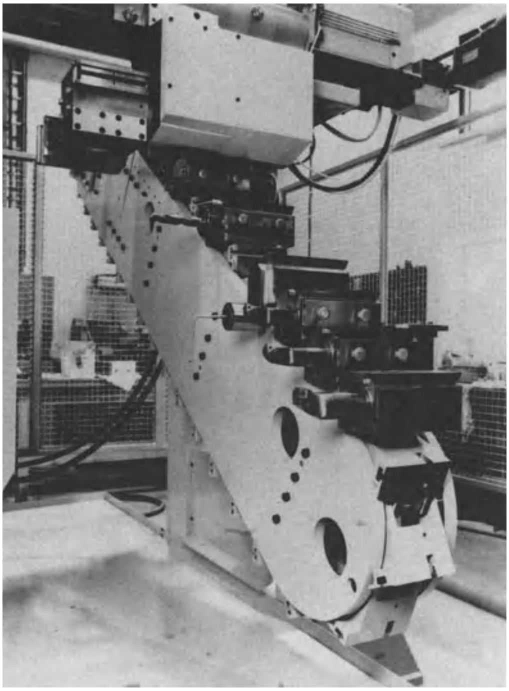


Fig. 1.24. Automatic toolchanger for a turning centre using a gantry robot. [Courtesy of SMG Co. Ltd.]

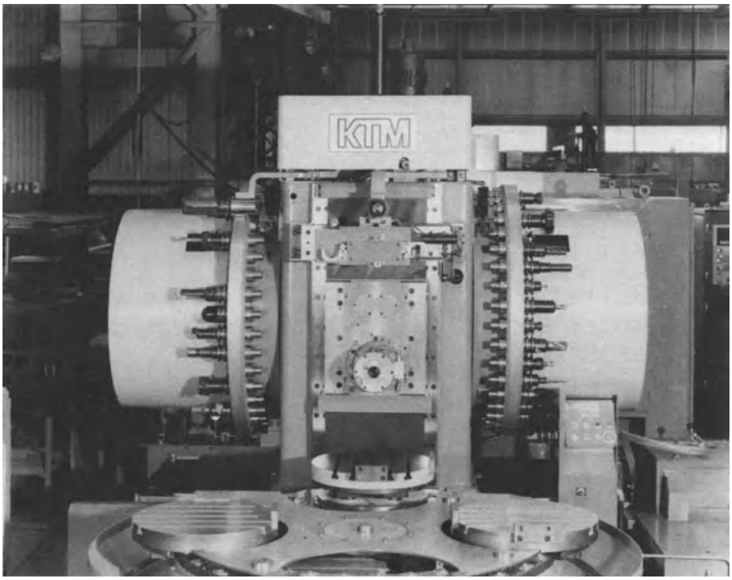


Fig. 1.25. Twin rotary carousels on a palletised horizontal machining centre. [Courtesy of FMT Ltd.]

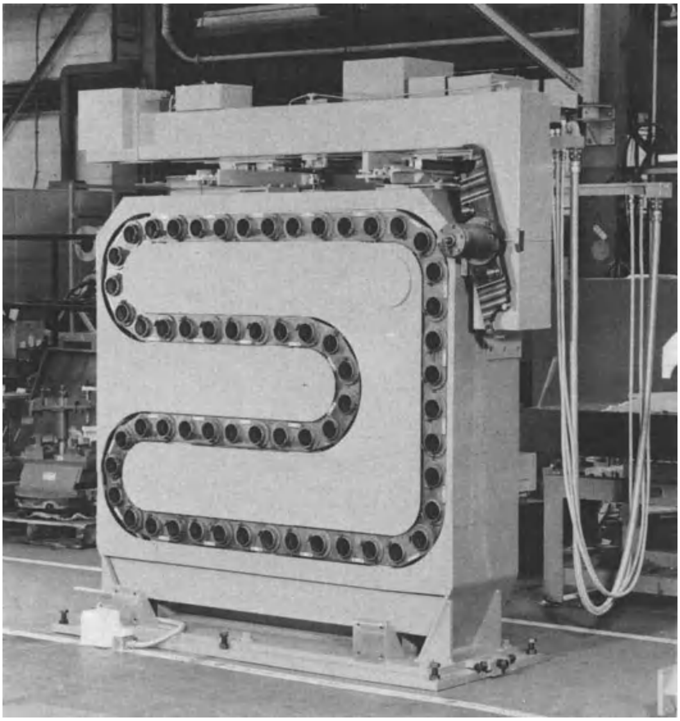


Fig. 1.26. A 60 tool capacity chain-type magazine for a machining centre. [Courtesy of FMT Ltd.]

magazine is depicted. This type of tooling configuration lends itself nicely to the "banking of magazines". With the "banking" approach to tool storage, the inventory of tools held can be increased by positioning side-by-side similar tool magazines allowing the capacities to be increased in steps of 60. Thus with only one magazine 60 tools can be held, with two 120 tools may be carried, with three "banks" 180 tools can be used on the machining centre. Obviously there is a finite limit to how many magazines can be "banked" for each machine tool and when a greater capacity is required this means using a different approach to tool delivery. More will be said on this topic in chapter 6. Yet another chain-type method of tool carrying is that shown in Fig. 1.27, where two magazines of tools are situated above and below one another and this application also lends itself to the "banking" technique, up to a maximum of three banks – giving a total of 270 tools. As can be appreciated by observing the photograph, the range of tooling carried by such magazines is immense. The tooling inventory ranges from: small drills and endmills, to multi-spindle drilling heads, special-purpose tooling and large side-and-face cutters mounted upon stub arbors, to tool-sensing probes (i.e. touch-trigger probes). Clearly, when large diameter tools are held in their respective tool pockets, then the adjacent pocket either side of this tool must be left empty to avoid them fouling one another. This fact can be appreciated by looking at the large diameter face mill shown in the bottom left-hand position of the lower magazine in Fig. 1.27 and at other positions in the photograph. Whenever a large tooling load is to be carried by a magazine it is important to "balance" the loads within it, by situating the heavy tools evenly throughout the tool pockets as this

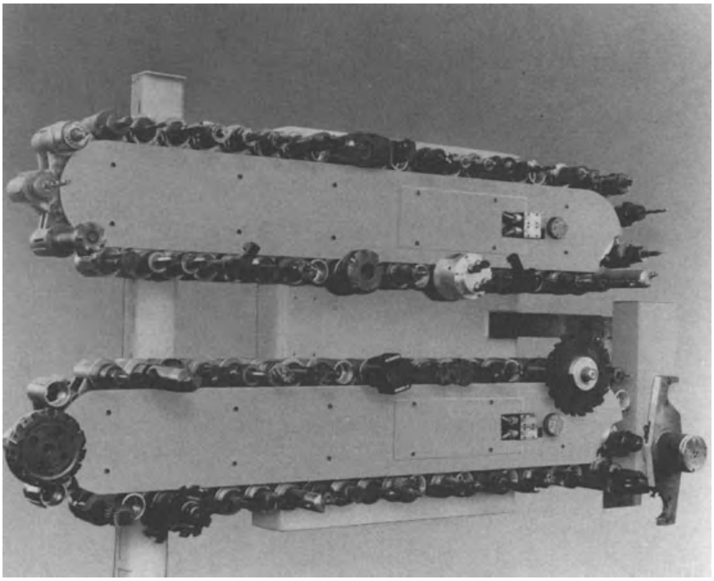


Fig. 1.27. A 90 tool capacity auto-toolchanger magazine (chain-type). [Courtesy of Cincinnati Milacron.]

ensures that an out-of-balance effect is not created in any particular area of the chain. This approach to "balanced" tool loading within the magazine can be appreciated from Fig. 1.27 where the large tool masses are distributed throughout each chain. If out-of-balanced tooling occurs there is a tendency for high inertial effects to be present within the chain and this may lead to premature seizure of the chains or tools jamming.

When a really large scale tooling capacity is needed – often in an FMS environment, rather than with the large "stand-alone" machining centres, then the "hive" tooling approach is often used. This simply consists of "racking" the tools in a storage unit and using a tool transfer mechanism to deliver them to the machine tool. This "hive" method allows a high density of tooling to be achieved in a relatively small floor area.

It has been shown in the previous comments and photographs that great importance is given to the tool change mechanism, as this will directly affect the non-productive idle times during the manufacture of a part. In order to achieve efficient tool transfer the tool changer has recently been the subject of intensive design changes by the machine tool manufacturers. Typical of a large-scale tooling complement with a heavy-duty tool change mechanism is the one illustrated in Fig. 1.28, where the whole assembly can be appreciated. This assembly will form the basis of an explanation in a step-by-step manner of the actual tool changing sequence (Fig. 1.29). In Fig. 1.29a, whilst the machine tool continues performing the cutting operations, the magazine is rotated by the shortest route until the required pocket appears at the tool change position – in this case a twist drill will be the next tool chosen. The machining is completed and the double tool change arm removes the drill from the pocket (Fig. 1.29b) and slides down to the position where tool changing can begin and whilst this is occurring the magazine rotates to the empty pocket which is ready to receive the slot drill. In Fig. 1.29c the photograph shows how the double tool change arm has swung through 90° and gripped the slot drill in the machine's spindle. The double

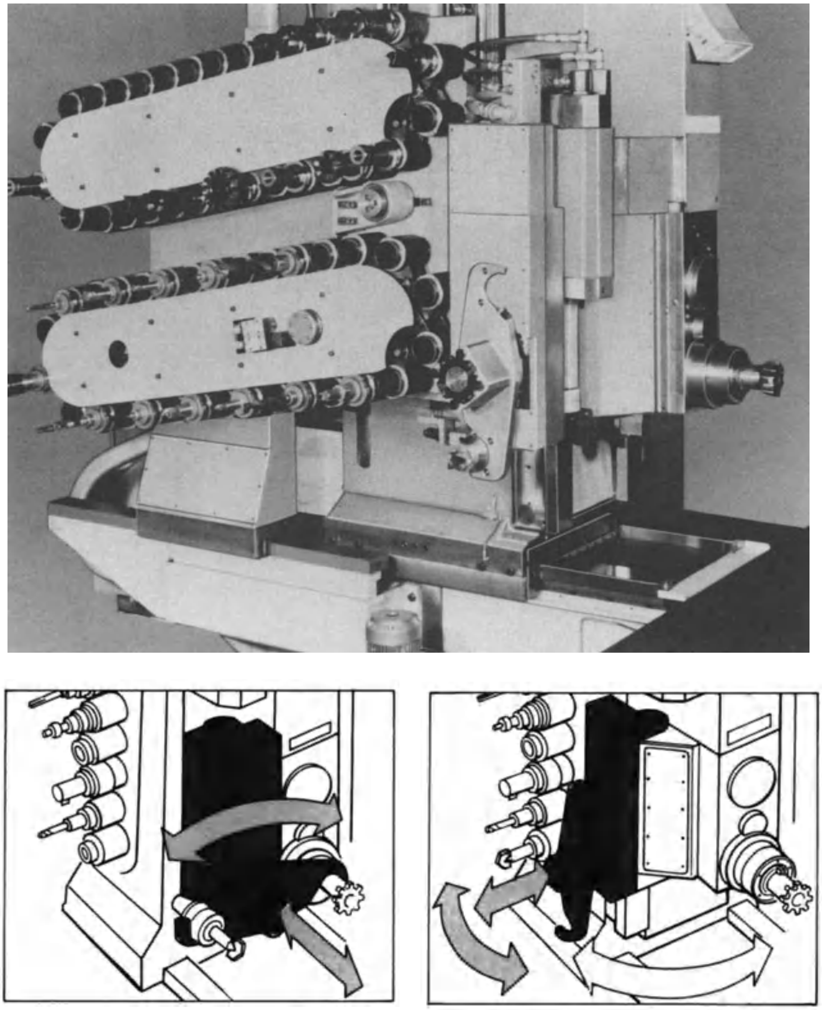
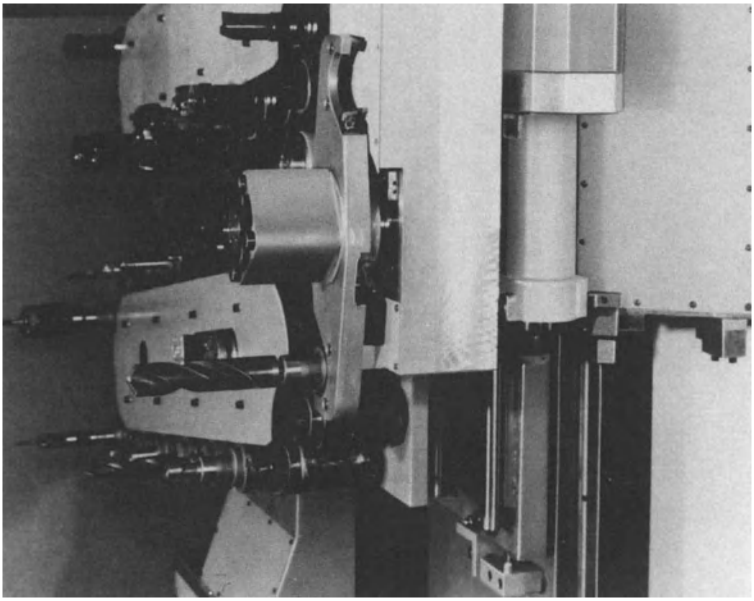


Fig. 1.28. Automatic toolchange using a double-ended index arm. The diagrams show the tool index arm movements. [Courtesy of Cincinnati Milacron.]

arm then indexes through 180°, after the hydraulic draw-bar has released the pull stud on the tool adapter and lifted clear of the spindle nose (Fig. 1.29d). It places the twist drill into the spindle nose, then it is free to withdraw from the vicinity swinging back to the tool chain to place the slot drill into its correct pocket, so that cutting can recommence. Several points should be made before we dismiss this tool changer from our thoughts. During the removal of the slot drill from the spindle nose by the hydraulic draw-bar, once disengaged from the pull-stud on the tapered tool adapter it has an air-blast through from the back of the tapered seating face. This blast of air removes any debris situated in the vicinity of the spindle nose and continues until the new tool is firmly seated in the spindle taper. This continuous air-blast will also clean the new tool of any debris which it might have picked up, allowing a positive seating in the spindle nose.



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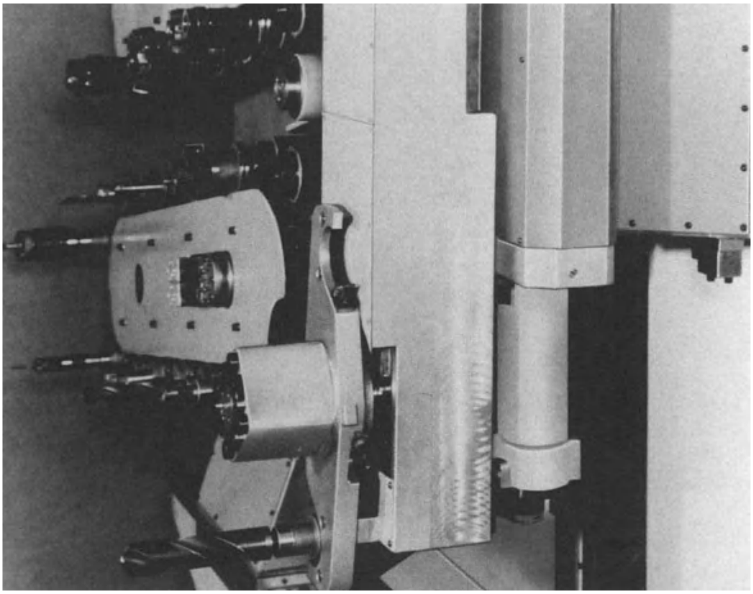
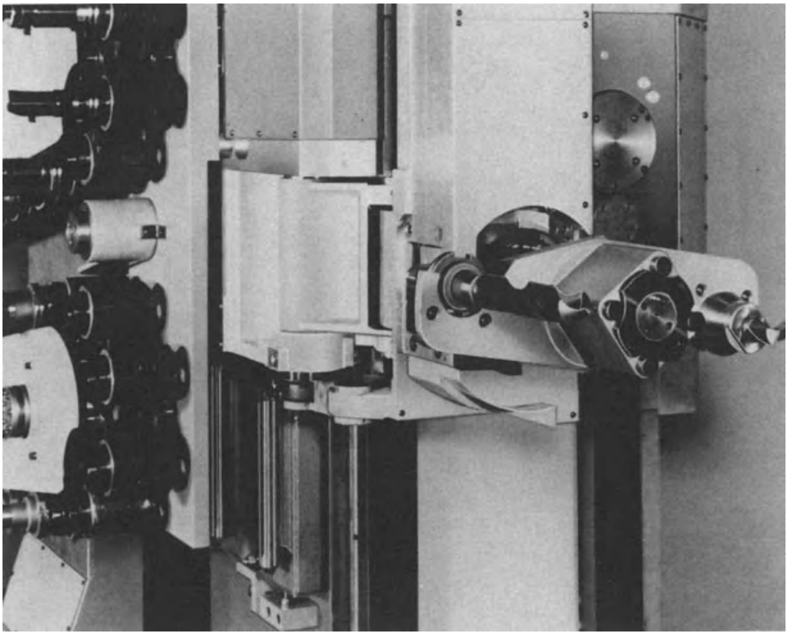


b

Fig. 1.29. **a** Whilst machining continues, the tool is found in the magazine (twist drill). **b** The double arm removes the drill from the pocket and the magazine rotates to the empty pocket ready to receive the slot drill (in spindle). **c** The double arm unit swings through 90° and grips the slot drill. **d** The double arm indexes through 180°, placing the drill in the spindle. It then withdraws and puts the tool in the pocket and machining recommences.



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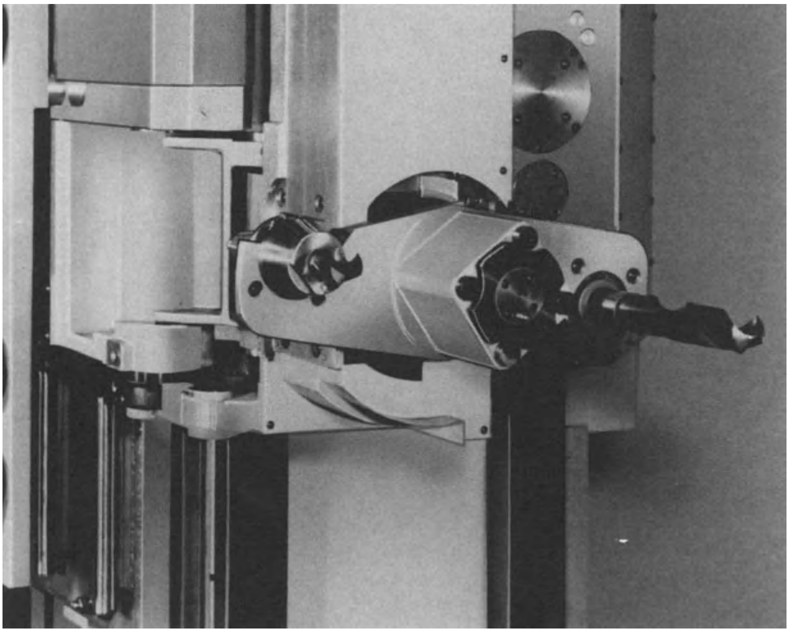


d

A tool-changing sequence similar to the one described in Fig. 1.29 would have a cut-to-cut time approaching 20 s and is reasonably slow compared to some of the latest versions offered. This is not meant as a criticism as these heavy-duty systems, and tool loads of necessity would suffer from inertial effects if there were great increases in speed. However, some of the lighter-duty machine tools with smaller tooling capacities and light tool loads can literally be swung over the Z-axis of the machine's spindle and the cutter. It is then positioned in its correct pocket by a downward slideway motion of the Z-axis, in the case of a vertical machining centre. The axis travel is then reversed and the magazine is rotated until the new tool is below the Z-axis and this tool is picked up by the movement downwards of the Z-axis slideway and when it is clear of the magazine the whole tool carousel will swing out of the way. This tool change mechanism has fewer moving parts than most conventional systems and relies on the fast up and downward motions of the Z-axis. It can typically change tools in less than 2 s, giving a cut-to-cut time of 4–5 s. Many tool changers utilise pneumatic arms for the relative motions of tool changing and it is essential to have an adequate air supply in order to minimise pressure drops which can jam the tool change mechanism during cutter removal. If tool change arms become stuck, then there is a recovery sequence of button-pressing, but the whole problem may be minimised by having enough air available to meet the demands from all other areas of the machine shop.

Special purpose auxiliary tooling equipment is available for machining centres and sophisticated and highly adaptable numerically controlled u-axis programmable milling heads can be fitted, for the machining of complex part geometries. Angled and swivel heads allow the machine tool to cut surfaces not readily accessible to the normal tooling. This means that an extra break-down and resetting of the work-holding equipment is reduced, as would be the non-productive idle times. Multi-spindle drilling and tapping heads, on the other hand, give the programmer the ability to drill, tap, counterbore, etc., a series of holes in just one Z-axis motion of the slideway. This has the affect of drastically reducing the machining time for a similar part produced using conventional machining technology and becomes a useful cost-effective addition to any medium-to-large term batch production.

1.4 CNC Principles of Control

When the early machine tools were designed there was an obvious emphasis on manual operation with the slide positioning being controlled by human involvement. To achieve this level of control "men" used their "sensors" – eyes and ears – whilst the central processing unit – the brain together with servos (arms and legs) – allowed them to control machine tools by communication of all these interrelated functions using the central nervous system. Until the advent of micro-electronics this method for machine control was the best system of universal adaptability available, but it suffered from serious shortcomings:

a period of lengthy training was required for the craftsman
people can easily become distracted
a person's performance is dependent upon their physical/mental condition
their efficiency is inversely proportional to time
their speed of operation is limited

If these obvious disadvantages could be overcome using the latest CNC technology, how should it be developed? At the heart of any computerised machine tool is the machine control unit (MCU); this is the connection between the programmer and the machine tool. If a part program is written with/without the use of computer assistance, it must be produced in a suitable medium for conversion by the MCU into machine motions via electrical, or hydraulic servo-mechanisms. During the early 1950s the numerical control units tended to be bulky, whilst today's CNC utilises the latest microprocessor technology. The early NC systems were "hard-wired" – meaning that functions such as interpolation, tape format, positioning methods of slideways and others, were determined by the electronic elements built into the MCU. Purchasers of early NC machinery had to specify whether they wanted the equipment to function in an absolute, or incremental format and so on, as this considerably affected the cost of the MCU. The advantages gained by having a large range of programming options had to be weighed against a healthy cost penalty.

By the early 1970s electronics had become more sophisticated so that complete minicomputers were being fitted to CNC machine tools; this meant that the previous "hard-wired" options were now contained within the software package. As a result of these software options, greater flexibility of programming was possible utilising computer logic for specifying commands in absolute, incremental and polar coordinates, etc., making them infinitely more capable, but at no real extra cost. Other bonuses directly related to computer usage included the ability to be programmed at a later date using different tape formats, as these are within the computer logic at its time of original manufacture. When one considers the CNC designed MCU, it can be readily appreciated that the "soft-wired" controllers are significantly different from their older "hard-wired" cousins and have an "executive program" allowing the controller to "think" as either a turning or machining centre. The company building the CNC will load an "executive program" into it and the machine tool company will modify it to suit their requirements. In this manner the machine tool builder will use a portion of the memory for such features as: interface logic, tool changer control and so on, to give the controller the ability to be used in a specific type of machine tool.

The latest CNCs are incredibly sophisticated using a visual display of programming parameters on the cathode ray tube (CRT), similar to a TV screen. However, the real difference lies in the fact that the screen is often a multi-function type and can display the full operational and parametric data together with screen graphics; more is mentioned on this topic later when considering CNC programming and types of controllers currently available. Together with the functions concerned with actually running the program, other necessary functions that are also displayed include: diagnostic maintenance backup and trouble-shooting guidance together with many other features that may be displayed on CRT.

Any CNC has an internal memory store for keeping and listing a library of previously proven part programs and until recently these were volatile in nature. This meant that if there was no battery-backup when the machine was shut down then all the programs were lost. This was obviously undesirable, therefore non-volatile "bubble" memories have overcome the problem associated with saving the "hard-copy" punched paper or magnetic tapes as they are often termed. These "bubble" memories refer to the method of charging (ionising) particles to give the "sense" of memory. The "bubble" memories can maintain and retain the part program in their memory for many years without use and degrade very slowly. They can be "refreshed" if called into the active memory area and then restored, if necessary, at any time. The main draw-back with storing programs that are not used very often, is that the available memory is soon exhausted and it is usually more profitable under these conditions to save any infrequently used programs in "hard-copy format". Recently, some CNC systems have been up-graded to 32-bit microprocessor hardware, allowing a degree of artificial intelligence (AI) to be used to overcome and enhance the programming of parts, but more will said about this feature later when we consider part-programming techniques.

1.4.1 Machine Tool Control Systems

Slideway positional control systems may be classified into three different groups, these are:

an open-loop system
a closed-loop system, with indirect measurement
a closed-loop system using direct measurement

Considering each system in turn and illustrating their mode of operation and control using simple block diagrams will be the theme discussed next.

An Open-loop System (Fig. 1.30a)

Open-looped systems by definition do not use any form of feedback control and as such neither the slide movement nor its velocity is monitored. With such a system, the motor will simply drive the slideway to the desired position by means of a pulse count electrically generated. A command signal is sent to the stepping motor and it assumes that when the required count of pulses has occurred, the machine slide has moved a certain distance. As no form of slideway monitoring system is present, this method of control is relatively cheap to construct; however its real draw-back is that any errors that are present will obviously accumulate. As mentioned above, these open-loop systems for slideway motion and control rely on stepping motors and their method of operation will be mentioned later in this chapter.

A Closed-loop System with Indirect Measurement (Fig. 1.30b)

Any closed-loop system has two extra elements that are not present on open-loop systems. These are the measuring system and its comparator. The measuring head is attached to the ballscrew assembly, so that as it is rotated by the energised drive servo the head will begin to monitor the angular displacement then compare it with the value required by the comparator, using a feedback signal. The command/feedback signalling occurs continuously. If the slide movements are compared with an open-loop system, then the whole action seems to be much more "controlled" giving a feeling of a higher degree of precision to the system. One problem associated with this indirect feedback control system, is that it is prone to suffer from "torque effects". These effects are a result of minute twisting of the ballscrew as heavy cuts are taken and this problem cannot be monitored – and hence controlled – by the comparator, thus a small error can occur in dimensional accuracy of the part.

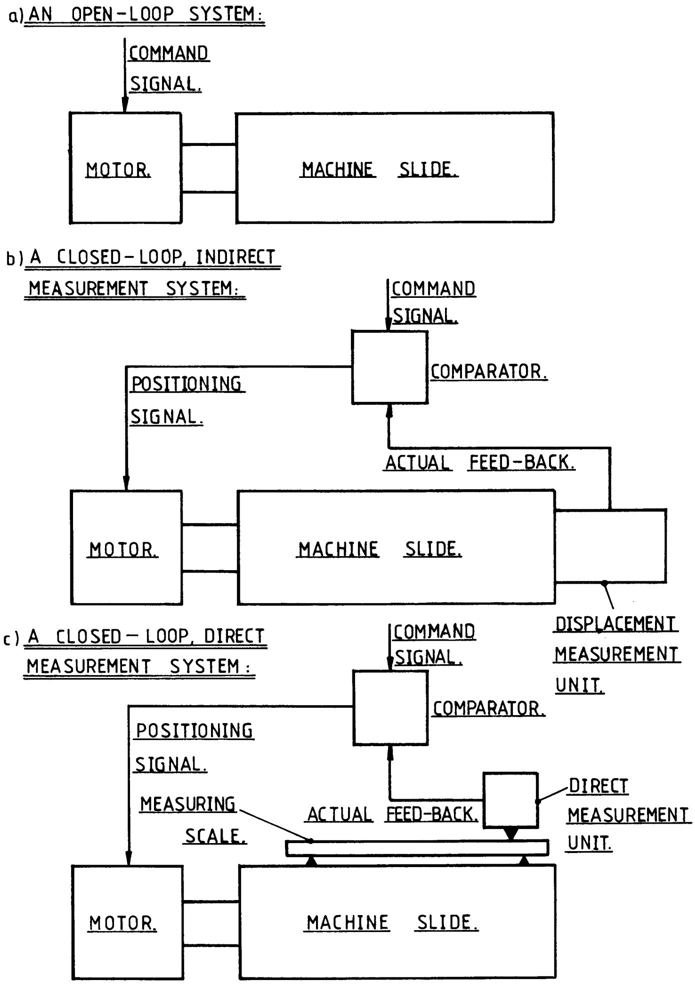


Fig. 1.30. Typical control systems. [Courtesy of Sandvik (UK) Ltd.]

A Closed-loop System Using Direct Measurement (Fig. 1.30c)

Systems using a direct measurement closed-loop can be thought of as an almost "ideal" method of control, as they measure the slideway position directly and hence the workpiece. To obtain measurement of the slideway movements the linear measuring scales are mounted along the length of each slideway. As with the indirect feedback system, the same comparator principle is used, but because the measuring scale runs the length of the axis travel it improves slideway determination and higher positional accuracy results, without the effects of torque reactions affecting the readings. Invariably, linear scales are a costly option which most machine tool builders offer and they are becoming more popular as the demand for higher accuracy components drives the pace for better quality products by the consumer. Linear scales need protection from the machining environment, but offer elimination from backlash, pitch error in the ballscrew and torsional effects.

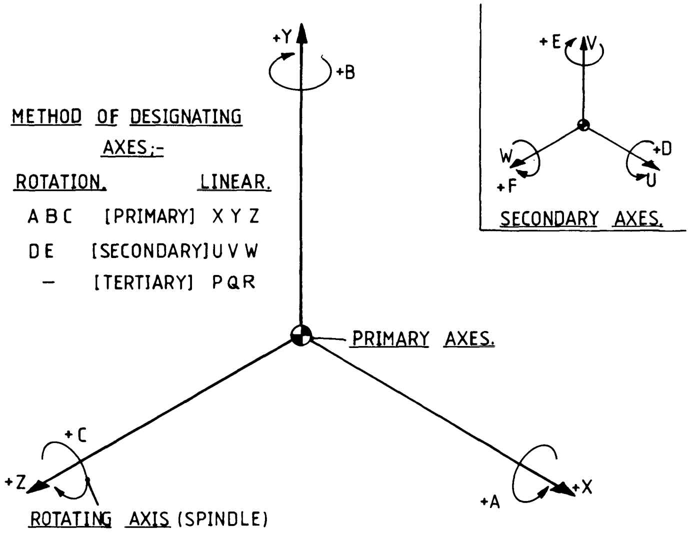


Fig. 1.31. Designation of the machine axes.

NB: to a certain extent the pitch error can be compensated for, once the machine has been calibrated. Calibration to eliminate the errors occurs by programming a laser interferometer to take account of the slideway pitch errors in the ballscrew. Thus as the program for the machining of the part occurs, minute slideway adjustment of its position is undertaken keeping a higher precision than the ballscrew would otherwise suggest.

1.4.2 The Designation of Machine Tool Axes

The BS3635 Part 1: 1972 and the German VDI proposal 3255 have identified CNC machine tool axes with the following three-dimensional mathematical system: X, Y and Z using upper case letters. The direction of movement along each axis is denoted by a plus (+) or minus (−) sign, from an established datum. Together with the primary axis designations, there is rotational notation around each linear axis and this is specified by A, B and C in upper case.

These linear and rotational motions are illustrated in Fig. 1.31; however, a number of rules are observed when considering motional kinematics:

coordinates are perpendicular with respect to each other and primarily refer to the workpiece, with the direction of the machine tool motion being derived from them

for all machining phases such as workpiece swivelling, the coordinate system is retained

following the mathematical direction of rotation, the angles should be stated clockwise from the datum – looking in the positive direction

the origin of the coordinate can be positioned outside, or inside, the workpiece and with care in the axes selection, only positive coordinates will result. The alternative would be a mixture of positive and negative coordinates, which might add to confusion when programming.

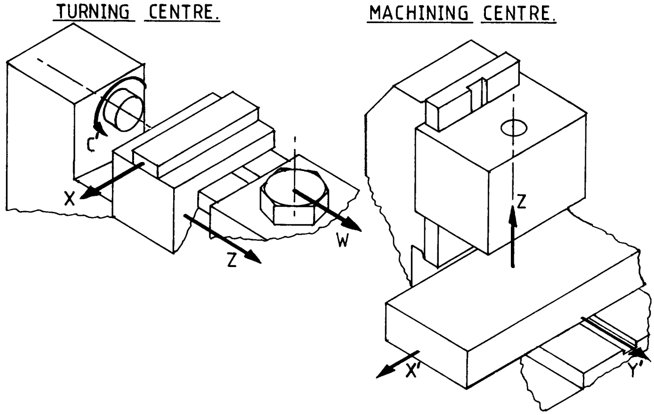


Fig. 1.32. Machining axes designation as applied to machine.

When one considers the methods for axes identification on turning and machining centres (Fig. 1.32), we note that in both cases the rotating axis is always Z. So in the case of a lathe or turning centre, the workpiece rotates, whereas on a mill or machining centre it is the cutter. On a turning centre the next principal axis is the X and two others are shown, the workpiece rotation C′ – that is counterclockwise, with C being clockwise rotation, and when the machine tool is fitted with a secondary turret, the notation is W. The secondary axes system U, V and W is independent and parallel to the primary axes X, Y and Z respectively, as shown in Fig. 1.31. A third, or tertiary, linear motion with the axes recognition of P, Q and R is again parallel to and independent of X, Y and Z which can also occur. Thus the secondary linear motions are those nearest to their parallel and independent primary axis respectively, whilst the tertiary axes are obviously farthest away.

The characters D, E and F are normally used to designate secondary angular/rotational motion either parallel to A, B and C, or about special axes. To confuse us even more, D may be associated with a tertiary feed function and E a secondary feed function!

When axes designations are assigned, it is assumed that the cutter moves in relation to the workpiece. We know that this is not always true and on many machines the workpiece moves relative to the cutter, which means that the workpiece moves in the opposite direction to the tool. Under such circumstances, it has been stated that each axis should be designated by a prime mark (dash). In Fig. 1.32, the milling application shows this notation, namely X′ and Y′. All of this seems rather complicated, but fear not, the programmer need not be too concerned with prime designations. If one considers that the X axis moves to the right along a plane of the workpiece, when facing that plane, with Y moving up and Z moving out, this simplifies things considerably. So, if the cutter moves over the workpiece, or vice versa, this possible confusion becomes of minor consequence. The main concern is to obtain the correct finished geometry on the workpiece and to achieve this aim, the programmer must know the machine type and its basic axes designations. To put it another way, the programmer needs to know which axis is, for example, say, the Y, and what is the plus direction, and which is the minus, and this is so for each linear and rotary axis.

Just to complete the intricate picture of axes designations, if a multi-spindle machining centre was to be used: motions, or axes that are parallel to and "slaved" to the principal axis, are designated as follows: the principal axis is Z, and say the two "slave" spindles would be Z2 and Z3 respectively. This would be true for a gantry mill with three spindles working in unison on a profiling application.

1.4.3 The Positional Control Modes Used on CNC Machine Tools

Other than classifying machine tools by their cutting processes, it is also possible to distinguish them by the method used for positional control of the slideway motions. Broadly speaking, there are three main positional control categories used in classifying all CNC machine tools:

point-to-point
straight-line (or paraxial as it is sometimes known)
continuous path control

These methods of positional control systems will now be briefly reviewed.

Point-to-Point Controlled Machines (Fig. 1.33a)

The applications of point-to-point machines might be to either drill and tap, or be used in a punch-pressing operation. The system works on the principle that once the command signal has moved the slides to a particular point – usually a fixed set of cartesian coordinates – then the table is clamped and the cutter begins machining. The manner in which the cutter is positioned over the next feature to be machined is irrelevant and can be seen by the cutter path in Fig. 1.33a. At first glance, it looks as though a random cutter path occurs to the next feature, but this is not the case. In fact, the controller works on the following principle (see Fig. 1.33a): if the cutter can move in a straight line it will, as shown by positions 1 and 2 in the diagram. However, when the next hole is after hole position number 5, then the motion is for both axes to move simultaneously at rapid speed. Thus the approximate angle of 45° occurs until one of the coordinates is reached. This causes one axis to cease moving and motion occurs along one axis until the final position is reached.

NB: All movements are undertaken at full speed.

The requirements of the controller are relatively unsophisticated, with a fast response to the slideway motion produced through needle roller, or linear bearing types, or indeed using air bearings, as the loads are low.

Straight Line, or Paraxial Control (Fig. 1.33b)

If a milling operation is the requirement from one feature to the next, then there is usually a feedrate associated with this movement. Therefore the previous point-to-point method of control would be useless, as each axis must be monitored continuously under full control. Paraxial control was a system developed quite early on, which gave machine tools better control and adaptability than the point-to-point variety. However, to the author's knowledge, there is no machine tool company that solely offers this type of positioning facility nowadays.

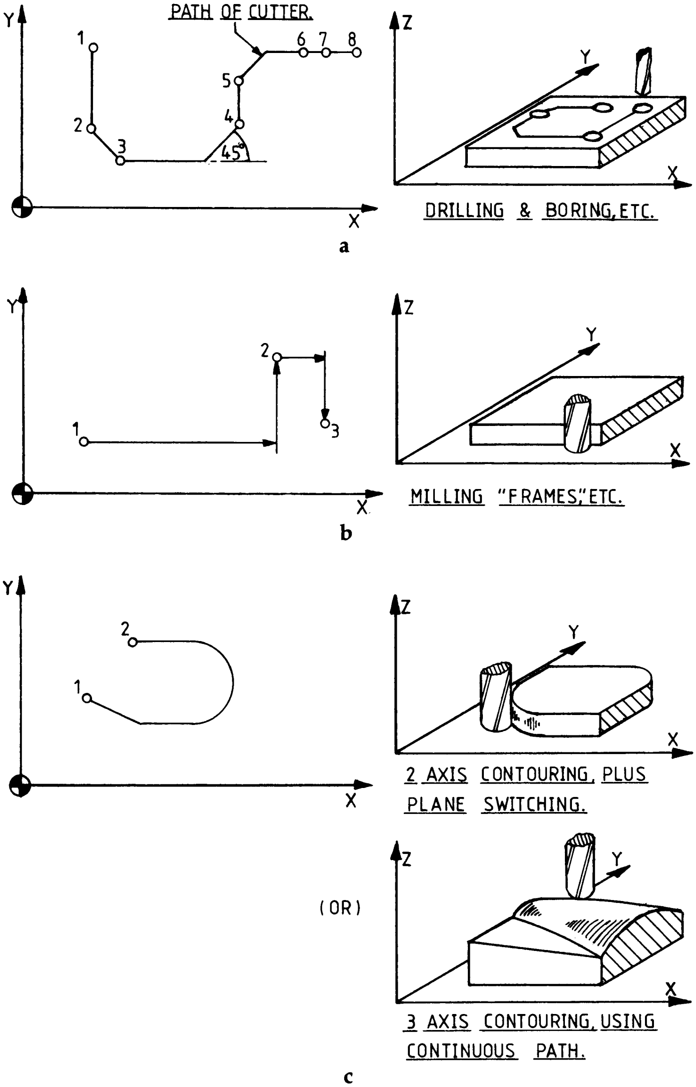


Fig. 1.33. Various types of control modes. **a** Point-to-point control. **b** Straight line or paraxial control. **c** Continuous path control.

Continuous Path Control (Fig. 1.33c)

Contouring systems such as the continuous path type are by far the most common types in use today. They have synchronised drives for feeding, providing an accuracy of positioning anywhere within the "work envelope". These universal controls can be used for point-to-point positioning and can rapidly vector from one coordinate to the next; they can also be fed in a straight-line motion or be used for contour feeding applications. When contouring, the tool's position must be continuously controlled and this means that the controller must frequently change the relationships of the linear motions of two or more axes in order to generate a contoured profile on the workpiece. The control path must have an interpolator, so that it can calculate continuous path positions until the target point is reached. To illustrate the requirements of such a contouring operation, if we consider that a contour is to be machined on a turning centre, then to discriminate between one point and the next on the X/Z plane, then the rectilinear movements must maintain an X:Z path ratio with a speed control that governs the feed drives in the exact synchronised ratio of fx:fz, for the shape to be successfully produced on the workpiece.

On most machining centres, they use two and a half axes for continuous path control, where two axes are used for circular and one for linear interpolation when machining three-dimensional (3D) shapes of reasonable complexity. If, however, a "true" 3D or multi-path milling control is required, then a more sophisticated machine tool is usually desirable. Mention should be made of the fact that even when controlling only two and a half axes, if the information has been post-processed on a CAD/CAM work station, then intricate 3D shapes can be successfully machined, but more will be said on this topic later.

It has been mentioned that when we are controlling axes an interpolator is used; so what are these interpolation methods and how do they differ? This will be the subject considered under the next section, where most of the popular interpolation methods will be reviewed.

1.4.4 Interpolating Methods on Machine Tools for Control of the Cutter Path

In a strict mathematical sense, if we know where the coordinates of two points are in space, then as long as we define any position between these points we are "interpolating" and this is what a control system tries to achieve. There are many techniques used for the interpolation of the cutter path that have been developed over the years, with some of them losing favour of late. The principal interpolation techniques used are:

linear interpolation
circular interpolation
parabolic interpolation
helical interpolation
cubic interpolation
involute interpolation

The first four have been shown schematically in Fig. 1.34 and a brief review of each type will now be considered.

Linear Interpolation (Fig. 1.34a)

As its name implies, this method produces programmed points connected by straight lines, whether this distance is close or far apart. Motion can be achieved in any number of axes simultaneously. As an example of this, if we consider a machining centre's axes configuration, it can produce linear interpolation on the X, Y and Z axes for spatial point movement and B and C for rotating motions. Thus, on a 5-axes machine tool it would be incrementing feeds at differing rates to allow for contour machining to be undertaken.

When a contour is to be machined using linear interpolation, then the higher the number of individual points present, the closer this approximation is to a true curve

(Fig. 1.34a). To achieve this feat, the controller requires a high data processing ability and using such methods it is possible to theoretically control the cutter path around any complex shape, notwithstanding the geometrical limitations of the cutter orientation to the workpiece. A major problem with using this interpolation method, is that when contour machining, the part programs tend to be of vast block length. Incidentally, this was one of the major reasons for the demise of NC punched paper tape as a storage medium for complex contours. This point brings us nicely to a consideration of the reasons why circular and parabolic interpolation have become popular, in particular the former technique.

Circular Interpolation (Fig. 1.34b)

Interpolation using circular motion control is the next order of CNC movement and has become a standard feature on most machine tools today. Principally, its obvious use is in the machining of circles, or portions of circles – or their approximations. Minimal data is needed to generate the necessary circular motions. Normally, all that is required are the arc centre coordinates and the end points of the arc, together with the circle radius to complete the programming as well as the direction of cutter movement around the feature. On most machine control units (MCU), the circular interpolation requires that the circle span be broken down to a single pulse output of approximately 0.0005 mm. This output is termed the "pulse weight", however, most systems resolve to 0.001 mm. Automatically, the interpolator will compute enough of these "pulses" to describe the circular cut, then the controlling signals will be generated progressing the tool's path along this feature. Hence, the cutter path around a circular arc will be within plus or minus one "pulse".

Circular interpolation may only be used on two axes planes at any instant and will not interpolate on all three simultaneously. By utilising a series of arcs, a free-form shape may be closely approximated using fewer data points, giving a truer profile than by linear interpolation.

Parabolic Interpolation (Fig. 1.34c)

Interpolation by parabolic means is an even higher order than the others mentioned so far and has been almost exclusively used by the automotive industry in the past, for the manufacture of free-form shapes. To define the curve using parabolic interpolation, three points are needed: two end points and a mid point (Fig. 1.34c), as a parabola has a "unique" focus. This technique defines a curved profile with better than 50:1 fewer programming points than by linear interpolation. The major disadvantage of parabolic interpolation, when compared against the linear method, is that to program a shape with this technique a more specialised programming language is necessary and for this reason it has lately fallen out of favour. The latest CNCs offering circular interpolation have vastly higher computing power than was previously available, allowing free-form shapes to be machined and this is another reason for the decline of parabolic interpolation.

Helical Interpolation (Fig. 1.34d)

Owing to the fact that many operations previously machined on the turning centres can now be undertaken on machining centres has meant that a new form of inter-

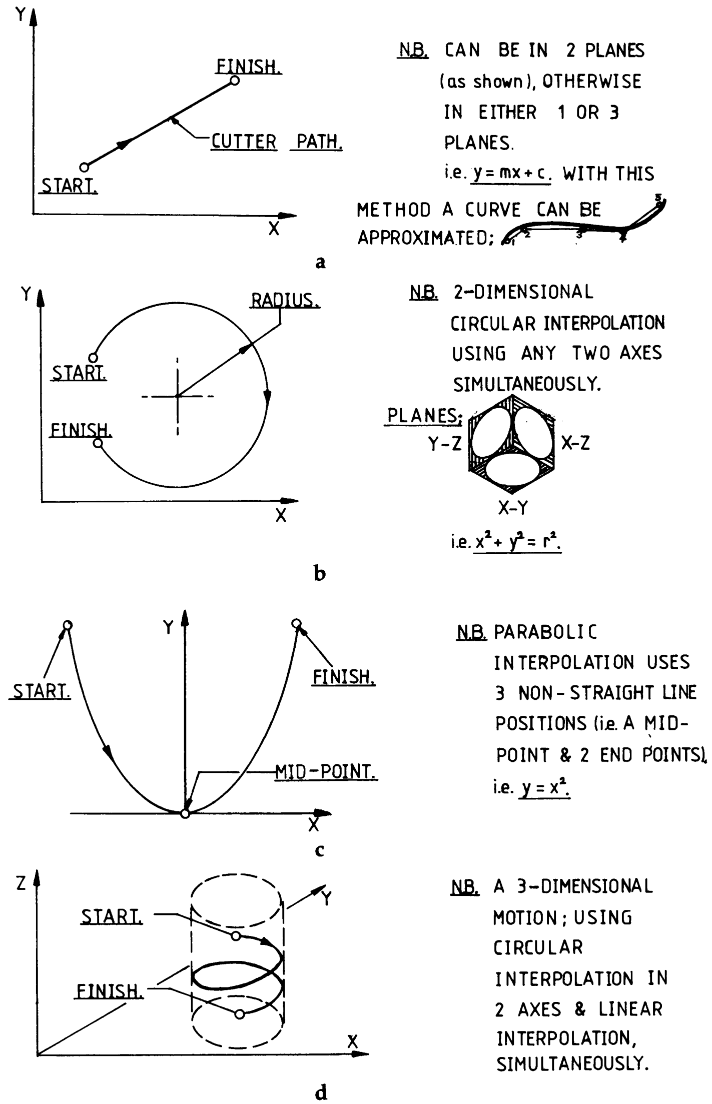


Fig. 1.34. Interpolation methods. **a** Linear interpolation. **b** Circular interpolation. **c** Parabolic interpolation. **d** Helical interpolation.

polation has been developed. Helical interpolation allows programmers to exploit these new capabilities, giving them the ability to mill internal and external threads. Helical interpolation utilises two axes providing circular interpolation whilst simultaneously providing linear interpolation in the third axis (Fig. 1.34d). This helical interpolation feature allows single or multi-start threads to be generated on the workpiece successfully.

Cubic Interpolation

In a similar manner to parabolic interpolation, the main users for this technique are the automotive and aerospace industries, where it is often required to machine free-form component geometries, but even here, there are only a limited number of users. Using cubic interpolation, that is the ability to produce a third degree curve, gives the programmer the ability to generate complex profiles with a small number of data inputs. It describes curves accurately and allows for the smooth blending of one curve to another without geometric discontinuities. The programmer uses customised software when describing free-form shapes and does not have to write cubic interpolation executive routines.

Involute Interpolation

Recently, the introduction of involute interpolation has been found on some CNCs. This technique allows the programmer to specify gear tooth forms based upon an involute form, to be quickly and accurately defined using just a few data inputs.

General note: When considering the variety of interpolation techniques available then the following observations based on the part geometry to be machined can be made. If the profile is:

a straight line – use linear interpolation
a circle – use circular interpolation
a helix – use helical interpolation

if none of these, use linear interpolation – to approximate the curve, but never allow the cutter path to deviate more than the component's tolerance.

1.5 Measuring Systems for Machine Tool Path Determination

To determine the slideway position of each axis of a machine tool, an electronic measuring device is required and this monitors and compares the present position with the command position for every movement of the axis. Various criteria must be considered by the machine tool builder when selecting a suitable measuring system, such as: the accuracy and precision, its reliability, the length of total traverse and the expected maximum velocity of the slideway motion, together with the cost of fitting such a system. To compound the problem, there is no specific measuring device used throughout industry, and by way of illustrating this point, it is possible to select either a closed or open-loop system with rotary or linear monitoring, which may have either direct or indirect feedback using an analogue or digital signalling method. As such a choice is available to the designer for axis monitoring systems, then each type has certain advantages and, of course, limitations. However, as so many methods of monitoring the slideways exist, only some of the common systems will be discussed.

1.5.1 The Stepping Motor (Fig. 1.35)

A common method of assessing the rotational displacement of the ballscrew on the lower cost machine tools is by way of drive by the stepping motor. This open-loop device does not monitor the axis position, but relies for its accuracy on discrete steps that the rotor can be rotated through in order to achieve the desired linear displacement via the ballscrew rotation. To describe the types of stepper motors available

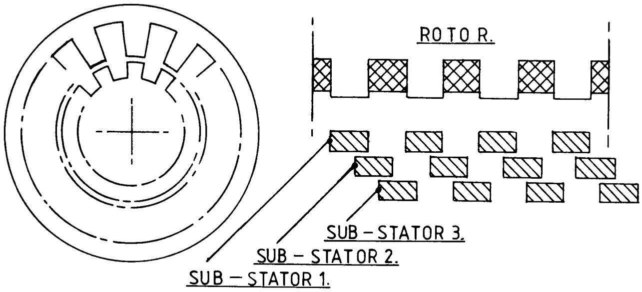


Fig. 1.35. The principle of the stepping motor.

would need considerable space, so only a simplistic view of its operation will be given. As a rule, stepper motors fall into two categories: the permanent magnet motors, and variable reluctance motors, but there are hybrid constructions which feature some of the functions of each type.

Basically, the stepper motor utilises the well-known principle that unlike poles attract; if one assumes that the rotor and stator were made to appear like toothed wheels (Fig. 1.35), with the general convention being for the external teeth on the rotor and the internal teeth on the stator. With this approach, if we consider that the alternative teeth are magnetised as either a "north" or "south" pole, this means that the corresponding pole on the rotor will be attracted to the opposite pole in the stator. Assuming now that we turn the stator, this would also turn the rotor, but naturally the stator is not physically turned as it is the fixed part of the motor, although it is possible to turn it electrically.

Normally a number of sub-stators are used to make up the total stator, with each sub-stator being displaced from the next one by a "step" of 5°–10°. If the sub-stator is now sequentially energised – that is one after the other – the rotor is attracted to the next pole and so on. So as the poles are displaced a definite distance, the motor is said to "step". Most stepper motors use 3 or 4 sub-stators, so that once the last one has been energised, the cycle recommences at the first. Whenever the stator is energised in the reverse direction, this causes the motor to run backwards. In this manner, it is possible to convert digital signals directly into a defined distance, enabling an open-loop CNC motion to be achieved.

1.5.2 Indirect and Direct Methods of Control of the Slideways

It is worth restating that there are two basic methods of controlling the slideway position prior to describing in detail closed-loop systems: indirect and direct techniques. Fig. 1.36 schematically illustrates the two methods of monitoring slideway position. The indirect method utilises the ballscrew for positioning, whilst the slideway positional measurement is the linear distance travelled, which is monitored and subsequently fed to the computer controlling the axis. Alternatively, the direct method of slideway measurement uses a long, permanent scale fixed between the machine's non-moving casting and the reading head to the moving slideway. A major bonus of such a system is that the slide measurement does not rely on the ballscrew accuracy and the presence of possible backlash, or indeed, the motor drive for positional accuracy. These advantages of backlash and torque reaction elimination occur with

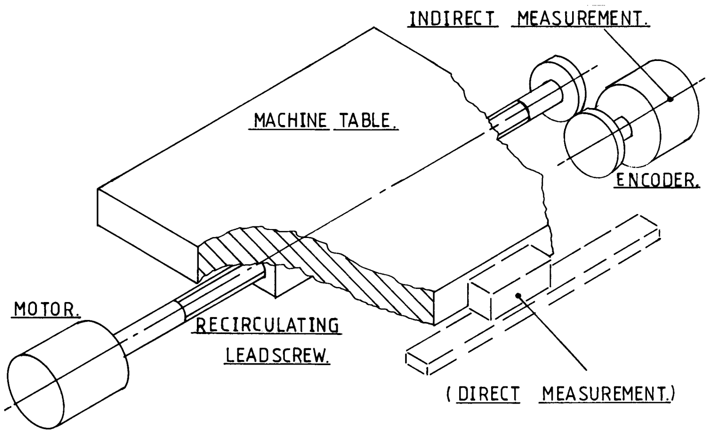


Fig. 1.36. Indirect and direct measurement.

direct measuring techniques, although they are present during heavy cuts with the indirect methods and as such the "direct" methods give greater determination and precision of slideway positioning. It should be noted that "Abbe's principle of alignment" is still not complied with, owing to the fact that the table ballscrew drive and the measuring position of the fixed scale are not coincident. Abbe's alignment principle states that "the measuring plane and the measuring position should be coincident", whereas in reality there is an offset between the cutter path and its measurement plane, which might cause errors to be induced during cutting operations.

Analogue and Digital Measurement

Earlier it was stated that there are two types of measuring principles: analogue and digital. The analogue system implies that a signal such as an electrical voltage magnitude will represent a physical axis position, or to say it another way, we use the physical variable of distance to represent a voltage. A specific slide displacement will be "analogous" with an induced voltage; for example: 15 V equals 150 mm travel of the slideway from its datum. Conversely, the digital measurement technique is usually a pulse counting device, which counts the discrete pulses that are being generated by a direction sensing grating as the axis moves. These digital systems will now be considered in more detail.

Digital Measuring Systems

A digital device can be either of linear or rotary configuration, with two main principles used:

photo-electrical systems
inductive scanning methods

It is worth mentioning that inductive scanning techniques are not used on CNC machine tools, because they have a relatively large resolution which excludes them from the precision applications of this nature.

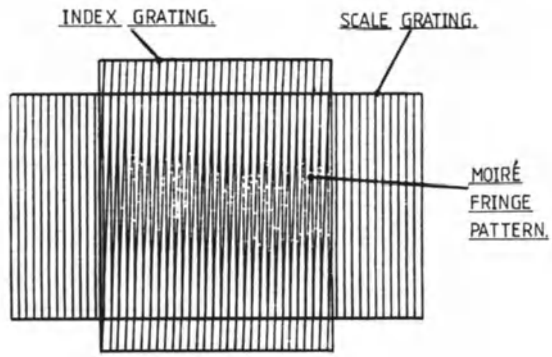


Fig. 1.37. The principle of optical measurement based upon Moiré fringes.

By way of introducing digital systems, the photo-electric slideway positioning technique will be reviewed initially, using a lamp or fibre optic unit together with photocells and some form of grating, and then some other methods will be briefly considered.

The Principle of the Optic Grating

The optical grating principle is based upon the well known "Moiré fringe effect" and is shown in Fig. 1.37. Optical gratings may be made from glass, or a reflective strip onto which is marked, or photo-etched a series of parallel lines closely and uniformly spaced together. Effectively, the same equally spaced lines occur on both the index and scale gratings. The long fixed scale grating extends over the length of the machine tool's axis travel, with a short index grating overlaying it, being held in a reading head. The lines of both gratings are set at a small angular displacement to each other. This causes an interference effect between them at the intersection of the lines. This pattern is termed a Moiré fringe.

In practice, when the slideway is moved the lines on the two scales are displaced and, as a result, the fringe pattern travels at right angles across them, with their direction of movement being dependent on the plus or minus direction of the slideway, as shown in Fig. 1.38. A dark fringe pattern is produced across the width of the grating and moves in the sequence shown in the illustrations. Now, if a collimating beam of light is placed either through the glass gratings, or reflected from it – depending on the system used – then a change in the light intensity occurs as a result of the fringe pattern motion being of sinusoidal form. Photo-electric cells are strategically positioned to detect this fringe pattern, converting it from light energy into electrical energy – pulses. These pulses are counted, relating to the number of lines displaced on the scale grating as it passes through the reading head. If the line pitches are known precisely, then the slideway displacement can be monitored. The reader should gain an appreciation of this phenomenon by a practical demonstration using two hair combs, with one placed over the other – but at an angle to it. Whilst holding one still, to represent the fixed grating and moving the other, to indicate displacement of motion over the index grating, a fringe pattern can be crudely shown to move upwards or downwards depending whether motion is to the right or left hand. This shows the basic effect of a Moiré fringe operating principle.

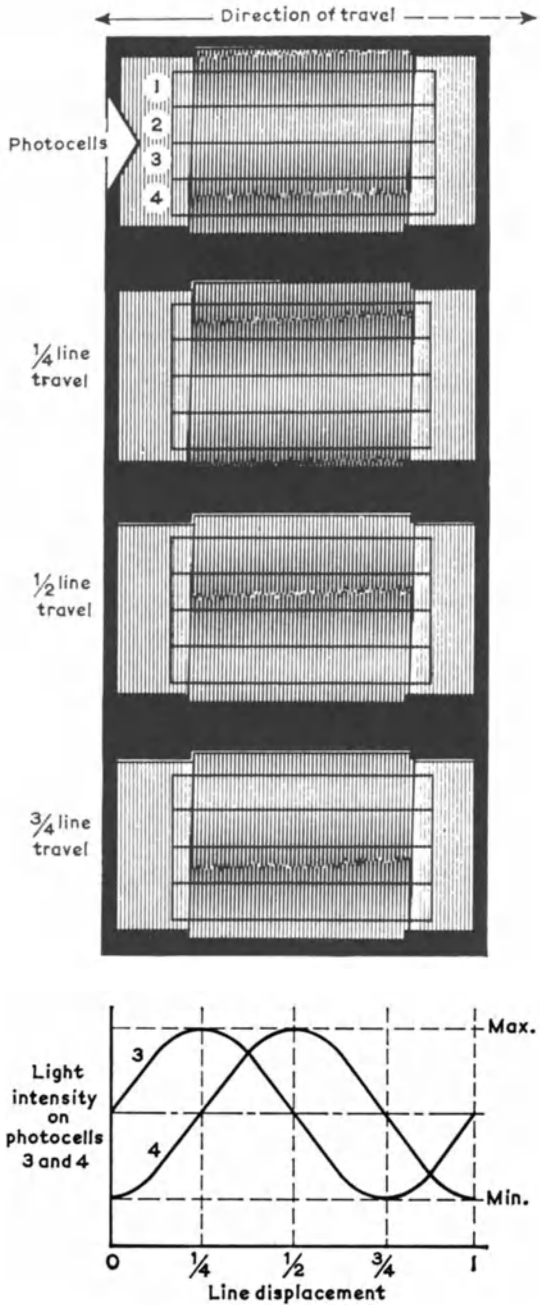


Fig. 1.38. Four-phase fringe system with resultant waveforms. [Courtesy of Ferranti Ltd.]

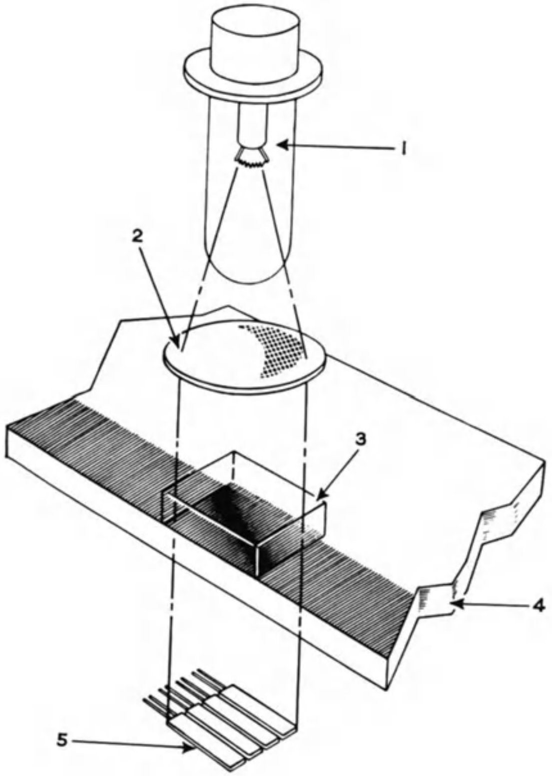


Fig. 1.39. Optical arrangement used with line and space transmission gratings. 1, exciter lamp; 2, collimating lens; 3, index grating; 4, scale grating; 5, photocell strips. [Courtesy of Ferranti Ltd.]

In order to gain some degree of discrimination from one fringe to the next, four photo-cells are usually spaced across the grating's width. As a result, four pulses per cycle occur, with each pulse representing 0.005 mm if the pitch of the gratings is 0.02 mm. The sense of slideway direction can be obtained, by registering the order in which each photo-cell is energised. Each axis when in motion produces generated pulses, and an electronic decimal counting device sums them up, adding or subtracting them from their various slideway displacement directions. All axes can be set to zero at any convenient position and a comparator unit compares the actual slide position with the command position and if a difference occurs, corrective action by the servo-drive system results.

Typical arrangements of the optics and their respective Moiré fringe assemblies are shown in Figs. 1.39 and 1.40, for glass and reflective gratings, respectively. These optical configurations are perfectly acceptable for lower accuracy machine tools, but if high precision continuous control is required, then a more complex arrangement is necessary. The upper diagram in Fig. 1.41 illustrates the previously mentioned incremental mode type, whereas in the lower diagram the sophisticated high accuracy approach for continuous path CNC uses more tracks to detect movement, with the distance quanta doubling for every extra track added. In Fig. 1.42 an enlarged version of this absolute scale method can be seen, using this "V-scanning" principle as it is

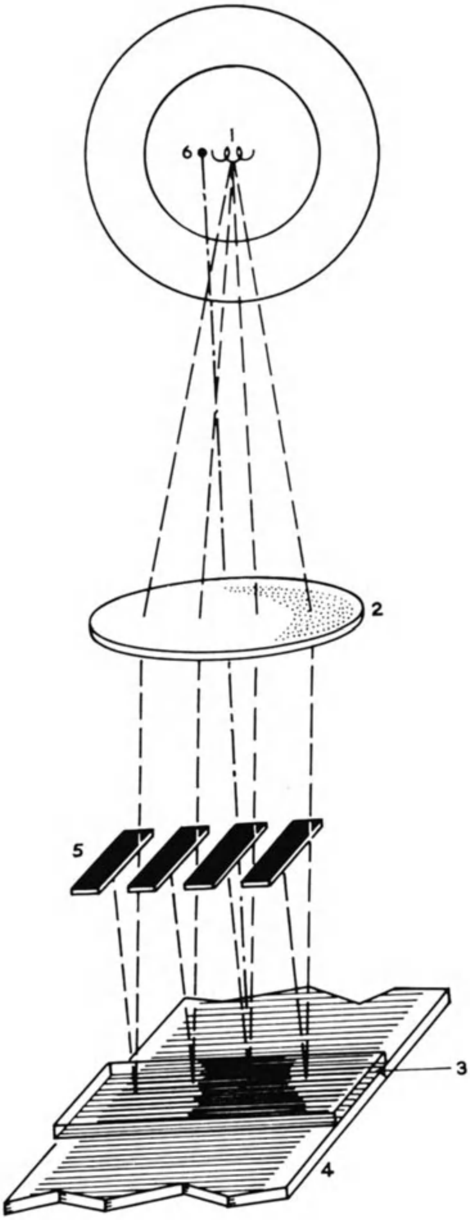


Fig. 1.40. Optical arrangement used with reflecting gratings. 1, filament; 2, collimating lens; 3, index grating; 4, scale grating; 5, strip-silicon photocells. [Courtesy of Ferranti Ltd.]

often termed. It is worth discussing how and why this arrangement improves the accuracy of slideway positioning of machine tools over the previous systems mentioned so far. Any CNC machine tool uses binary coded decimals – numerical control, with the top diagram in Fig. 1.42 schematically illustrating a binary signal stretched

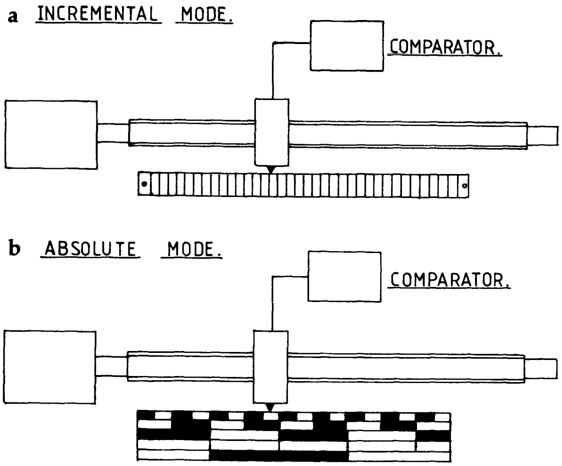


Fig. 1.41. Modes of measurement. **a** Incremental mode. **b** Absolute mode.

out for the slideway length in longitudinal tracks. When the slide is moved, a binary signal is produced and can be analysed, allowing the exact position of an axis to be established. A problem arises with this technique in that the photo-diodes cannot be exactly positioned so that all tracks are "switched" at the same time, leading to the likelihood of faults in the reader system. The problem is overcome by using a "grey-code" switch track and a V-form reader. The photo-diodes are arranged in the V-form with the finest track using a single photo-cell, whilst other tracks have two photo-cells positioned such that they are in the middle of the respective distance quanta producing the so-called V-form. This configuration offers the advantage that only the finest track needs to be very accurate, meaning that its calibration is much easier to achieve.

There is a wide range of rotary and linear monitoring systems available to the machine tool builder.

Analogue Measuring Systems

A brief discussion of analogue systems was given earlier in this section and they can be either rotary or linear measuring devices. The principle of operation of analogue devices is that an inductance of an applied reference alternating current occurs from a stator to a rotor, or vice versa, when of the rotary variety. The latter system known as a "Resolver" will be mentioned first, and its cousin, the linear resolver known as the "Inductosyn", will complete this review of analogue techniques.

The Resolver (Fig. 1.43)

The operational procedure of the resolver is that if the rotor is lined up with the stator, then the induced voltage is at a maximum and when the rotor is at 90° to the stator, the voltage induced becomes a minimum. By counting the number of times the voltage reaches zero, it is possible to determine how many times the resolver has

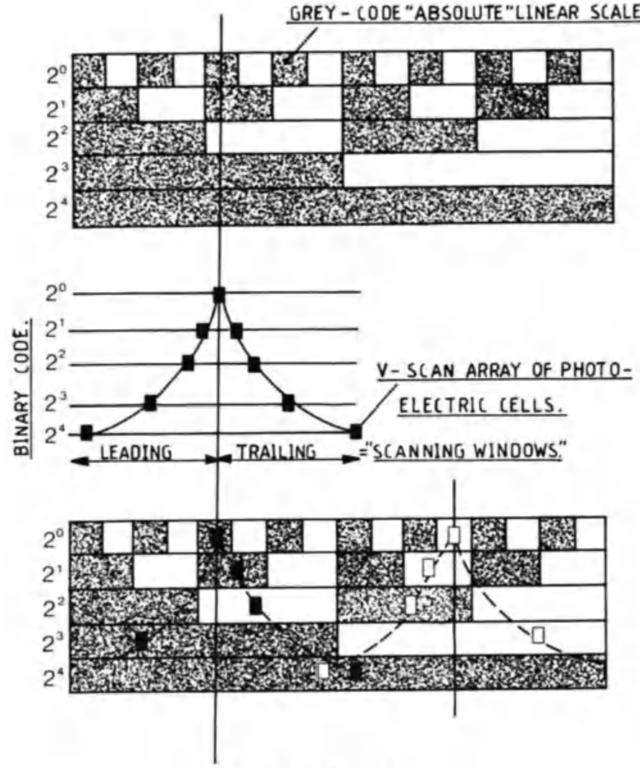


Fig. 1.42. V-scanning.

turned and this being connected to the ballscrew assembly, determines the table's position. A further feature of the resolver is that the phase is altered so that at each zero mode there is a phase shift of 180°. By using the commonly practised two-phase secondary winding technique where each winding is displaced at 90° to the other, then the phase displacement and amplitude are "resolved" into their respective sine and cosine components and can be analysed for slide displacement. A typical resolver has a slideway resolution of 0.01 mm.

The Inductosyn (Fig. 1.44)

An inductosyn is simply a resolver that has been "straightened out". The system uses a printed circuit winding that is etched onto a carrier board and fixed to the length of each axis of the machine tool. The winding carries a reference AC voltage with a frequency of 1–20 Hz. Superimposed over the winding running the length of the slideway travel, is a short slider. This slider has etched onto its surface two windings that are displaced electrically at 90° to each other. The resulting induced signal is "resolved" in the same manner as the previous analogue method discussed for the resolver.

A typical resolution of the inductosyn is 0.0025 mm and like the optical grating system discussed earlier, it finds many applications on CNC machine tools. A general

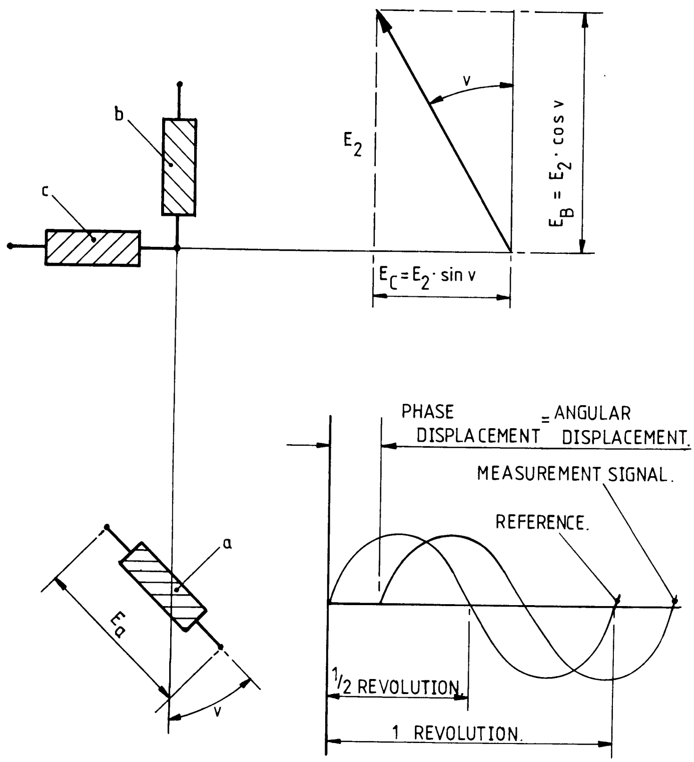


Fig. 1.43. The principle of a resolver.

assembly partially cut away is shown for slideway monitoring in Fig. 1.45 and a rotary application for a fourth axis on a horizontal machining centre in Fig. 1.46.

The Laser (Fig. 1.47)

The laser offers the ultimate in position monitoring devices presently attainable, but is still under development at the time of writing. However, it cannot be long before such systems are adopted by machine tool companies for ultra-high precision work. It offers the major benefits in a high resolution, direct reading, closed-loop and linear control system for slideway positioning. To monitor the slideways, a stabilised laser interferometer, coupled to customised optics, together with an electronics and software package, produces the high resolution required and should be available in the future. A data transfer rate equal to the laser reference frequency can be achieved.

A typical laser arrangement of an expected 3-axis closed-loop control on a machine tool is shown in Fig. 1.47. The stabilised helium–neon continuous wave two-frequency laser head sends out a beam which is bent, split and reflected around the machine tool axes and then back to a receiver unit, closing the loop.

There are several major advantages with such systems apart from the high resolution of around 10 µm, including the much sought after ability to compensate auto-

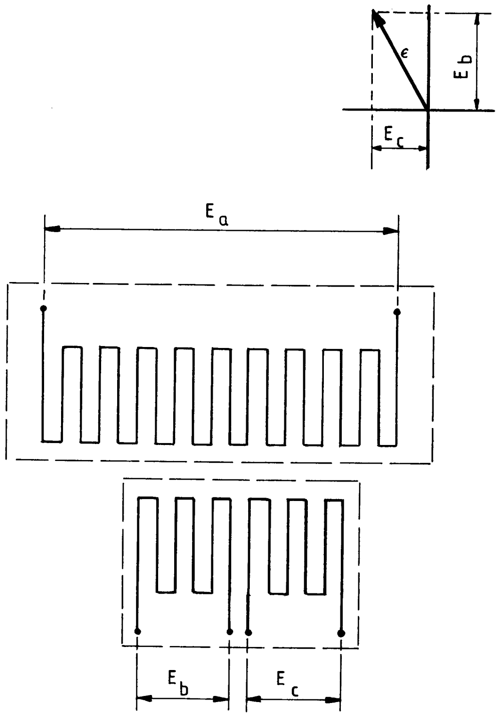


Fig. 1.44. The principle of an inductosyn.

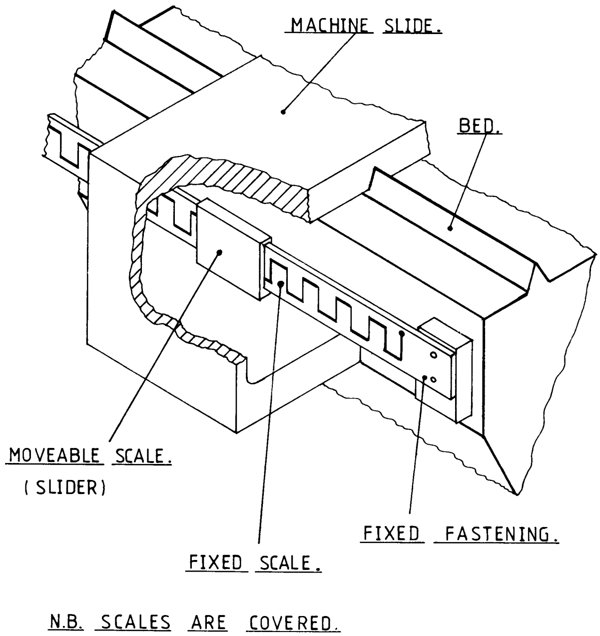


Fig. 1.45. A linear inductosyn. NB: scales are covered.

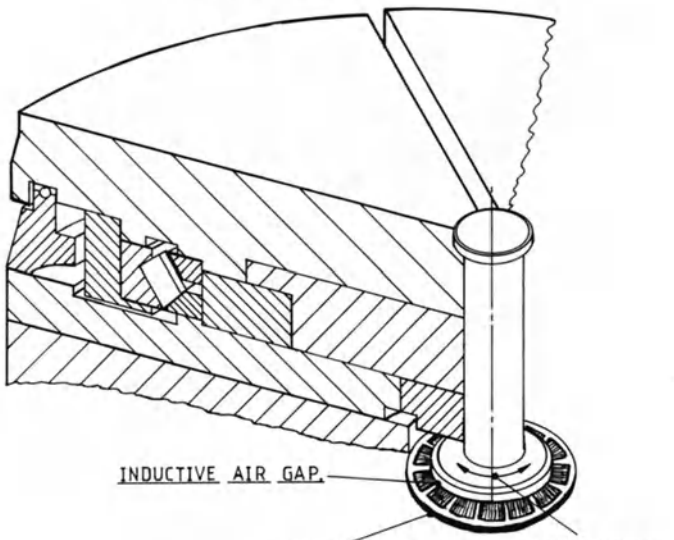


Fig. 1.46. An application of a rotary inductosyn.

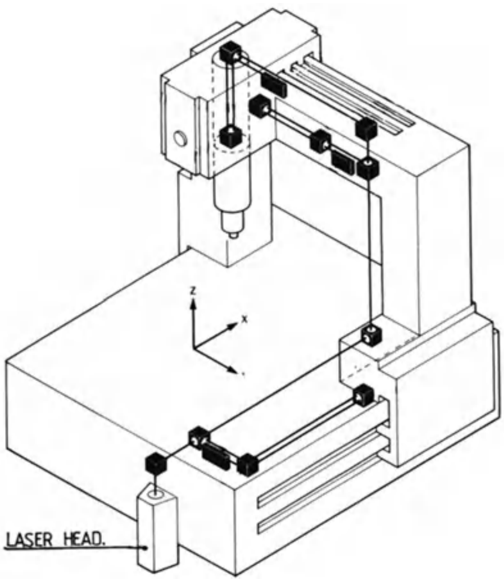


Fig. 1.47. Closed-loop position monitoring using ultra-precise linear interferometers/laser. [Courtesy of Habn & Kolb (GB) Ltd.]

matically for ambient temperature changes, humidity and air pressure, which is a major problem in most machine shops.

1.6 A Review of Typical CNC Machine Tool Configurations

This section is not meant to be an exhaustive account of all the available machine tools utilising CNC; that would require a book on its own. However, the comments and photographs will be confined to reviewing turning centres and CNC lathe configurations and then go on to briefly describe machining centres and CNC mills that are currently available.

Let us begin the review by looking at probably the most popular turning centre configuration currently available and shown in Fig. 1.48. This slant bed turning centre has a 2-axis controlled turret holding a dozen or so tools in its turret. This allows both right- and left-hand tooling to be situated in the outer ring of tool pockets, with the inner ring being used in the main for hole-making operations: drilling, boring and tapping. A partially programmable tailstock is a standard feature which can be latched up/down to provide workpiece support, using centres. The tailstock's barrel can be programmed to move in and out with a hydraulic pressure regulator controlling the barrel's pressure requirements. This feature is important whenever long, slender workpieces require centre support to avoid them buckling or distorting under the hydraulic pressure application. However, the barrel is not feed programmable for drilling, but it can be used in such a manner if physically connected to the cross-slide and a Z axis motion is programmed with the tailstock latched up. The cast iron slant bed drops swarf into the tray and is carried away by the continuous chain-type swarf

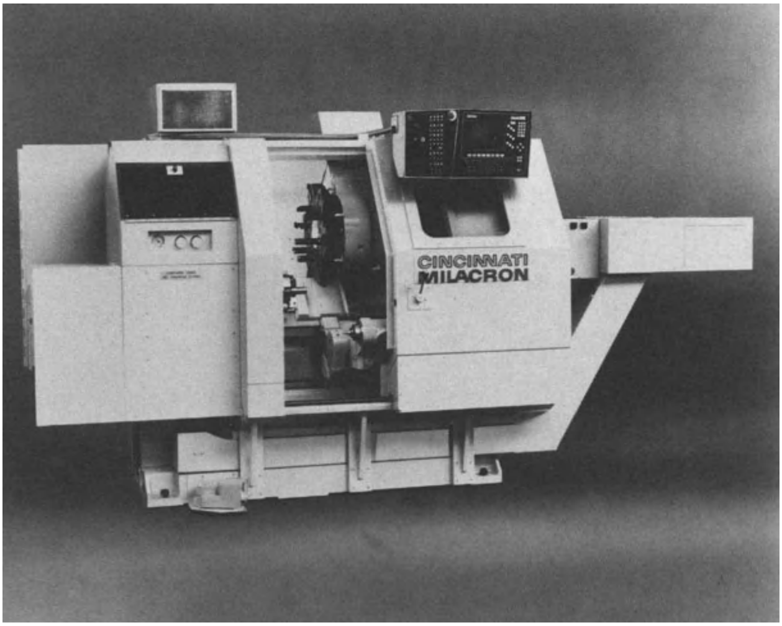


Fig. 1.48. A 2-axis turning centre with programmable tailstock. [Courtesy of Cincinnati Milacron.]

conveyor to a receptacle. The CNC has full colour graphics capability, displayed on a large CRT.

A more sophisticated derivative of the previous turning centre is a twin turret 4-axis machine tool (Cincinnati Milacron, Cinturn 8C, Series 1408, CNC Chucking Centre), but in this case without a tailstock fitted. The CNC has been up-rated allowing the full control of 4-axes, but in this case in a rather unique manner. When programming the part only the X and Z axes of the top turret need be considered and where appropriate the U and W axes of the bottom one can be used to perform simultaneously machining operations such as "balanced turning" where necessary. This feature gives a 4-axes turning centre the ability to manufacture parts much faster, thereby improving the overall productivity considerably (see Fig. 1.4). As well as the "balanced turning" operations on long diameters, useful operations using, say, one tool turret for external and the other one for internal work can be accommodated easily. The penalty for such turning flexibility is obviously a much more expensive capital outlay to purchase these machine tools. As with the previous 2-axis machine, a swarf conveyor is a standard feature and essential when such high stock removal rates are possible. It is worth mentioning that programming this 4-axis machine requires the programmer to be concerned with only two primary axes, X and Z, as the secondary motions of U and W are taken care of by the CNC, including collision protection – which is a rather unique programming aid.

If even greater flexibility and increased productivity is required from a turning centre, then the levels of sophistication of machine tool axes configurations can be increased immensely. Probably one of the most sophisticated turning centres available is the Gildemeister (UK) Ltd, GT 50, featuring twin turrets and twin spindles (Figs. 3.11 and 3.12, Volume II) – fully programmable with the ability to use "driven tooling" for the machining of prismatic features on turned components. Incidentally, both of the previous turning centres discussed can be operated with driven tools – milling, drilling and tapping operations from their turrets if so ordered in such a configuration from the machine tool builder. It is very easy to see that a considerable number of axes may be controlled through the CNC and seven to nine axes are not unusual nowadays. The unique feature of having a twin spindle facility is that the main headstock and chuck is used for all "normal" "chucking" operations. The opposing co-axial spindle (Fig. 3.11, Volume II) can slide down the bed once features to be machined by the headstock are completed by the top turret and grip the component in synchronised rotation whilst the workpiece is still rotating. This allows the component to be withdrawn, or supported whilst parted-off prior to withdrawal enabling "back turning operations" to be completed on the rear of the workpiece by the lower turret (Fig. 3.12, Volume II). Whilst the "backface" machining operations are under way, the front facing top turret begins simultaneous machining of the next workpiece so that two components are being machined at the same instant of time. Such universal applications do not come cheap, but have expanded manufacturing abilities offering great savings in productivity and if the company has the throughput of work to justify this level of capital expenditure, then pay-back periods are significantly reduced. The control console of this advanced turning centre has remarkably few switches and buttons present to confuse the programmer/operator and the sophisticated and customised software is where the "intelligence" of the CNC machine resides. It is interesting to note that even this degree of advanced turning centre control is not the highest level available, as on some machines the jaws, or even the whole chucks can be automatically (Fig. 3.27, Volume II) changed allowing much greater workholding flexibility and this is without even considering the automatic tool and workpiece sensing devices, yet to be reviewed.

Yet another derivative of the turning centre theme so far discussed is the configuration used in the Pittler Petra, where a front loading arm will load workpieces onto twin spindles after removing the previously machined parts. Different components can be manufactured simultaneously by both of the independent slideways offering considerable versatility. When higher production dictates this type of automatic machine work loading, then greater volumetric throughput can be machined on identical parts at the same time, as two can be produced in the time it takes to manufacture one. Once again, a short slant bed is incorporated for each turret, and naturally a swarf conveyor is an essential item in view of the volume of swarf produced. Part delivery can be automatically achieved through the use of workpiece conveyors or gantry loading systems, whichever is applicable to the company's needs.

Whenever there is a call for ultra-precise components and particularly of highly accurate surface finishes, then a totally different CNC turning philosophy must be adopted (see Fig. 2.27). To obtain the ultimate surface finishes produced by single-point tooling, demands a machine tool with exceedingly high r.p.m. to cope with the speeds necessary, using natural diamond turning tools, together with much greater rigidity, and even more important is the high vibration damping capabilities required when using mono-crystalline diamonds. These capabilities are essential in order to minimise cleavage of the natural diamond tooling cutting edges whilst machining parts at high speed. As a result of the specialised cutting edges needed for this type of machining, the tooling and its fixturing tend to be relatively simple in concept. The CNC diamond turning lathes can machine complex geometric parts as well as relatively simple part geometries with exceptionally fine feedrates, offering superb surface finishes. A degree of automation can be incorporated into such machines by using bar-feeders, or automatic part loading facilities coupled to automatic chucks. Often these machine tools have unusual work holding facilities utilising, for example, vacuum chucks and faceplates and other such methods.

This brief review of CNC turning machine tool applications would not be complete without a mention of the vertical lathe illustrated in Fig. 1.49. Often such specialised turning machines are used to manufacture large squat and irregular-shaped components which may offer out-of-balance problems, or workholding difficulties on conventional turning machines. Typical of such products manufactured are volutes, or gear crushing rings which are made from exotic materials which are exceedingly difficult to machine. As machine tool rigidity is of prime importance on these machines, with their portal construction being a typical feature, the requirement is for good torque–low speed power characteristics with high volume production being of secondary importance in this case. Tooling needs as a result, tend to be of simple, but robust construction and fine feedrates can be programmed. Owing to the relatively long cycle times necessary for machining exotic materials, or if rotating out-of-balance loads, the low volume production which results dictates manual rather than automatic loading of workpieces. Once again, a simple and strong, but effective method of part clamping is considered to be of prime importance here.

The diversity of machining centre and milling machine configurations available to the would-be purchaser is vast and depending upon the part complexity, size and volume produced, there is a range of machines on offer. The horizontal machining centre shown in Fig. 1.50 is typical of its genre, offering 4-axis control, 3 linear and one rotary for pallet/workpiece rotation. An automatic pallet changer with eight pallets is incorporated with the adaptability of workpiece fixturing and component diversity being displayed. The photograph shows a range of fixtures on each pallet, such as: cubes, tombstones, or special-purpose varieties allowing the wide variety of components to be accommodated from small to large dimensions. It is possible to tool-

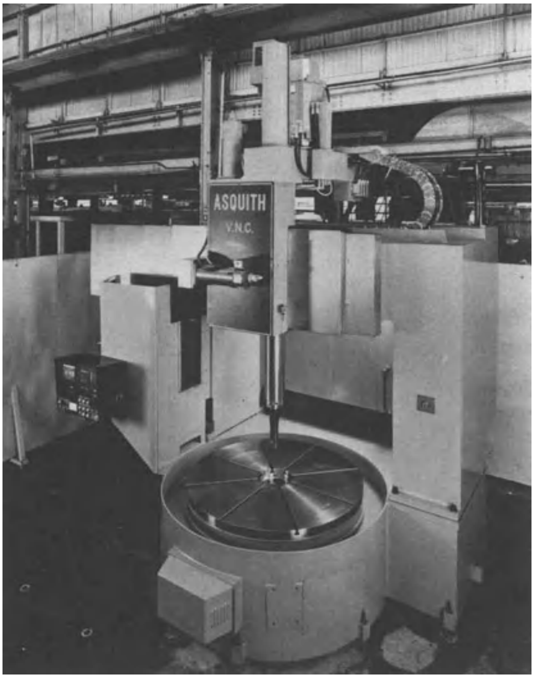


Fig. 1.49. A CNC vertical turning lathe. [Courtesy of Asquith 81.]

up a fixture to carry many small components on each pallet and this gives a degree of medium-volume production to such machines. Obviously features such as swarf conveyors, adaptive control and tool and workpiece monitoring systems can be incorporated, together with further "tool banks" when appropriate.

The CNC has to be quite sophisticated in order to cope with all the likely permutations of component piece-part programs that need to be stored in the memory. Not only does the controller need a part scheduling ability, it also requires further controls to orchestrate the relative auxiliary devices included on the machine, typically, a pallet recognition system, tool management and magazine handling together with touch-trigger probing software and adaptive control through some form of torque controlled machining (TCM) capability. These aspects offering a degree of intelligence into the machine tool will be the theme of further discussion later in chapter 2.

A popular machining centre often used in Flexible Manufacturing Cells or Systems, is the 4-pallet horizontal machining centre illustrated in Fig. 1.51. Obviously large machining centres of this type offer great flexibility in the ability to cope with a diverse range of parts. A key feature with such machine tools is the crucial areas of part fixturing and cutting tool management, if the benefits from such a costly machine tool are to be realised. The machine has a sophisticated CNC necessary to carry out not only the part programs, but tool and machine monitoring through sensors, for example: adaptive control, tool breakage detection, and workpiece probing, coupled to thermal drift compensation devices and refrigerated spindle assemblies, plus many more techniques desirable in the "stand-alone" machine, or ones used in the unattended machining environment. Machine tools having the likelihood that they will be used in

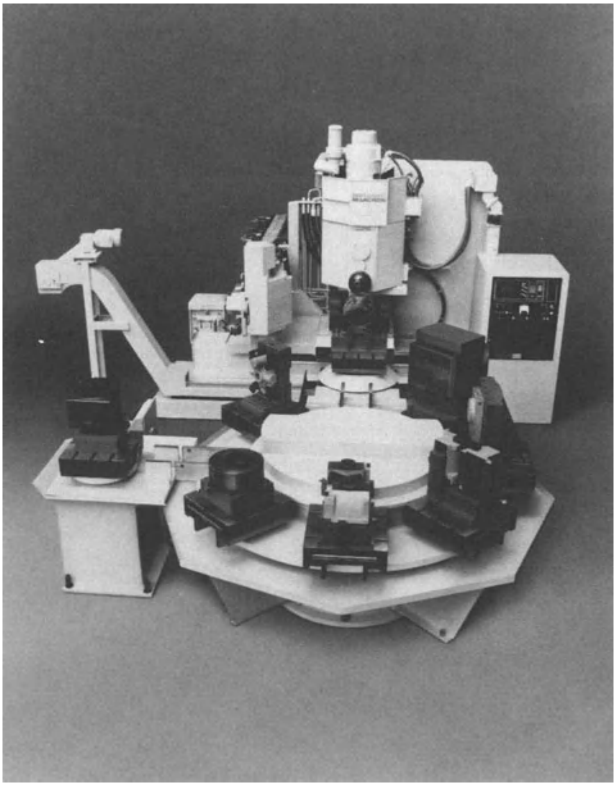


Fig. 1.50. A machining centre (horizontal) with rotary pallet changer. [Courtesy of Cincinnati Milacron.]

Fig. 1.51. A large 4-pallet machining centre (horizontal) with 4-axis control. [Courtesy of FMT Ltd.]

a variety of "stand-alone" or automated configurations of necessity must be built around a "modular principle" previously discussed; this ensures that part delivery can be universally accommodated through: rail-guided vehicles, AGVs, gantry robots, or universal 6-axis robots. Not only can a host of part delivery systems be interfaced to these machine tools, but table sizes and weight capacities can be changed to suit the customer together with the "working envelopes" as necessary.

All CNC machine tools do not of necessity have to be highly complex and sophisticated equipment as described in Fig. 1.51. There is a good case for CNC control principles to be adopted whenever it is necessary to machine large components using the gantry or portal type of machine tools. Invariably these gantry milling machines have simpler CNCs from the point of view of auxiliary software options, such as tool management and part scheduling abilities, but concentrate on the software enhancements needed to machine divergent part geometries likely to be encountered by such machines. Typical of these larger scale machine tools is the one pictured in Fig. 1.52 where a custom-built machine tool is manufactured to cater for the large flat-type of components, but at relatively low volume production rates. Once again, these machines can be purpose built to the customer's requirements and as a result can be considerably larger than the one shown in the photograph. This machine tool (Fig. 1.52) does not have automated tool changing abilities as speed of manufacture is not the dominant criterion, moreover the ability to machine large components, or small to medium-sized batches at one set-up, is its main function. However, automated tool changing can be supplied and it then becomes a large capacity machining centre.

The next machine tool to be considered in our review highlights a different approach to piece-part production, giving it the ability to manufacture free-form shapes typically to be found in the aerospace and automotive industries, rather than the more usual prismatic part geometries mostly catered for in less sophisticated machines. This machine (Fig. 1.53) is a five-axis twin pallet vertical machining centre offering two

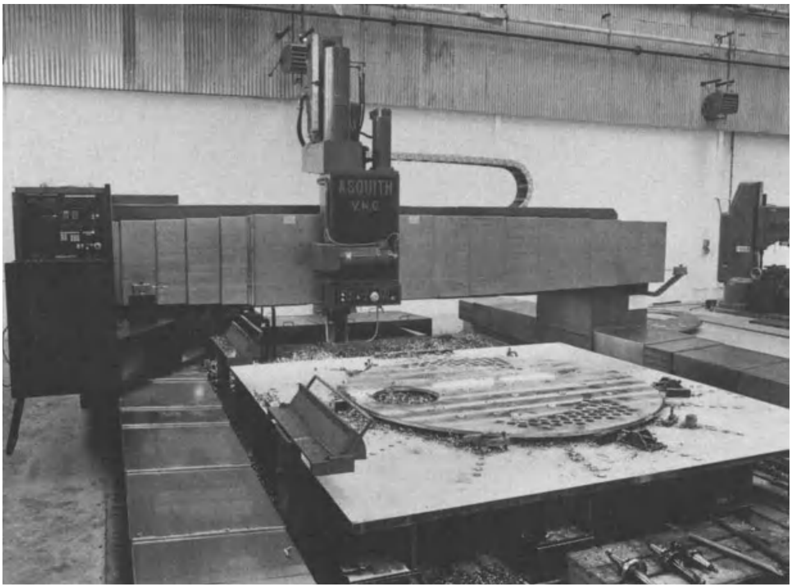


Fig. 1.52. A moving gantry vertical milling machine. [Courtesy of Asquith 81.]

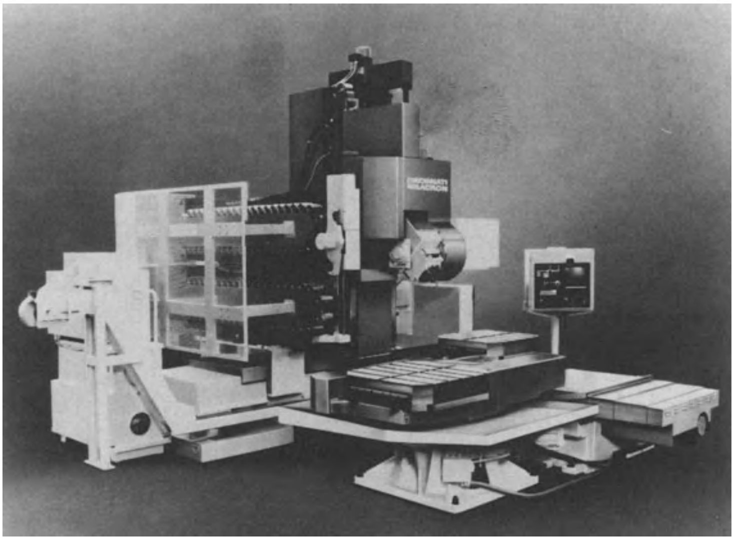


Fig. 1.53. A large 5-axis twin-pallet machining centre. [Courtesy of Cincinnati Milacron.]

linear axes to the table, a rotary pallet motion, with a linear motion to the column and a rotary axis to the tool head assembly. Such range control over a greater number of axes allows the cutter orientation to the workpiece to be continually monitored and changed, giving it the capability to present the cutter normal to the surface which is a requirement when machining many complex geometrical components. As expected on such a universally adaptable machine tool, the tool library is of large potential capacity, and can be extended to even greater size if necessary. These machine tools may be custom-built, but are expensive. As before, swarf conveyors and the usual health monitoring equipment for tool and machine protection can be supplied if appropriate and the CNC in this case is quite a sophisticated device.

By way of a comparison with the large-scale CNC milling machine depicted in Fig. 1.52, the more compact fixed table travelling gantry CNC mill shown in Fig. 1.54 is a more popular alternative. This machine is more easily automated; tool changing and axis speeds are less restricted owing to smaller inertial and momentum constraints. A swarf conveyor is supplied on this machine tool and full slideway protection from swarf and debris is incorporated into its design. This slideway protection is an important feature whenever high-speed routing heads are fitted as swarf volume and velocities are very high. Often these gantry/portal machine tools require hydrostatic bearings for the table, owing to the large weight capacities that can be held on tables, as separation pressure between conventional slideways would cause problems for the smooth CNC linear motions normally required.

To complete this appreciation of just a few of the diverse range of CNC machine tools available today, a 6-axis vertical CNC machining centre is illustrated in Fig. 1.55. The table in this case has two linear and one rotational axes present, whereas the column offers one linear motion with two rotary motions to the main spindle assembly. This amount of control over linear and rotational axes truly allows the cutter to machine highly complex free-form geometries to parts as depicted in the photograph. These machine tools can be programmed directly through the CNC, or more typically

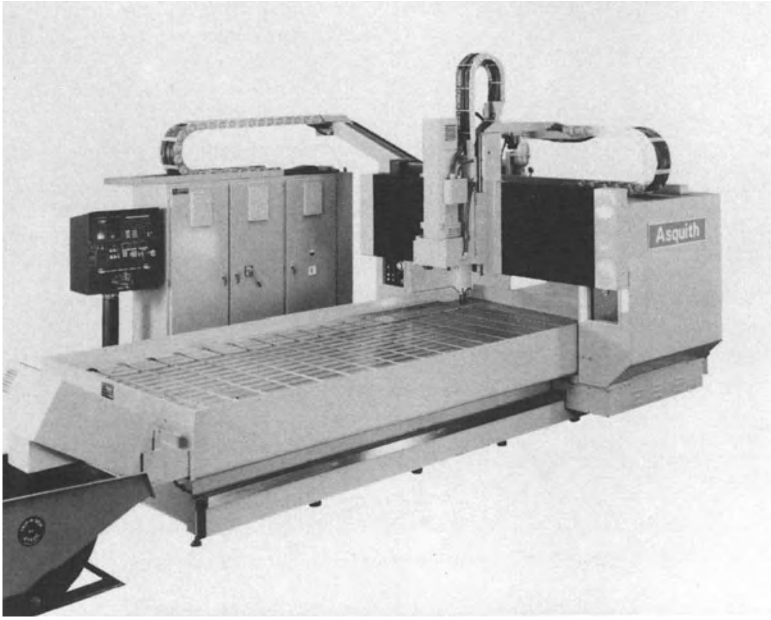


Fig. 1.54. A fixed table travelling gantry milling machine. [Courtesy of Asquith 81.]

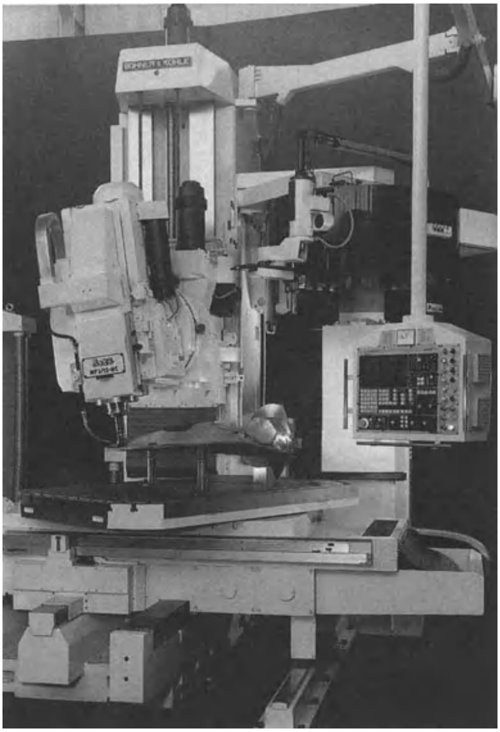


Fig. 1.55. A 6-axis machining centre cutting a complex curved component. [Courtesy of Bohner & Kohle.]

nowadays, a direct numerical control (DNC) link is established to the machine tool from a CAD/CAM workstation. As with most of the previous machine tools mentioned, this machine, as shown, can be supplied with/without tool magazines and automatic tool changing equipment as necessary. All of these photographs showing unguarded machine tools are more usually purchased fully guarded when high metal removal rates are a major requirement for operator protection.

The metal cutting machine tools described in this chapter are of no practical use if they are not "tooled-up" with the latest efficient and productive cutting tools. The first chapter of Volume II discusses the correct tooling philosophy to be adopted, as well as many other important tooling considerations demanded by any competitive manufacturing company today.

Chapter 2

Current Developments in Flexible Manufacturing Cells and Systems, Leading to Complete Computer Integrated Manufacture

2.1 Introduction

In Volumes II and III we will be concerned with a discussion about stand-alone turning and machining centre technology and related activities, such as tooling, workholding, and cutting fluids. This chapter will consider how best to achieve a degree of automation using equipment and looking into the relative merits and drawbacks of such implementations. Prior to discussing the role of currently available FMC/S solutions, it is probably worth defining what we mean by "Flexible Manufacture" – whether one is describing either a cell, or a system. The definition favoured by the author is a modification to that proposed by an early investigation commissioned in America by the US Task Force Study: "Two or more machines coupled to either a robot, or an automatic transfer mechanism for the machining of parts". This loosely describes, in the most basic terms, the requirements for a flexible manufacturing cell; in fact we must qualify this definition by saying that, according to an FMS builder, such systems must be "as rigidly flexible as possible!". This means that either a cell or system should have a degree of flexibility within rigid constraints in order to perform in anything like a flexible manner.

During the early 1980s, companies were investing in large-scale FMS and often these were doomed to failure, principally because lack of rigid constraints of either part handling, tool management, compatible communication protocols plus error-recovery procedures were not strictly formalised – this is where our rigid constraint is essential. As a result of the above, many manufacturing departments became somewhat disenchanted with such complex FMS solutions to their variable production scheduling needs and in recent years have been more inclined to favour the cell approach, or the progressive integration of stand-alone machine tools into cellular configurations. This latter technique of a step-by-step approach to FMC integration, allows a company to not only build up their production capabilities in a proven and steady manner, but also to minimise the capital expenditure. It is then spread over a longer time-scale, whilst simultaneously gaining experience and confidence in the assurance that each machine tool element within the FMC offers real benefits to the manufacturing capabilities, rather than the possibly dubious merits of an ill-conceived and executed feasibility plan. Any feasibility study must be carried out utilising computerised simulation techniques in order to obtain a realistic appraisal of both current and future manufacturing capabilities, but more will be said on this, and other related topics affecting production, later in this chapter. Such highly productive equipment placed into a conventional manufacturing department, without thought to the logistical problems associated with its implementation, leads inevitably to, at best, bottlenecks disrupting the harmonious flow of parts, to, at worst, complete failure and chaos within the company, with "loss of face" for all concerned.

In the following pages, we will try to alleviate such disastrous and ill-fated implementations, by attempting to describe not only the range and scope of FMCs presently available, but some of the systems that lead to complete computer integration of the manufacturing factory, as depicted in the case-study towards the end of the chapter. Lastly, we will look at how part accuracy is becoming the most important manufacturing characteristic and the steps a machine tool builder must be prepared to go to achieve ultra-high precision workpieces. During our discussion, frequent mention will be made throughout the chapter, to such topics as "logistics", computer integrated manufacturing and so on, in order to attempt to give an overview of not only flexible manufacturing strategies, but integration themes.

2.2 The Importance of "Logistics" in a Flexible Manufacturing Environment, its Feasibility and Simulation during the Development

In any highly productive environment such as a flexible cell, or system, the throughput time and capital turnaround are major factors that influence the cost of production. Quite simply, the machine tool is just a link in the total chain: from receiving an order, to part supplying and then invoicing the customer. When considering investment, it is appropriate in most cases to rearrange and organise any existing manufacturing facility, in small steps and over an extended time, rather than building a so-called "green-field site", as this objective is much less drastic whilst increasing the utilisation of our present manufacturing equipment in conjunction with the considerable reduction of throughput time. Clearly, this is not a simple task, especially if one considers that during the amortisation time for such investment, any in-house production will need to be adapted to an ever more rapidly changing market condition. This fact is true, whether the company is investing in: stand-alone machines, cells, or systems. The crucial problem is always how this new production facility can be organised and harnessed to the existing overall manufacturing capabilities. Such a problem might be compared with a surgical transplant, where all that we know is that it can only succeed if the body does not reject the new organ, accepting it as a harmonic unit of the system. Seen another way, we are confronted with interfacing and communication problems that need to be planned and solved with care, to ensure that everything will remain compatible after any subsequent investments.

Not only do we expect compatibility from our current and future plant needs, but also from the human involvement in the manufacturing facilities. From a company's design, organisation and planning departments the personnel at all levels interpose control restrictions between the planning/manufacturing areas, whether computer support is available, or not. Often, in many production shops there may still remain several conventional machine tools and associated methods/sequences that are primarily dependent on man, resulting in workpiece calculations for the whole facility being strongly orientated towards the labour rates. Even when a company has taken steps towards computer-integrated manufacturing (CIM) methods, the effect of man still plays a part, albeit a minor role. Man is at the focus of any traditional manufacturing facility and it is the function of computer-integrated manufacture to minimise human activity within the day-to-day control process. Furthermore, by utilising CIM it is possible to reorganise everything in such a manner that computer algorithms can be used purely for the planning and mechanised sequences of manufacture.

It is not only the management that must be trained appropriately to cope with changes in manufacturing, but shop-floor level employees also – in the same way as it is necessary to train somebody in programming aspects when involved with CNC machines. So far, companies involved in computer-assisted manufacturing have found that the demands on operating personnel do not reduce, but can be considerably higher than for conventional routes of manufacture – often termed "job-enrichment" in the United States. This term encompasses the concept that an enriched quality of working life results from operators being associated with flexible manufacturing systems. There are many more aspects of responsibility for the operator in an FMS system than for the operator running just one machine tool. As a result, FMS operators need to have a broader view of manufacturing. Instigating a third shift together with some weekend working will only be viable from a sociological point of view if the manufacturing system can be successfully buffered in the first and/or second shift, then run with limited manpower on the third. A third shift cannot yet be run in an unmanned "lights-out" operation. That situation is still a few years away, in terms of total integration of hard/software functions. As a result, the unattractive night shifts will perpetuate, together with weekend working, for some time to come, requiring certain key personnel for either supervisory or maintenance tasks. Such working arrangements mean that problems will remain in terms of the pay structure and social politics area until these points are resolved.

Formulating a manufacturing facility into an unmanned environment is limited by the amount of additional and out-of-proportion expenditure; particularly when short part-cycle times exist, the costs for fixtures, pallets, buffer stations etc. will, in most instances, prove uneconomical. This point is thought to be relevant when one considers the personnel savings – or lack of them – as a result of much manpower effort being expended simply loading and unloading parts in the preceding and subsequent shifts, respectively. This makes a nonsense of our reasons for automating the manufacturing process in the first place.

Many companies deciding to invest in flexible manufacturing cells or systems would normally instigate such technological innovation in a step-by-step expansion – unless a "green-field" site was chosen for this new production facility. About 30% of all flexible manufacturing systems are planned as an integrated and "overall" concept in a single or double expansion stage. Companies investing in such systems are normally "batch-producers", who have the advantage of being able to take the step to flexible manufacture clearly and decisively, leaving behind the concept of rigid manufacture. Without question, these companies adopt this manufacturing strategy basing their investment strategy on the unequivocal desire to be able to react in a more rapid and flexible manner to fluctuations and changes in market conditions. It is also apparent that company investment strategies consciously accept certain cost increases which arise through this demand for flexibility. The diagram shown in Fig. 2.1 illustrates that as far as "pure" manufacturing costs are concerned, the route towards greater flexibility will inevitably lead to higher production costs. Although these additional costs incurred can, to some extent, be offset by new disposal strategies typified by "just-in-time" inventories.

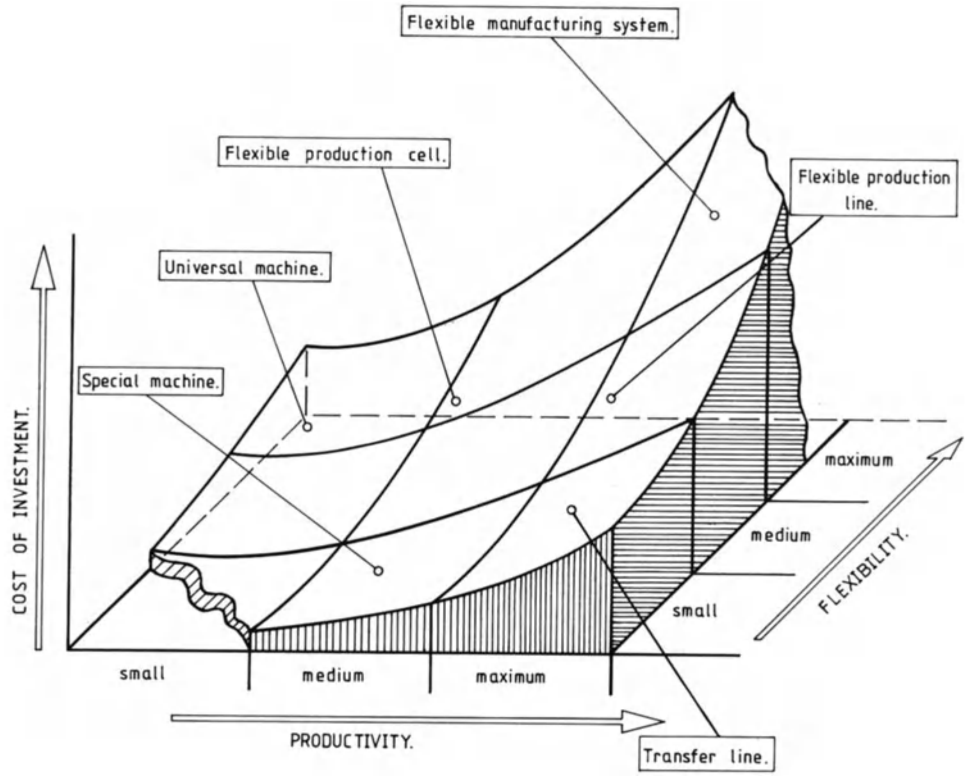


Fig. 2.1. A comparison of manufacturing systems based on the following criteria: automation level, productivity and investment costs. [Courtesy of Scharmann Machine Ltd.]

Logistics as a Company Strategy

In any company, solving the logistical problems requires a series of basic decisions to be taken, with possibly the crucial one being to purchase integrated software for all the technical and commercial fields of planning. The corporate decision to standardise software will ensure high data topicality together with simultaneous and redundancy-free data keeping. In essence, what this means is that for both production planning and control, we are in a perpetual state of readiness for information regarding: delivery deadlines; order status; parts availability; through-put time; capacity loading; costs. However, logistical problems can only be consistently overcome, if such responsibility is singularly authorised for all activities affecting orders and the establishment of organisational rules is centrally instigated.

Any logistical activity begins long before a customer places an order and in terms of the context of production program planning, the turnover target for the financial year must be established and any rough planning at this point helps. With the manufacturing aim being to ensure a balanced capacity peak in the bottleneck area, basic deadlines can be established for orders. Allocation of delivery deadlines in the offer phase is a second function of rough planning, with possibly the most important third-stage function being the periodical follow-up of the order once it has been placed. The

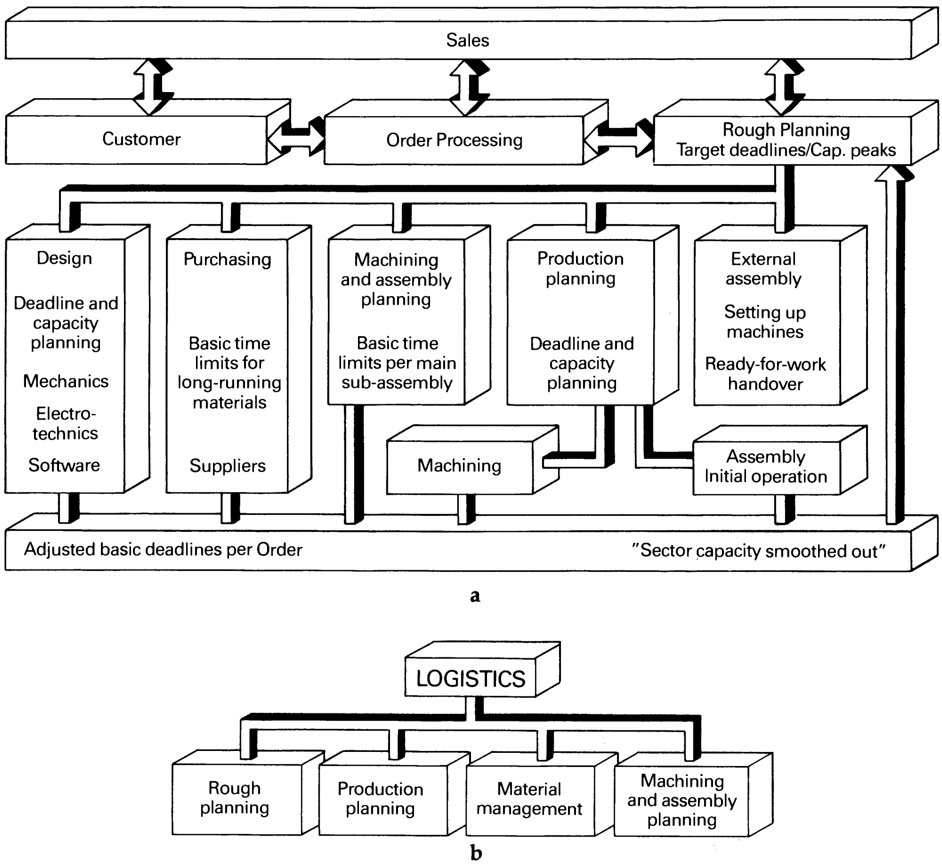


Fig. 2.2. The importance of logistics as a company strategy. **a** The concept of integrated logistics. **b** The "key" sectors of logistics in manufacture. [Courtesy of Scharmann Machine Ltd.]

block diagram in Fig. 2.2a highlights the theme of integrated logistics as conceptually realised by a machine tool manufacturer.

In logistical terms, for all departments participating in processing the order, basic deadlines must be calculated in terms of network plans. Simultaneously, the projected estimated capacities are loaded into these bottlenecks and a position plan is produced for the optimum exploitation of the manufacturing space. Such deadlines are repeatedly matched with those in specialist departments, until an agreed schedule has been defined and area capacities have been smoothed out. The established basic deadline framework is the binding target for all participants and the reference for all alterations. Acknowledgement of these scheduled activities will ensure that an immediate follow-up of the order occurs. Therefore, if deadlines are exceeded, methods are directly sought to compensate for any delays in the schedule. Such rules ensure that it is not left to the final (assembly) stage before attempts are made to reduce delays, but that prompt action occurs early on and at every stage of order processing. From a customer's point of view, this means that information about an actual order status is always available and in general guarantees the meeting of their anticipated delivery dates.

More precise planning normally occurs in the areas of production planning and materials management, with the basis here being the part list's orientation and its influence on final assembly of product. In a similar fashion – in terms of material requirements – it provides a clear description of the order relating to deadlines and capacities in the working schedule for, say, a mechanical fabrication, or the coordination of detail for assembly activities. It is, of course, very important to have a homogeneous transition from a rough to precise planning stage, for there to be an acceptable overall planning strategy. Furthermore, any activities that have been specified at the rough planning stage will be progressively replaced by precise plans once the period of order processing has begun.

When an order network has been derived from the parts list, any fabrications and assembly orders belonging to a customer order are related to each other and this will immediately highlight any mutual dependency of products. It follows that the consequences of any interruptions in the run of work can be easily established and countermeasures introduced.

The organisation of CNC activities, such as preparing, administering, and distributing all the information necessary for such machine tool operations, is largely concerned with either the production of individual, or job-lot manufacture. Integration of CNC activities can be incorporated still further into the logistical strategy by having computer-aided production planning with a CNC programming system – possibly CAD/CAM integration, with direct numerical control links established to both the machine tools and tool preparation facilities.

Finally, for new and modified designs, it is of the utmost importance that in the early stages of a product's design any work is closely supervised, with effective communications established in order to eliminate possible sources of error and therefore difficulties, before one gets to the final manufacture and assembly stages.

The importance of logistics in the company's manufacturing strategy is shown schematically in Fig. 2.2b, where it acts as a focus for integration of rough and production planning, material management, machining and assembly planning. This coordination of multiple planning functions highlights problems prior to and during manufacture, smoothing-out bottlenecks, minimising errors whilst manufacturing, and considerably shortening product development times. By incorporating the theme of integrated logistics within a company, a framework is provided for a "simultaneous" – or as it has recently been termed a "concurrent" – engineering strategy to be developed. This technique has shown conclusively that it will drastically reduce and simplify new design concepts and shorten product lead to the market, with all of the implied cost savings.

Before a company decides to purchase a flexible manufacturing cell, or system, it must carry out a feasibility study, considering not just the parts (and their costs) to be manufactured within such a facility, but the implications of placing highly automated plant into the current production area and how it might affect the harmonious flow of parts through the factory. As such, it is often necessary to simulate the plant within the constraints of the manufacturing department to gain an appreciation of likely problems. These topics we will now address, before looking in detail at typical automated installations to be found in most advanced countries in the World today.

2.2.1 The Feasibility Study – a Vital Element in any Advanced Manufacturing Strategy

Any company embarking on the purchase of highly productive equipment such as a flexible manufacturing system must, of necessity, conduct a feasibility study in order to be assured that such a large capital outlay will considerably improve the company's performance for its perceived market. The design, its development and installation, can be thought of in three distinct stages:

project planning and realisation
system integration into manufacture
project responsibility

In order to achieve a successful implementaion, the feasibility study can be subdivided into three further categories:

first stage – a quotation planning study
second stage – an order planning and FMS quotation
third stage – ordering the FMS and its project management

Let us now look more closely at each stage to try and build up a picture of how one might instigate and develop a successful flexible manufacturing system.

The Quotation Planning Study

First, we must consider the amount of work involved in the logistical implementation, which would take into account an analysis of the expected workpieces to be manufactured, normally grouping parts of similar geometries, or processes, together – termed "group technology". It is then important in the preparation of the concept to document in some detail, all pertinent facts. Simultaneously, a team of interdisciplinary engineers is chosen who will embrace a range of technologies, system planning, and the computer systems to be utilised within the perceived FMS. Once these factors have been established, it is possible to calculate the costs, draw up a quotation and present it to the company's management for acceptance.

An Order Planning Study and FMS Quotation

From now on, feasibility activities become more inter-related and a detailed examination of workpieces to be machined occurs with part families being firmly established – the "group technology" theme again. Part fixturing concepts are explored and if necessary pallet sizes are decided. Concurrent activities of mutual interest concerning the workpieces are collated and data relating to the whole machining process – including the means of manufacturing part features are determined, together with the concept of their storage: pallet pools, stillage stations, buffering and the part transportation system to be incorporated – either rail- or wire-guided AGVs, flexible flow systems, robots (floor, or gantry types). Simultaneously, peripheral equipment (subsystems) is specified which will influence both the FMS layout and its productive capabilities. Machining times, together with the computer and transport systems, will have a considerable impact on the prospective plant layout, and their preselection at an early stage is necessary. This will focus our attention towards possibly two, or at most three, potential systems that can be "modelled" by simulation (see section 2.2.2). The critical stage has now begun where one attempts to establish a representative "model", around which all our final decisions are made. The alternative simulation "models" will define: the system layouts, material supply routes, tool handling strategies, and compare the chosen "models" under realistic production conditions, running them over specified time-scales to assess potential "bottlenecks" in the system.

Once the alternative "models" have been simulated, their respective documentation is produced in order that a final manufacturing decision can be made, taking into account capital costings, manufacturing output, flexibility of production and amortisation cost factors. Furthermore, the documentation generated includes not only anticipated quotation costs and a description of the chosen system's performance, but also the plant layout's and their respective specifications.

The Ordering of the FMS and its Project Management

By now, the team involved in the feasibility study will know all the relevant facts, enabling them to be in a position to award a contract, with the assurance that such a study has highlighted the expected advantages and weaknesses in the manufacturing concept. Hopefully, the latter problems are only of a minor nature and will not unduly affect the project. With the contract awarded to either a single-source vendor, or a multi-sourcing with overall project supervision by a specified company, such details as production planning and system design can be developed from the functional specification. Whilst this is being undertaken, training and, later, works acceptance will eventually occur – usually on the vendor's site. Sometimes when a large system rather than a cell is built, it would be installed at the company's manufacturing facility, which would have the correct infrastructure by now in place, with foundations and services prepared at an earlier stage in the project.

Assembly of the complete installation including machine acceptance trials, peripheral equipment acceptance and computer system integration, is established and as usually expected, a direct numerical control link to the in-house CAD/CAM system occurs. Lastly, a complete justification for the whole manufacturing facility installed is initiated, where run-offs of parts within the system are compared with the master schedule laid out during the project's conception, so that the company is assured that the installation is meeting its productive requirements. After acceptance by the company, a close working relationship will have been established between the customer and vendor and this continues into the guarantee time and often beyond.

Any prudent company deciding to install such highly sophisticated and comprehensive equipment must, of necessity, conduct a well-disciplined and planned feasibility study in order to ensure that the project achieves its manufacturing objectives. Such a study will then be sure to come in at cost, on time and having the desired production capabilities. We have seen that possibly the key element in any prospective dynamic part-scheduling facility, namely a flexible manufacturing cell, or system, requires simulation to ensure that it meets the functional specification developed during the company's feasibility study. This can be "modelled" either with an in-house simulation system or, more usually, by the vendor's system. In the following section we will consider the "simulation modelling" in more detail, looking at two currently available systems.

2.2.2 Simulation Techniques, the Key to Successful System Integration

When a simulation "model" is developed the objective is to predict the effects of alternative actions – "what/if" conditions. It utilises the computer-driven electronic "models". Such "models" are created by the user producing graphical, or alphanumeric data illustrating situations expected within a proposed, or alternatively, "real-life" operation over an accelerated time-base. In recent years, there has been an increasing emphasis on integrated systems in which machines and peripherals are linked, thus reducing lead times and work-in-progress levels, and maximising resources. Simulation has many beneficial features and can be applied across a range of technologically innovated areas, such as:

a feasibility design tool

a preliminary study when making modifications to a current system

a method of capturing/studying a system's parameters then incorporating them into a "host" computer

showing the affects of altered time scales on the system

an aid to study the extremes of an operational system's capability without the risk and expense of disrupting production

a training tool for operators reducing the expense, or inconvenience, involved in using the actual system

Simulation comes into its own when there are indeterminate variables, typically queue times and breakdowns that preclude the exclusive use of mathematical techniques to predict the system's performance, or the result of a series of events. The aim when using simulation packages, is to attempt to achieve the right balance of resources – men, machines and work transportation – then to establish how they might be organised to obtain the maximum effect. The method by which the electronic "model" is created and manipulated is dependent upon the simulation language chosen for the software package; it is also influenced by the process to be simulated. Basically, three types of simulation language are used in the determination of a simulation "model":

"PROCESS"-based: these are primarily concerned with continuous processes – by which the resources pass through the plant – that are used exclusively in manufacturing activities

"ACTIVITY"-based, often termed two-phase programs, that are concerned with discrete time-periods and are best suited for "modelling", then simulating batch-type manufacturing systems

"EVENT"-based, known often as three-phase programs and can be used in a similar manner to the "ACTIVITY"-based methods, but with more modelling discrimination

In our discussion we will consider only the latter two languages – "ACTIVITY" and "EVENT"-based – as they apply specifically to the batch manufacturing found in flexible manufacturing production. Any "ACTIVITY"-based language considers the start, duration and end of an operation as just one activity, with the various resources coming together to undertake a sub-routine. Only after this sub-routine, such as loading/unloading the machine tool, has been completed will the clock advance. In the case of "EVENT"-base languages, each event is considered separately with the clock advancing at each time there is a change of state and with our last example, loading and unloading would be described as separate events.

The simulation process can be basically considered in three stages:

system definition and creating the model outline with captured data

writing/proving out the electronic "model" within the computer

operating and redefining simulation runs until acceptable results are obtained

As one would expect, creating a system "model" is the most demanding and critical stage of the simulation process; furthermore, as the computer simulates this "model" and not the system, successful operation depends on how accurately the "model" represents the system. The well-known saying "garbage in, garbage out!" means that our model developed is only as good as the data gathered. The "model" includes structural and physical relationships combined with the system's time-based interactions; so, by defining our problem and highlighting critical points whilst collecting data – this being difficult and time-consuming – then building/validating the "model", we will obtain a realistic representation of simulation.

When "model" building, the programs can range from those that are mathematically-based – having a complex structure developed with a knowledge of high-level computer languages, such as Fortran, enabling it to run using powerful simulation programs – to these running on microcomputers in such a way that "modelling" is invisible to the user. The more powerful discrete event simulation methods are usually used with mainframes/minicomputers, but some systems have specific hardware developed. These systems are more specifically used by expert programmers and are designed to handle any problem capable of being "modelled" in discrete event form. Such "modelling" is a long process requiring a thorough understanding of the system, although one system has reduced the keyboard input time using a front end code generator, which is an additional program enabling an interactive input of "model" data in English.

The number of visual interactive systems is increasing, allowing non-experts to use the programs, being in effect validated "models" into which the prospective system "model" is fed. As such, these systems are particularly relevant for "modelling" flexible manufacturing systems, or when tool management systems need to be simulated. This is not a limitation compared with the more sophisticated simulation packages, as it allows the non-expert to understand the software functions more easily, whilst gaining confidence in programming. For this reason, these data-driven visual systems are gaining acceptance – particularly since they cost a fraction of the high-level programs, whilst being much easier to use. Possibly the main benefit of the visual interactive systems is that they give the user an easy means of explaining the system "model" to the decision-makers within the company. This on-screen pictorial mimic which has an interactive ability is much more acceptable to management than the more common but traditional tabular output of simulation results.

As we have seen, the more powerful systems require experts, taking time and requiring proficiency in programming ability; this inevitably confines such systems to areas where cost-effectiveness becomes paramount. Whatever simulation system is chosen for the task, whether the manufacturing project is complex or relatively simple to simulate, then the preliminary planning should not account for more than 1% of the project's capital cost. The preliminary model created would be appropriate for additional detailing in order to fully test and optimise the proposed system. Any further detailing to the simulation depends upon the complexity of the system, but also the "law of diminishing returns", meaning any direct savings found by further enhancement of the model, must be levied against greater costs. Typically, the cost of gaining proficiency in the simulation system and its annual running costs can approach £30 000 – for an advanced system that is fully capable of general use, and whose cost must be taken into account.

With some companies, having an in-house simulation system is vital, but whenever a company needs to "model" only occasionally, then it might be more appropriate to use a consultant. Using a consultant to build the simulation "model" can be achieved at a fairly low cost, prior to the heavy investment needed to assess the feasibility of the project.

In Fig. 2.3 a range of simulation "models" can be seen, depicted in either cells or systems, produced by two of the leading simulation software companies. The "models" shown in Fig. 2.3a–c are presented to the user in a plan form, whereas the "models" shown in Fig. 2.3d–f are oblique views of the simulation. In both cases a range of colours can be used to identify the dynamic moving elements, such as pallets, or automatic-guided vehicles and at any time the machine utilisation rate, personnel utilisation, product routing and quality control objectives can be assessed in a real-time sense. By running the "models" over a specified time-base it is possible to see if "bottlenecks" occur at certain times and by amending the layout – introducing either new machine tools, or re-routing parts – "what/if" conditions can be assessed.

Therefore let us consider the logic used in Fig. 2.3a–c; the "models" are described in terms of "entities" which engage in "activities. An "entity" represents a resource, such as a CNC machine, robot, conveyor, or palletised part, whose behaviour is being simulated, whereas an "activity" is the state in which an "entity" remains whilst an operation takes place over a period of time. The time of the "activity" is previously calculated and once it has begun it continues for the time duration, unless the logic of the "model" allows the process to be interrupted. For example, a machine tool and its associated workpiece might be engaged in a specific machining operation which could be interrupted by, say, a breakdown. When an "entity" is not involved in an "activity" it waits in a "queue"; thus a machine might wait in a "queue" when there is no part for it to currently machine. With any "entity", attributes can be used to describe it in greater detail, for example, a machine tool's attributes would be its speed, range of operations it can perform, and the last time it has been maintained. The life of a typical "entity" might consist of several "activities" and "queues" and the manner in which "entities" travel around the "model", from one state to another, can be represented in an activity cycle diagram (not shown).

When one requires to change the status of the "model", then by cycling through the three dynamic conditions of "start", "time" and "end", further what/if conditions will result and help the programmer to assess the "models" viability. Let us look a little closer at these three phases:

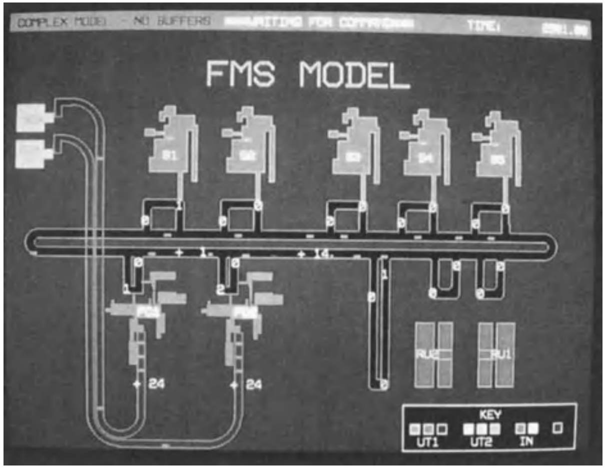
"start" – checks the conditions of each "activity" in turn to see if any can start. The "activity" number establishes the checking sequences and obviously the priority between competing "activities". The logic dictates that an "activity" may only start if the approprate "entities" are available in the correct "queues". If an "activity" can begin, the "entities" are moved from their respective "queues" to the "activity", with the time being written next to this "activity"

"time" – this is needed to locate the "activity" or multiple "activities", with the earliest end time and advances the simulation clock to this time

"end" – the "activities" due to finish at the new simulation clock time; it moves the "entities" to the destination of the "queues". At this point, the "activity" returns to the "start" phase

Such simulation practice proceeds for as long as necessary, to verify the logic, observe behaviour of the "model", or to collect statistics.

The simulation "models" depicted in Fig. 2.3d–f, allow a dynamic simulation package to be used, producing complex and realistic "models" through a "building block" approach, making a knowledge of programming unnecessary. "Models" are built using a series of "blocks" which prompt the user to input information that accurately represents the process to be simulated. These "blocks" take the form of a logical sequence that makes the "models" easy to read and understand, with on-a



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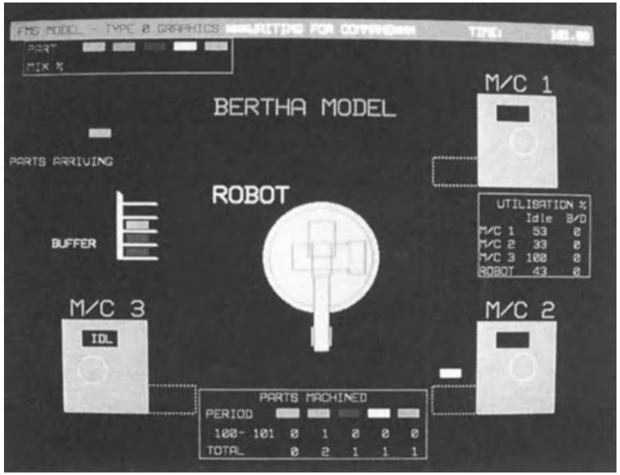

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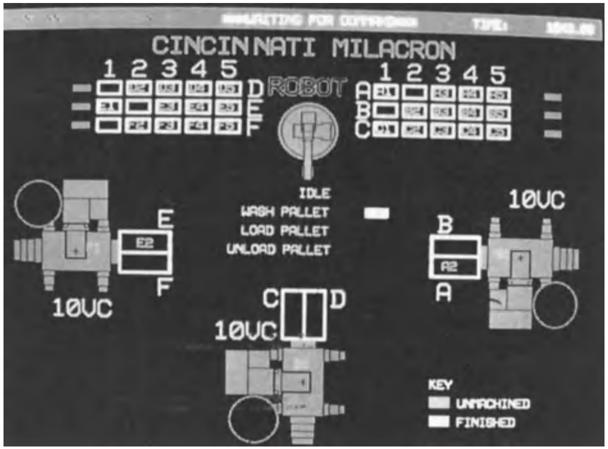
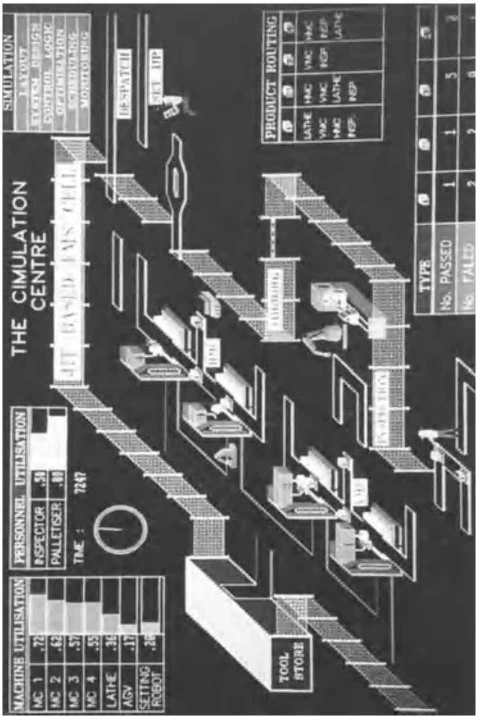


Fig. 2.3. Two simulation software packages illustrating how the efficiency and potential feasibility of prospective FMS/C can be assessed and then run over a preselected time-base to determine "what/if" conditions in a dynamic situation. **a–c** This package highlights a range of plan views of both FMS/C models. **d–e** Oblique simulation of an FMS, showing the dynamic time-base changes in manufacture and its "zooming" capabilities. [**a–c** Courtesy of P-E Consulting Services. **d–f** Courtesy of Cimulation Centre.]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PERSONNEL UTILISATION
TOOL STORE
PRODUCT ROUTING
SIMULATION

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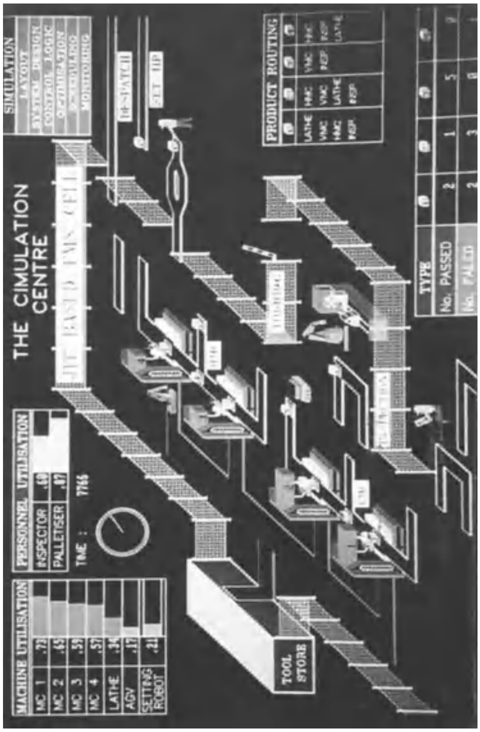
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PERSONNEL UTILISATION
TOOL STORE
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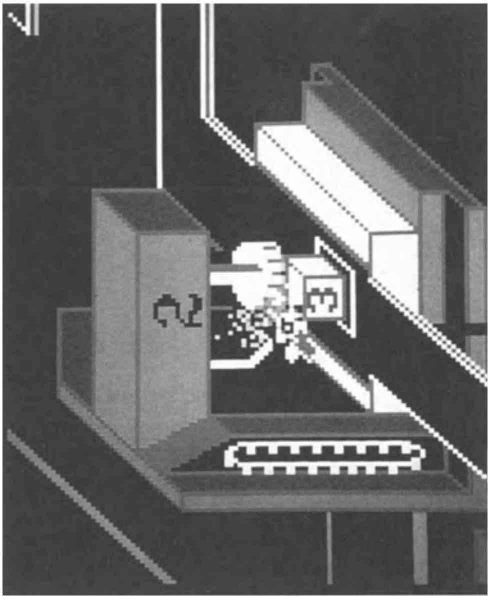

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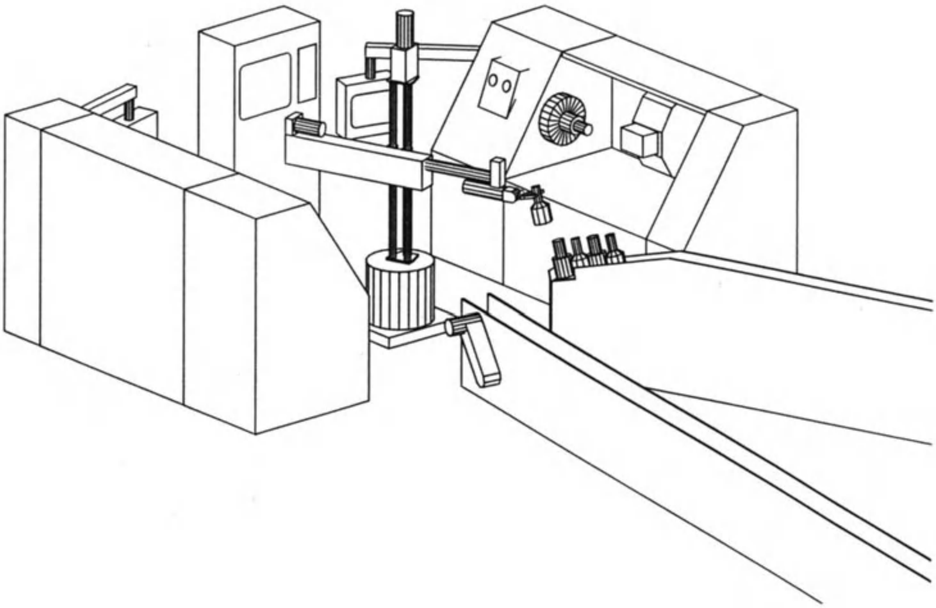


Fig. 2.4. A simulated robot-loaded turning cell with "hidden line removal", used in feasibility studies for cells/systems. [Courtesy of BYG Systems Ltd.]

screen prompts to further enhance the documented flowchart. Once the "model" has been completed, then what/if experimental data is read prior to performing a simulation run.

The graphics are so designed that even a novice can develop 3-dimensional colour layouts, allowing the user to see the process in operation relatively quickly. An interactive feature can be called-up to help analyse what is happening to the "model", allowing the user to step through the "model" whilst watching the graphics being continuously up-dated. Alternatively, the simulation can be run until a certain condition occurs, then halted to establish the reasons for occurrence. A menu generator can be used allowing the "model" builder to develop a series of menus, enabling the simulation to be operated by an unskilled user. Such menus allow variables to be modified, then the data collected and stored for subsequent analysis. Data can be read from existing computer files so that a simulation "model" can be loaded with an up-to-date start position. If a user has a knowledge of computer languages, there are interfaces for Fortran and "C" subroutines. CAD drawings can be displayed onto the screen so that movement can be superimposed onto the most complex of backgrounds.

A partial view of the dynamic simulation model can be seen (see Fig. 2.3d,e) and where an area of special interest occurs, then a zoom facility enables the user to observe the "workings" of the model in greater detail (Fig. 2.3f). The complex "model" can be observed at any time and the "model" will continue to run in real-time, even when one moves ahead to a new time-frame to see what might be happening at that time to the "model".

Before we leave this theme of computer simulation, it is worth briefly describing one of the three-dimensional advanced "modelling simulation of mechanisms" – such as robots and their tasks – that are currently available.

The system shown in Fig. 2.4 is an advanced kinematic "modelling" technique that is used in conjunction with an integrated three-dimensional-solid "modeller" to simulate both mechanisms and manipulators, as well as for conventional robots. Although a robot is depicted in both Figs. 2.3b and 2.3c, it does not have a truly "modelled" kinematic design which is necessary for the detailed analysis for actual implementation, whereas the "model" shown in Fig. 2.4 is a detailed scaled model of the true working environment. Such "models" are created using textural, or interactive graphical techniques and can be displayed as either a wire-framed form or with the hidden lines removed (Fig. 2.4), or optionally with full solid shading. New structures can be readily "modelled" and added to the system in complex relationships, enabling animation to detect clash problems between kinematic members automatically. This enables the user to verify that the "model" has collision-free operation, often within restricted areas.

By using such dynamic and realistic "models" of the actual working environment, the optimum placement of the moving elements and their relationship to the fixed elements can be achieved, which reduces the planning and design cycle considerably. Typically, a feasibility study of an FMC takes days rather than months and is certain to work, as the verification has been proven off-line and away from the production environment. This eliminates the costly mistakes that could arise if such a "model" had not been simulated and keeps the project time to a minimum. As with the previous simulation "models" discussed, the relative time frame can be moved to any point in the cycle and many further enhancements on the robot's optimisation within a cell can be achieved. Typically, the robot "modelled" can highlight the motions of the elements in terms of their range of angular/linear movement and how often they are activated during the simulation task. If in the case of a six-axis robot, only four axes are being used at almost 100% motion, then by modifying, or changing the layout slightly, all axes can be utilised at less than their theoretical motional limits. This allows a much better working relationship of the robot to its environment to be established, improving its optimisation.

Once the user is content with the proposed robotic cell, and all of the logical and positional information has been established – including input/output signals to control any peripheral equipment, the processing of sensory inputs, path control data, and high-level programming structures such as loops, branches and wait instructions – then it is possible to down-load the program to the robot controller. Once the program has been accepted by the robot's controller, then assuming the peripheral devices have been adjusted accordingly, the robotic cell can be run in its working environment.

This completes our review of some of the simulation packages available and their potential in removing the uncertainty when considering the prospective feasibility of an FMC/S. In the following section we will consider some typical plant layouts of cells and systems, before going on to mention how communication between machine tools and peripheral devices is achieved and look at some typical configurations of such communications.

2.3 Flexible Manufacturing Cell and System Configurations

The machine tools and peripheral equipment discussed so far function more than adequately in a "stand-alone" form which is by far the most popular method of production layout used by companies today. If this is the case, why do we need to invest large capital sums and increase the complexity of manufacture by using an FMC/S? There are some important reasons why such a plant configuration is necessary, not least of which being the opportunity to increase the company's profits whilst gaining a return on capital; possibly even more important is allowing the company a degree of flexibility to react to market and design changes. It is true to say that only certain production environments can truly gain from the implementation of such automation (see Fig. 2.1). Furthermore, this statement can be qualified by maximising the main advantages to be gained from total flexibility – a difficult test at best – and focusing upon a "Group Technology" (GT) approach to manufacture. Using this "GT" philosophy to obtain maximum benefit from the plant, processes are either grouped together in the form of a cellular manufacturing facility, or workpieces – where common features require similar production methods – further improving the cell's efficiency. Possibly the major advantage of such a flexible approach to the manufacture of parts is the unprecedented opportunity to drastically slash the hidden costs of production such as: work-in-progress, overheads and indirect labour. Any inroads that can be made into such areas will be a significant saving within the company, with the additional benefits being:

untended operation on third shift, or minimal manning on day shifts – reducing labour costs
improved machine tool utilisation
50% reductions in any work-in-progress
setting up times reduced
workpiece accuracy of more consistent quality
production techniques standardised
delivery times shortened
planned maintenance procedures – giving capital equipment a longer life
less floor space for plant – as manned access is minimised
opportunities for part/tool inspection during the machining cycle
part scheduling and re-routing of workpieces during planned maintenance, or unanticipated machine failure
interfacing to: MRP, MRPII and CAD/CAM peripherals through DNC links

2.3.1 Flexible Manufacturing Cells (FMC)

In recent years, more companies are seeing that the cell approach to untended machining is the way forward, as it can be developed using a step-by-step build-up of the major elements and in such a manner spreads the capital costs and hence risk, over a longer period. Secondary to this point, but some may feel just as important, is the experience and confidence gained by the company starting with a smaller and less complex cell – often beginning with a "stand-alone" machine tool – then progressing through stages to a larger FMC layout. Typical of this strategy is the FMC shown in Fig. 2.5, where it can be seen that two horizontal machining centres and one turning

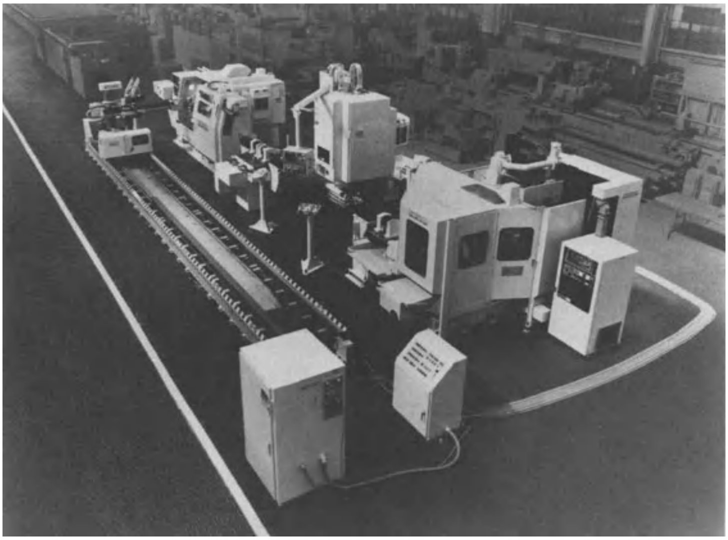


Fig. 2.5. Turning and vertical/horizontal machining centres in an FMC configuration together with robot-loading rail-guided vehicle. [Courtesy of Cincinnati Milacron.]

centre have been connected together by a rail-guided vehicle (RGV). This RGV has the ability to supply preset palletised parts by the carrier via the pallet stocker, or tooling from the tool centre. There is a two-way dialogue between the machine tools, peripherals and the system computer at all times, which up-dates, or re-routes work (in the case of an anticipated shut-down of one of the machining centres) with continual part tracking and tool scheduling/up-dating. In such a manner high machine tool utilisation can be achieved – over 90% efficiency is possible throughout the working day.

This type of FMC can be seen throughout many of the industrialised countries of late and gives a degree of flexibility of production within reasonably rigid constraints, in that such systems have often been called "prismatic cells" – but even here one must be careful to qualify this statement, as some rotational features can always be accommodated using either interpolation techniques, or special-purpose "U-centre" milling heads. Such cells can start with just two machine tools, then be progressively built up to a complete machining complex, comprised of six, or more, machining centres. However, when one reaches this level of complexity then it becomes important not only to utilise floor space effectively – often if this is to be the case, then staggering machine tools on alternate sides of the rail is necessary – but in addition, adding further RGVs to serve the extra machining centres. It is advisable by now to have completed a simulation of the enlarged cell layout, to obtain the maximum benefit from not only the extra machines, but the best utilisation of the RGVs proposed to service these machines (see section 2.2.2).

If a company is predominantly machining parts complete from bar stock cut to prescribed lengths, rather than the general machining of prismatic features, then a cell with a configuration similar to that shown in Fig. 2.5 might be the answer. Here, a rail-guided vehicle has a load/unload robot situated upon it and it is free to move up and down the track supplying parts to the turning centre, or the vertical/horizontal machining centres. Normally such an FMC would be fully guarded in the vicinty of the track and robot's moving elements, but for clarity this has been removed. As parts to be made by such a cell often differ only marginally in detail – the "GT" philosophy again – then the cell controller (shown in the foreground) can be of a much simpler design and of relatively low-level sophistication. This is prudent, as it reduces both the cost of the overall supervision, often needing only a programmable logic controller (PLC) to fulfil the production requirements, whilst having the major advantage of simplifying error-recovery – one of the greatest problems associated with down-time on FMCs – but more will be said on this topic later.

The pre-cut bar stock is stacked onto a workstation in such a manner that the robot's gripper can grip the parts easily – a range of delivery solutions can be used here to simplify either programming of the robot, or identify differing stock diameters and lengths – such as gravity feed chutes for parts, or flexible flow systems with automatic size identification and buffering incorporated into the equipment. Part delivery is not the major problem, however, as component fixturing, scheduling, monitoring and robot delivery is more critical – but even here, if both the dynamic simulation layout in combination with robotic simulation has been previously undertaken, this latter problem will have been addressed.

Whenever a company is likely to embark upon the development of a cell into a totally integrated system often covering a considerable floor space within the production facility, then there is some justification for elevating the supervisory control room over the plant so that engineers are positioned strategically above the facilities and have a clear view of the equipment. Usually such an environment is clean, relatively quiet and air-conditioned, which is an important point, as such personnel must spend considerable time within this area. Equipment in this control room will not only monitor the immediate and everyday functions performed on the machine tools – tool management, part status, scheduling, SPC – but is connected to the "outside world", to other departments, through communication links – ethernet, manufacturing automation/technical office protocols (MAP/TOP) – or even to other companies involved in Just-in-time (JIT) or similar activities.

The strategic placement of the centralised and elevated control room is critical to any further plant to be added to the cell at a later stage, as visual confirmation of machine tool and peripheral equipment status can be verified accordingly. However, even when the most well-planned floor layout has been built, there comes a time when the simple visual confirmation of a manufacturing activity becomes counter-productive and under such circumstances the real-time dynamic simulation takes on a greater significance for part status confirmation within the control room.

Often when a company is involved in a "highly-focused" production activity, then it is important to obtain the most advantageous machining capability possible by linking similar manufacturing processes together. In order to minimise possible work-in-progress activities, parts might be palletised and conveyed around the cell, then loaded by a gantry robot to a turning centre. This machining philosophy is used in the two machine turning cell described below. The workpieces might be loaded onto "coded" Europallets – several at a time and then delivered to each machine tool. Part scheduling is accomplished by a supervisory cell computer situated on one of these machines and can be used to a range of work-related activities such as: machine control, logistical part handling, tool strategy and management, together with machine monitoring. Such a controller, as one might expect, is MAP compatible and is not only easy to understand and use, but offers significant advantages in any error recovery situation.

Not only does the cell have the ability to automatically load workpieces into the turning centres, but a gantry robot can be used to change complete chucks for another rescheduled part without stopping the manufacturing process. It might also be used to load/unload quick-change tooling at will. By utilising a very universal and robust gantry robot it could also transfer workpieces to a part monitoring stage where a range of automated metrological equipment can be accommodated to inspect critical dimensional features of the component. Such an on-machine inspection facility would inspect the parts such as rotational features, using an automated caliper gauge which up-dates tool offsets during its inspection and can generate statistical process control (SPC) data to control the machining process, whilst production continues on the following part.

The major advantage of utilising another machine tool of similar specification, is that a balanced production flow between these two machines can be more readily achieved and in so doing, the overall utilisation rate is improved. Furthermore, if for any reason one machine tool is taken out of commission through either a preventative maintenance procedure, or unexpected machine failure, its work can simply and speedily be switched to the other machine tool, without too much lost production. In such a manner, down-time is drastically reduced and a vast improvement in the overall cell utilisation rate occurs.

The final cell to be discussed in this section is depicted in Figs. 2.6 and 2.7. The author has had the unique experience of designing this cell and taking it through the commissioning stages and final acceptance, in conjunction with a large machine tool builder in the UK. It was envisaged as a "turn-key" package – where specific parts were originally designed and the cell was brought on-line to machine such components. In this way, the total concept of flexible manufacturing could be addressed from the initial feasibility study, through to conception. The Southampton FMC comprises the following hardware:

two axis turning centre, supplied with modular (block) quick-change and "sister" tooling, programmable tailstock and chuck, with swarf conveyor

three/four axis vertical machining centre, with modular (varilock) tooling, programmable vertical chuck, tool breakage detection, adaptive control and touch-trigger probing, with swarf conveyor

coordinate measuring machine of cantilever design, with motorised touch-trigger probing which can be controlled through either a micro-vax, or PC, for full colour graphics programming

six-axis electrical robot, having a special purpose back-to-back (offset movable jaws) gripper, hydraulically operated

cell controller with built-in CRT, having both a "QWERTY" keyboard for programming cell production requirements and special-purpose controls for: interrupting program cycles, inspection calls, changes of batch sizes, etc.

optical tool presetter with on-line tool offset facilities

direct numerical control link to CAD/CAM equipment for completely automated design, manufacture and inspection

Customised software was developed and communications are orchestrated via the cell controller, through the robot controller, to trip input/output devices on the various machine tools and peripherals, such as to: open doors, close grippers, load parts into workholding devices, etc. The network topology used for communications is the "star" configuration (see Fig. 2.9a).

In order to obtain a realistic understanding of how such a cell operates, it might be prudent to run through the making of some typical parts during a conventional production cycles. Each of the machine tools within the cell can be operated in a "stand-alone" mode, so if one requires to run the system untended the supervisory

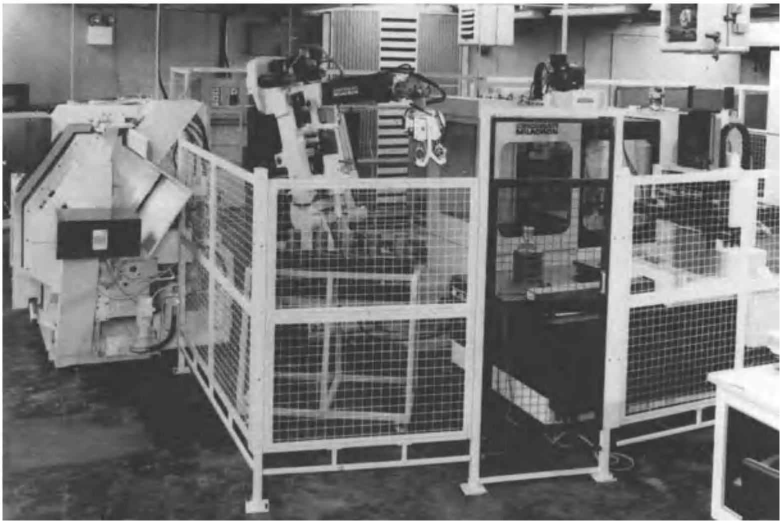


Fig. 2.6. A typical FMC installation (developed by the author and a machine tool manufacturer) at "commissioning stage" during the late 1980s. Initially, the cell was comprised of a slant-bed turning centre, a vertical machining centre, a 6-axis robot and a coordinate measuring machine. Later additions included an optical tool presetter and modular quick-change tooling, together with a CAD/CAM DNC link. [Courtesy of Southampton Institute/Cincinnati Milacron.]

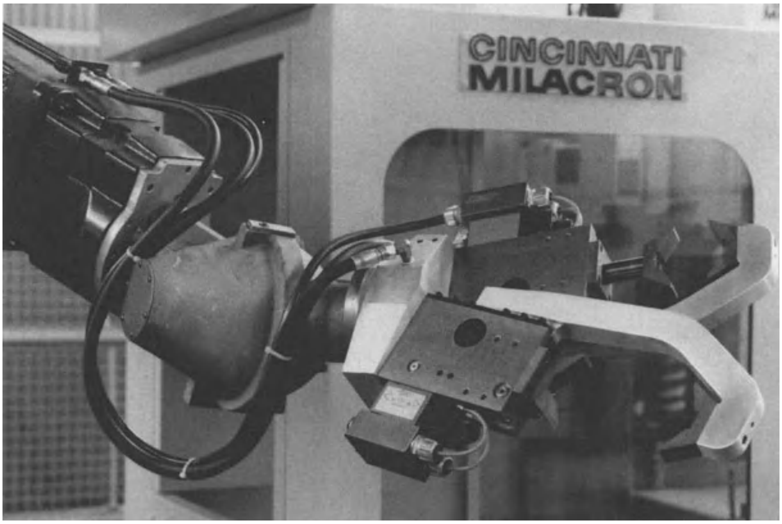


Fig. 2.7. Detail of the robot's gripper in the "Southampton cell" designed by the author. The hydraulically operated and offset back-to-back gripper has synchronised movable jaws, enabling fast load/unload of the parts (i.e. of varying diameters) and close access to the workholding equipment. NB: Jaw faces/ends can be quickly changed. [Courtesy of Southampton Institute/Cincinnati Milacron.]

control must be managed through the cell controller. This necessitates operating the equipment in the "cell mode", which is achieved by simply pressing the suitable button; however, before the cell can run, it is necessary to ensure initially that both machine tools are in "cell mode" and their axis and other peripherals are set to zero. The robot axes need to be datumed and set to zero and this is achieved at the cell controller by simply holding down a button whilst all six axes are set. Confirmation of each axis appears on the CRT display. Assuming that an appropriate number of pre-cut billets have been loaded onto the workstation, then the batch size can be stated and confirmed in the controller – assuming the respective part numbers have been called up from the CNCs on each machine tool. It is possible to identify over thirty discrete part programs for mixed batch manufacture within the controllers and these are assigned by the operator at will. Once these preliminary details have been established then the robot will move to pick up the first billet once the run command has been activated (Fig. 2.7). If the part requires turning, then the robot picks up the billet and moves toward the turning centre whilst signalling the turret to retract which opens up an access hole for the gripper at the back of the turning centre. At the same time, the programmable tailstock " latches-up" and a compressed air pipe connected to it blasts a stream of high velocity air at the chuck. This chuck, in turn, slowly rotates in order to remove any unwanted swarf trapped from a previous machining cycle. The robot gripper will move to load a billet into the chuck – the tailstock having previously "latched-down" and the air blast ceased and chuck stopped – the billet is gripped by the chuck and the robot retires from the working envelope. The turret comes forward and closes the hole at the rear of the machine and the part program generates the desired features on the part. Simultaneously, the robot returns to the workstation, picks up another billet for this batch and waits whilst the initial component is machined. At the end of the machining cycle the controller signals the robot to advance into the working envelope of the turning centre – having previously withdrawn the turret for access by the gripper; the gripper supports the part whilst the chuck jaws open and retires a short distance. The tailstock "latches-up" and the chuck rotates under the air blast, then lowers again, ready for the robot gripper to load the next billet, as before. It then retires from this vicinity, through its access hole and the machining of the second part begins.

It is worth pausing here to consider a problem that might have been difficult to overcome if it had not been anticipated. As the bar stock has had its "gripping diameter" reduced, this could mean that a very complex robot program needs to be developed to cater for a range of differing turned diameters, as the centreline of the robot will have changed with respect to the part. However, owing to the fact that both gripper jaws can move in synchronisation, the "gripping diameter" will not influence the robot's program. Furthermore, with the back-to-back offset design of this gripper (Fig. 2.7), it has the ability to get close to the chuck jaws, enabling it to manipulate small parts adequately. Finally, owing to the application of hydraulic pressure, it is possible to restrict the flow of oil and in this manner control the pressure applied by each jaw on the part, minimising damage on thin-walled components.

The robot will now swing around to face the side of the machining centre (Fig. 2.6) and the sidedoors are signalled to open, whilst the machine's table with its automatic vertical chuck will be in the desired position to accept the workpiece. The robot reaches into the working envelope of the machine tool and loads the turned features into the vertical chuck, which once again is hydraulically operated and of variable clamping pressure. It then retires and the doors are closed allowing the part program to machine the necessary prismatic features and some rotational features, utilising circular interpolation, if necessary.

Whilst this activity is continuing, the robot picks up its third billet and waits whilst the turning centre completes the second workpiece. It then goes through the identical unload/load sequence previously mentioned and with the third component machined, it now has the option for several activities:

waiting whilst this part is completed and then unload/loading the part into the machining centre – assuming it is the final part in the batch

picking up a fourth billet and waiting whilst the turned part is completed and loading that into the turning centre, whilst placing the second partially completed component onto the workstation. This is assuming, of course, that the machining centre cycle time is much longer than that of the turning center's. In fact, it may require several parts to be buffered in this manner, whilst the machining centre is still operating

loading a partially completed part into the coordinate measuring machine, if an "inspection call" has been activated. This could have been done to the first component as a "first-off" inspection procedure, if required

an interruption to this batch could have been decided to be necessary by the operator at the cell controller and different part programs would have been called-up from the unique identifiers within the turning centre's controller and the robot would load another billet when the third part had been completed

NB: The buffered partially machined components can be completed at will, whenever necessary, as it simply requires them to be picked up and machined to the desired part program. The position of each part is known within the cell's logic by the unique software developed for this cell.

Such flexibility of production and the options performed at any and every stage of the part's manufacture, gives one the capacity to respond quickly and efficiently to changes in production, quality problems on the machine tools (i.e. using touch-trigger probing), or alternatively, at the post-machining stage using the CMM. There are many more subtleties of both production and monitoring of either parts, or tools, that could have been mentioned, but not in the space provided. It should be clear to the reader by now that there are highly productive advantages to be gained by such a flexible manufacturing cell installation.

2.3.2 Flexible Manufacturing Systems (FMS)

The flexible manufacturing cells discussed so far have either been built up in a "step-by-step" approach, or as "turn-key" installations. FMSs, by their general nature, tend to be of greater complexity, whilst being situated over a larger area of the manufacturing facility. Such a large and complex installation means that either part- or tool-delivery systems to the individual machine tools need to be considered. A typical method of delivery used is that of the AGV (automated-guided vehicle, Fig. 3.26, Volume II) previously mentioned in section 3.8.1, Volume II. In such an FMS environment, the freedom gained in situating plant in the optimum configuration within the geographical layout of the manufacturing facility can be achieved, which would be much more difficult to attain using RGVs (rail-guided vehicle delivery systems; see Fig. 2.5).

A workpiece can be located onto its respective "coded" pallet and loaded through the machine tool's pallet-changing mechanism into the working area of the machine using an AGV. It is also possible to transfer simultaneously a part previously machined on its "coded" pallet back to the AGV and away for either further machining, or back to the centralised load/unload station. It is worth restating at this point, that such

Fig. 2.8. An FMS illustrating "pallet pools" strategically positioned for easy access of the wire-guided AGVs. Note the elevated control room. [Courtesy of Cincinnati Milacron.]

"coded" pallets need to be uniquely identified in order that the desired part is loaded onto its anticipated machine tool and that the correct part program is down-loaded from the machine control unit into the "active" memory area of the CNC controller. Such scheduling of parts, tooling, programs and so on, are the task of the host computer, which can dynamically schedule and re-schedule parts within the FMS as dictated by the contingencies of the "master schedule", or anticipated/unanticipated machine tool interruptions. Pallet "coding" for efficient workpiece tracking within the FMS can be uniquely identified in a number of ways and just some of these ways were described in section 3.8.1, Volume II.

AGVs can also be used to unload a magazine, or chain magazine of tools to either replenish a "sister" chain, or present a "new" range of preset tooling to the machine for further jobs, whilst simultaneously removing the "old" tool chain magazine and transporting it back to the presetting facility. In such a manner, tooling/workpieces can be quickly and efficiently loaded and unloaded to the FMS machine tools and other devices, such as: wash-stations, coordinate measuring machines, pallet-pools, servicing facilities, etc., according to the dynamic dictates of the scheduling requirements demanded by the host computer.

The machine tool just discussed, might well be part of a large-scale FMS as depicted in Fig. 2.8. In this installation in Phoenix, Arizona, USA a large-scale "turn-key" facility has been installed with numerous machine tools, having AGVs, "pallet-pools" and so on, controlled from an elevated control room, where the minimum of staff can supervise the smooth running of this FMS. Obviously, during the running of such plant, it is necessary for a certain amount of support staff to be present for tool-kitting and maintenance, but whenever practicable the facility can be minimally-manned during the night shift, as parts will have been buffered at the "pallet-pool" stations, together with additional "sister" tooling delivered to the machines as production demands dictate. This system is particularly noteworthy in that one major machine tool company was responsible for the complete FMS, from feasibility, through to customer acceptance/commissioning. This is an important point in a fully integrated and operational FMS, as one company has overall responsibility for the project from inception, through to completion. This means that the customer knows exactly who to contact with any queries regarding the day-to-day problems that might arise, whilst the machine tool supplier is in a position to fully support the customer's needs speedily and efficiently, without recourse to further dialogue with yet other companies involved in the FMS installation.

As one can by now appreciate, such a high level of computerised equipment necessitates considerable communication sophistication between the "host" and peripheral devices and when errors occur, through either faulty interlocks on moving elements within the FMS, or data corruption between the respective computers, then quick and easy "error-recovery" is the key to maintain optimum plant operation. It has already been alluded to previously that FMS "condition monitoring" sophistication is a critical element in the successful implementation of any FMC/S, however, more will be said on this topic later in the chapter.

In the following section the theme of system communications will be briefly touched upon, looking into the various "network topologies" and MAP/TOP techniques currently used, whilst attempting to identify the research direction that manufacturing systems "networks" are developing towards, in order that the reader might readily appreciate the levels of sophistication of present and future computer communication.

2.3.3 "Network" Topologies and their Use in CNC Machine Tool Applications

As we have seen in the previous section and more specifically in the case of the large-scale FMS depicted in Fig. 2.8, significant amounts of data transfer occur with such equipment having a considerable level of machine intelligence in order to perform the expected control functions necessary in such manufacturing environments. In recent years an almost limitless number of proprietary local area networks (LANs) have come to exist, or have been proposed, as some vendors have attempted to control standards in order to dominate their market positions. This has lead to a lack of industry standards and it is now clear that no single vendor can supply all of the communication needs desirable in an automated factory. Any vendor attempting to install translator boxes between peripheral devices within the FMS, to obtain successful communications, should be vigorously resisted by the customer, whilst it is also prudent to avoid single source suppliers of communication equipment. Furthermore, the systems limitations of the proprietary networks need to be stringently evaluated by the prospective client. Where standards do exist, they do not make the task of the engineer easy, as important decisions about modulation, access, media, topology, together with many other technical communication considerations must be made when producing a functional specification for an FMC/S. Let us consider these four primary independent variables in a little more detail:

Modulation
- (i) baseband: typified by the telephone network
- (ii) broadband: a typical cable TV installation

Access
- (i) contention
- (ii) token passing

Table 2.1. Characteristics of media transmission.

Transmission media	Bandwidth	Distance	Versatility of topology	Installation ease	Cost	Noise immunity
Twisted pairs	6 MHz (low)	Short	High	Moderate	Low	Low
Coaxial cable	300 MHz (medium)	Moderate	High	Easy	Moderate	Low
Fibre optics	300 MHz (high)	Long	Moderate ("bus" and "tree" Difficult)	Moderate	Moderate	Very high

(iii) frequency division multiplexing
(iv) time division multiplexing
(v) master-slave

(Transmission) Media
(i) twisted pairs
(ii) coaxial cable
(iii) optical fibres
(iv) microwave, etc.

NB: Let us look (Table 2.1) in more detail at the comparison between the first three types – transmission media being the most popular at present.

Topology (see Fig. 2.9)
(i) star (Fig. 2.9a)
(ii) ring (Fig. 2.9b)
(iii) bus (Fig. 2.9c)
(iv) tree (Fig. 2.9d)
(v) unconstrained (Fig. 2.9e)

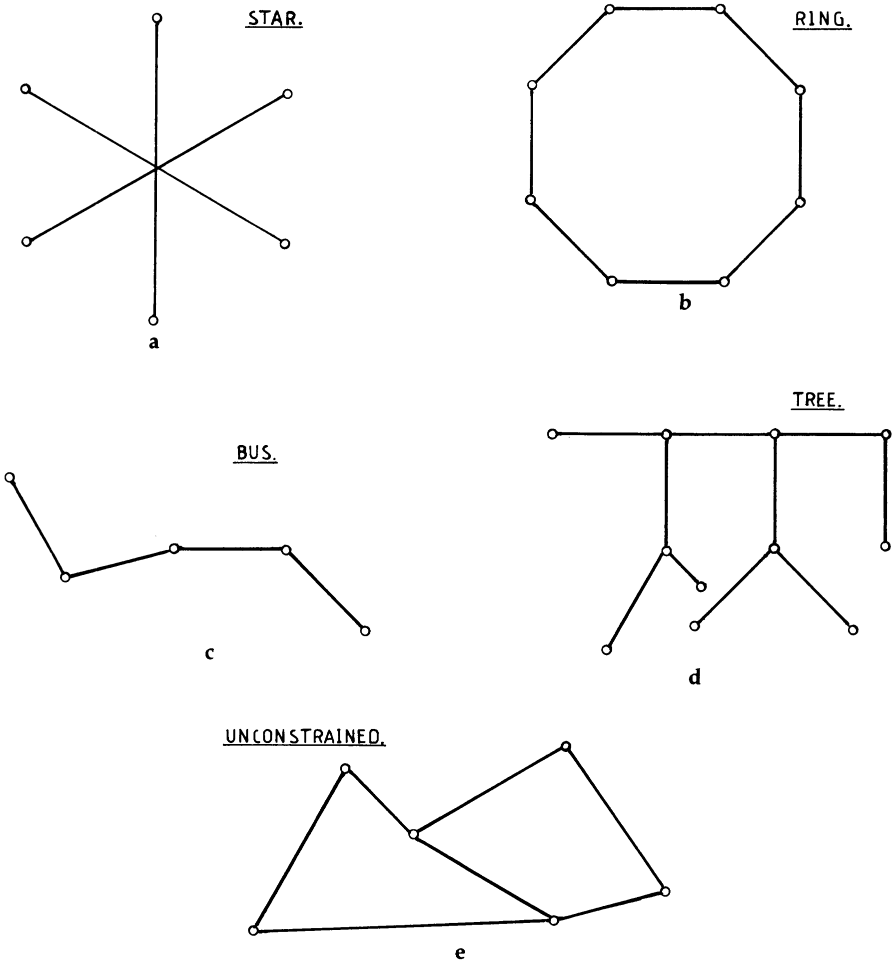
These variables are by no means an exhaustive list and at present it would be possible to produce over three hundred possible combinations. The engineer is thus presented with a series of decisions: "How then can my choice be made?". The answer will depend upon the intended use and we might ask:

"How expensive is the system?"
"What capacity is necessary?"
"What are the acceptable error rates?"

Such questions and many others must be answered if one is to obtain a successful integration of hardware/software devices within an FMC/S facility.

One local area network topology is a direct numerical link through a PLC to the "stand-âlone" CNC machine tool. Even here, in this most simple communications link, many companies still have problems associated with data transfer from host's, or CAD/CAM workstations. Such problems become exacerbated when different makes of peripheral equipment are connected to other types of network topology. In fact, this problem has been partially addressed in recent years by the OSI seven-layer model which is more commonly known as MAP/TOP, but more will be said on this topic in the following section.

If we consider the "bus" network topology and its related software in more detail, this will give the reader an indication of just some of the functions necessary for successful software communications within an FMS. For a range of peripheral hard-



Topology	Reliability	Interface complexity	Modularity	Flexibility	Cost
Star	Poor	Simple	Moderate	Poor	High
Ring	Moderate	Simple	Good	Moderate	Moderate
Bus	Good	Moderate	Good	Good	Low
Tree	Good	Moderate	Good	Good	Low
Unconstrained	Very good	Very high	Moderate	Poor	High

Fig. 2.9. Typical arrangements of network topologies and their different characteristics.

ware devices connected to a "bus" LAN, for a CAD/CAM link via a DNC link to be successful, a range of software is required. Here we can see that a vast array of software functions is required and these FMS technology orientated functions might consist of:

production planning administration
master data administration
  system configuration (system parameters)
  tools (nominal data)
  workpiece carriers
control data administration
  CNC part programs
  workplans
  production orders
status data administration
  system status (plant status)
  tools (actual measured data)
  workpiece carriers (pallets)
  workpieces
connection to tape punch reader – if necessary
alarm/error messages
synchronisation
message handling and print functions
setup and clamping calculations – for tool "balance"
automatic material flow control
  including connection to a transport system
machine tool programs
  for serial link
  for LAN
automatic tool flow control
  single part (workholding)
  pallet-based transport systems
tool setting machine connection
special machine connections
  wash machines
  coordinate measuring machines, etc.
short term shutdown
shift reports
CIM interface

In order to achieve secure data transfer and compatibility between a range of software protocols, it is highly desirable to use MAP/TOP communications philosophies and this will be considered in the following section.

2.3.4 Manufacturing Automation/Technical and Office Protocols (MAP/TOP)

Manufacturing Automation Protocols (MAP)

As we have seen in the previous pages, and no doubt as we probably know from personal experience, the linking of so-called "islands of automation" – namely turning and machining centres – to workpiece transportation systems and other devices in the communication world of manufacturing, known euphemistically as FMC/S, has a technical flaw – it has, until recently, been almost non-existent between different vendors' products. This, however, has not been true when a "turn-key" system has been purchased from a single vendor source, which has meant that most successful automation systems were commissioned from the larger machine tool companies. The problem here is one of secure data transmission (communication) between different vendors' products, such as a turning centre made by one company and a robot by another. This problem of the successful two-way transfer of data between devices associated together in an FMC/S has been addressed by the Manufacturing Automation/Technical and Office Protocols, known more commonly as MAP/TOP, which have, in their various versions, been to a greater or lesser extent a success.

Prior to a discussion on the methods by which data communication is presently achieved between automated equipment, it is appropriate to consider the historical background in the development of MAP/TOP. The automotive industry was one of the leaders in adopting automation into manufacturing plants in order to improve their competitiveness, which meant that they were one of the first to experience the problems associated with the lack of multivendor communications. It is generally agreed that General Motors, and to a lesser extent Boeing, in the USA were the instigators behind these communications developments. In 1980, General Motors, the largest company in the World at that time, set up a study group after the company turned in a loss of $780 000 000, its first for sixty years. Their findings indicated that around 40% of the total automation investment in the plant at their factories was being consumed in communication costs. This meant that the company had to come to terms with this drain on capital resources and they declared their intention to press ahead with the establishment of their own rules for communications and insisting that once the rules were established, they would become mandatory for all suppliers of equipment to General Motors. Thus, the General Motors MAP Task Force was established and it was their original intention to take the best solutions of the existing standards from around the World and incorporate them into a new protocol. Unfortunately, they shortly established that the standards organisations had not considered the complex communications requirements for manufacturing, so General Motors had to use existing standards whenever possible and supplement them with its own where applicable.

Possibly the first practical MAP demonstration for the public occurred at the July 1984 "National Computer Conference" in Las Vegas, when General Motors, along with seven suppliers, demonstrated four of the seven layers in operation – more will be said on these layers shortly. In November the following year, at the Detroit "Autofact 85" exhibition, there was a more ambitious display by General Motors and other vendors. On this occasion, twenty-one other companies were present, including: AT & T, Digital Equipment Corporation, ICL, Motorola, Gould & Allen Bradley, together displaying a MAP network with six layers in operation reaching the 2.1 specification. The American lead was being followed in Europe, and in March 1985, the European MAP Users Group was formed, along with ESPRIT initiatives on similar lines. With the MAP specification being 2.1, a very impressive "CIMAP" show sponsored by the Department of Trade and Industry was held at the NEC in Birmingham, with about seventy companies taking part. The dynamic demonstrations of MAP/TOP were on show to a privileged audience of engineers and the biggest hall was filled with a single network. Since then, a further refinement of the standard has led to MAP 3.0, which was previewed for the first time at the "Enterprise Network Event" in Baltimore, USA, in 1988. Around this time, much disquiet was heard

Table 2.2.

User programs	Application programs (not part of the model)	Server machines
	Layer 7	
Application	Manages lower-layer services including application programs	Application
	Layer 6	
Presentation	Restructures data to/from the standardised format used within the network	Presentation
	Layer 5	
Session	Name/address translations, access security and synchronises and manages data	Session
	Layer 4	
Transport	Provides transparent reliable data transfer from end device to end device	Transport
	Layer 3	
Network	Establishes connections between equipment on the network	Network
	Layer 2	
Data link	Establishes, maintains and releases data links	Data link
	Layer 1	
Physical	Encodes and physically transfers messages between adjacent devices	Physical
◄	**(Physical link)**	►

amongst the MAP vendors, relating to the frequent modifications to the standard and as a result MAP 3.0 was frozen for a period of six years, enabling some consolidation to occur.

So far, the reader has been introduced to the Open Systems Interconnection (OSI) seven-layer model adopted by MAP, but little detail has been given. Let us look a little deeper at these seven layers (Table 2.2), each handling different aspects of inter-computer communications.

If we consider each layer's application in turn, then at the bottom of the model one has:

1. *Physical.* This specifies the actual cable connecting one computer, or machine tool, to another and the type of signal that will pass over it – with General Motors specifying broadband. As we have discussed in section 2.3.3, broadband looks like a conventional co-axial aerial cable used in conjunction with television, being approximately 2 cm in diameter. Signals passed over it are analogue, modulated like radio waves to carry the digital information. The name broadband is derived from the fact that it is possible to transmit many different signals at a range of frequencies through the cable without interference.
2. *Data link.* This defines how messages are passed over the network, with each message entering the network being a package of information termed a "data-frame". This together with a specifying address is necessary to send it to the correct computer on the network. The problem here is in deciding when any particular "node" – this is a computer, or machine connected to the network – can transmit its message.

   Two common systems in use are "collision detection" or "token passing", with General Motors choosing the latter as being the more suitable for MAP. As its name implies, in "token passing" a "token" is passed from one "node" to the next. Only the "node" that holds the "token" may transmit messages and each can only hold it for a fixed period, before passing it onward.

3. *Network*. This decides the format of messages on the network and for this General Motors chose an existing standard termed "connectionless networking". In essence, this means that each message is self-contained, carrying its own address. By using this system, there is no need for one computer to form a fixed link with another to pass the message.
4. *Transport*. This contains the part of the protocol ensuring data integrity and unlike lower layers, a "node" establishes a notional connection with similar nodes at this level. When a message is sent, the transport layer at the transmitting "node" looks for an acknowledgement from its respective receiving "node". However, if it does not receive one, then it retransmits its message.
5. *Session*. This is a complete conversation between two "nodes", or computers and during this activity data may be exchanged between different programs running on each. As an illustration of this conversation, a host computer might be communicating with a programmable logic controller (PLC) in the plant. The communications link might be that the host is used to control production, but simultaneously it may be down-loading files, from the host, to the PLC, whilst receiving data from the PLC which may be used to maintain a record on the whole plant's database, held on the host computer.
6. *Presentation*. This handles the language each computer speaks. One computer might use a particular binary number to, say, represent the letter Z, whilst another binary number uses a different numerical value. Therefore, in order for them to be able to communicate with each other, they must both utilise the same data representation. Thus, the "node" that initiates the exchange of data will firstly ask if the recipient "node" uses its favoured representation. If the answer to this request is "no", then it tries a different approach until they obtain a common language understood by both.
7. *Application*. These are the programs that run on a computer and it is such programs that communicate with one another – the MAP objective being to enable them to exchange data. When General Motors initially attempted to instigate MAP, it had to develop its own protocols here as there was no International Standard, or group, to help them draw up such protocols. For example, in MAP 2.1 it included the following:

"Manufacturing Message Format Standard" (MMFS), pronounced Memphis, which is a language allowing machine tools, that do not have sophisticated memory devices, to talk to one another

"Common Application Service Elements" (CASE) which is used to set up communications with a remote "node"

"Transfer, Access and Management" (FTAM) which was a protocol developed by Boeing for file transfer between "nodes" with devices such as disk drives

When MAP 3.0 was launched, all three protocols were replaced by the "Manufacturing Message Specification" (MMS). The logic behind the central concept of MMS, is the "Virtual Manufacturing Device" or VMD. With this protocol, every computer, or machine tool looks the same to the network through the MMS and it actually looks like the VMD. Thus, all the actual functions of the "node" are "mapped" onto the VMD.

This completes our summation of the seven MAP layers and their respective functions, but before we go on to consider Technical and Office Protocols (TOP) and their relationship with MAP in an FMC/S, it is worth briefly mentioning how MAP has been adopted by the manufacturing community so far. Across a range of motor manufacturers, such as: Jaguar, BMW, Renault, Mercedes, etc., MAP networks exist, although it is perhaps not the complete solution, as lower grade network topologies might be more applicable to some manufacturers such as "MINI-MAP". The MAP standard is now in the public domain and its development is controlled through MAP user groups – the largest being in the USA. There is a growing influence in Europe, principally via the European MAP User Group (EMUG) and others being developed both in Japan and Russia. Such user groups will determine the changes that will be made in the future to MAP 3.0. However, the growth of MAP is not solely in the automotive industries, as automation companies, electronics firms, together with other interested concerns are also adopting the MAP philosophy of communications protocols.

Technical and Office Protocols (TOP)

In more recent times, a parallel pressure group for the standardisation of networks was established for applications in the engineering and office areas. The catalyst in this instance was the Boeing Company who introduced the Technical and Office Protocols (TOP), version 1.0 in November 1985. This, in turn, led to the formation of a TOP User's Group in December of the same year, together with the setting up of a joint steering committee for the two activities, so in most respects both MAP and TOP remain identical. Their differences lie in that they are designed to interface to different kinds of application software and also in the manner in which messages are sent around the network. As we have seen in the comments in the MAP section, this system uses a "token-passing" method, whereas TOP has chosen the IEEE 802.3 standard Ethernet-type CSMA/CD local area network, which has been implemented by many office systems manufacturers. Data transfer, however, can be interchanged between the two systems via a "bridge", or "router".

TOP protocols are more relevant than MAP in a design office, where data transfer times are less critical and the electro-magnetic environment less hostile. Furthermore, in the beginning, Ethernet networks cost about 80% less than the equivalent MAP network and even as MAP becomes cheaper, it is unlikely to undercut the cost of Ethernet. Alternatively, for a company involved in a substantial manufacturing operation, it may require a MAP broadband network and this could be extended into the design office, typically to the CAD/CAM system. There are many further options of configuring MAP/TOP networks – there are no firm rules and the theories on the optimum configuration change as MAP and TOP networks are implemented throughout industry. Finally, in recent years, both MAP and TOP have assumed the mantle of version 3.0 and in so doing, ensure the parallel development of these two standards.

2.3.5 Computer-Integrated Manufacturing (CIM) Networking Requirements

In general, the requirements which distinguish a CIM network from other applications can be loosely classified into three areas:

efficiency and flexibility of real-time multi-process communications
accommodation of equipment and environment heterogeneity
distributed network management and control

Let us consider each in turn in a little more detail, gaining a clearer picture of the technological problems to be addressed.

Efficiency and Flexibility of Real-time Multi-process Communications

Considering that computer networking technology is quite advanced for its specific application to a CIM task, it has not as yet been well characterised. Recently, a large body of analytical research has been produced for network control and communications in general, with the focus being upon "modelling" and performance analyses together with designing flexible manufacturing systems to accommodate future growth. However, this research has seldom considered the needs for real-time communications between the factory equipment such as multiple robots and multi-machine systems, where delays – as little as a few tens of milliseconds – might disrupt the process, causing losses in both production time and product quality. So, by producing formal characterisations and "modelling" of the entire manufacturing process, this will lead to efficient network architecture and more rapid error recovery.

Accommodation of Equipment and Environmental Heterogeneity

Computerised equipment for autonomous manufacturing, engineering design and office management may use their own specific languages, data structures and operating systems which may not be mutually compatible. Such problems of incompatibility can, in the main, be overcome by adopting a standardised layered network architecture, whereby individual computers can communicate to peer level counterparts in their own languages. To this end, the MAP/TOP seven-layer strategy seems the best solution in either a manufacturing or office environment, as has been mentioned in section 2.3.4.

Distributed Network Management and Control

From its inception, the objective of CIM is to unify the administrative, engineering, manufacturing processes, management and control functions of the integrated network which, of necessity, must be designed to support the distributed organisational structure within the company. Such a network should serve as the essential communication link for overall management of our integrated manufacturing process, whilst at the same time provide a degree of autonomy within local areas. The CIM network must, of necessity, continuously adapt to environmental changes resulting from: design modifications, reassignment of manufacturing processes, market demand, together with a host of other functions in a real-time sense. When attempting to provide timely communications between a large number of heterogeneous processes in a dynamic environment, the network management and control system must be aware of the status of all available resources over which decisions have to be made. Such decisions will include the efficient utilisation of resources of competing demand, together with: detection, isolation and recovery from failures – more will be said about this later. This can be partially achieved by incorporating human expertise into automated network management tools to provide: diagnosis, monitoring and dynamic adaption to failures, or planned changes in the CIM environment. The principal benefits of applying such artificial intelligence (AI) techniques to any network management control are the abilities to:

handle problems with ill-defined characteristics
assimilate/integrate information from a variety of heterogeneous sources

Conventional techniques such as the simulation experiments described in section 2.2.2, together with capturing program rules and heuristics would not be appropriate for knowledge and acquisition, unless sufficient expertise concerning network management had been developed. Under such circumstances, the "machine learning approach" – not relying upon heuristics – could probably provide the solutions to this problem. Yet another major concern to be considered is the security of the data, as networks provide electronic access to sensitive databases from remote modes. This problem cannot be over-emphasised when considering CIM network architectures; at all levels of information exchange, total security of data transfer must be achieved.

This completes our discussion about the networking requirements in CIM; it would have been easy to expand this section and look into current research activities in CIM networking, such as:

specification and analysis of network protocols
testing and standardisation of network protocols
lightwave and wireless communication
real-time communications, control and fault tolerance
network management and control

but this would necessitate considerable space and is, to some extent, outside the remit of the present text. In the following section we will consider the reasons why it is essential to have sophisticated condition monitoring techniques, to ensure that the plant is operating efficiently and that when faults occur, the type of error is speedily established and error recovery is quickly initiated.

2.4 Condition Monitorings of Intended Plant: FMC/S and CIM Installations

An unscheduled failure just for a stand-alone CNC machine tool can cause a loss of productivity averaging 11%. This problem is exacerbated as machines become integrated into an FMC/S; under such complex inter-relationships production losses can be up to 40%. When the theme of FMS was first introduced, extravagant claims were made for such systems and it is hardly surprising that experiences of failure bring them into disrepute, which may be the principal cause for the lack of installations in industry and discouragement of investment in these technologies. If industry is going to invest in integrated manufacturing systems across a wide area of application, then reliability and uptime must be improved. Let us now look at an advanced project associated with this topic, at present underway, by means of a case study to give the reader an appreciation of the general theme of machine monitoring.

In fact, a European "Esprit" project (504) has been running since the mid-1980s under the title "Development of fault tolerance in the control and management of a production system", with six companies involved. The multi-national companies include: AMTRI (Stewart Hughes Ltd) in the UK, Adersa (the French process control group), GRS (nuclear engineering specialists), the Technical High School in Darmstadt, Batelle Institute in Frankfurt and Ikerlan (the Spanish machine tool research centre). In December 1988 the £3.5 m "phase one" project was completed and this was followed by a more ambitious project (2349), with a budget of £7 m which is due for completion in 1992. Its "phase two" objectives were to build upon the hardware/

software techniques developed during "phase one", with particular reference to production environments within the automotive industry: namely improving the design of machines, acknowledging that faults cannot be completely eliminated, whilst attempting to improve the control and management of the plant.

One of the first tasks undertaken at "phase one", was a review of the trends in modern systems and determining how diagnostic monitoring might improve the plant in terms of availability, quality and reliability. The conclusion was that such performance monitoring as part of the overall real-time control structure of the plant will have a significant impact on its successful implementation and control. It became clear that in many instances of automated plant installations, little thought had been given to fault diagnostic concepts and when they were added, it was usually retrospectively and inadequately. The survey showed that integrated monitoring systems needed to consider the real-time status of all the plant: machine tools and associated equipment, the manufacturing process, together with raw material.

Therefore a major objective to control the machine operation was to use computer-based monitoring and diagnostics techniques, producing information which was fed around the control loop in such a manner that the system maintained control even under abnormal, or fault conditions. This concept was termed "fault tolerant control".

Fault Tolerant Control (FTC)

FTC conceptually means a system that is designed to tolerate faults and operates whilst these faults are being rectified. Such a system copes with abnormal conditions, by maintaining control whilst a recovery, or a shut-down program is implemented. FTC is related to adaptive control, depending upon a "bottom-up" application of advanced diagnostic monitoring to: machine tools, production processes and products. The speed at which the system collects/analyses the data required to maintain real-time control ranges from milliseconds, such as the case of tool breakages/collisions, to perhaps several days, when wear is detected in a machine tool gearbox.

This project's objective was to develop machine tools and methods necessary to build an FTC system suitable for use in a manufacturing plant, ranging from simply a stand-alone machine to a complex FMS facility. In order to achieve this level of control, it necessitated sophisticated data acquisition, analysis hardware and controlling software, in conjunction with sensors to support real-time process monitoring and in-process quality control.

First, a stand-alone experimental machine was used to determine the principles of fault diagnosis and computer "modelling" – highlighting the need to develop a fast, modular, multi-tasking computer for acquisition and analysis of real-time data and its synchronisation with the machine's operations. One of the major lessons learned from this stand-alone machine tool demonstrator, was the benefit to be gained from positioning sensors at the "heart" of the machine – hence the advantages gained from placing electrical transducer sensors at the hydrostatic oil spindle – providing direct tactile sensing signals. Secondly, a more ambitious demonstration was developed by Ikerlan in Spain – providing access to an existing FMC, comprised of a turning centre, machining centre, six-axis robot for loading/unloading tools and parts to the lathe, with an AGV providing palletised workpieces to the machining centre.

Initially, the principal task was a technical audit to define how the cell operated, establishing what sensors already existed, the failure modes in operation, communication used and how the cell was controlled. The FMC was activated upon the arrival of a workpiece blank, this being identified by a vision system which triggered the selection of programs, tools, robot grippers and other functions associated with this part's manufacture. The "host" computer had a database restricted to tool information, machine status, tool and billet positions, with very little in the way of fault recognition – this being confined to readily serviced items: blocked filters, malfunctioning switches, etc. In response to any error, the "host" simply shuts the machine down and in so doing severely limits the functional operation of the cell. Therefore a Data Acquisition and Analysis System (DAAS) computer was situated at each machine and interfaced with its controller and through the network to the "host". Software for interpreting fault conditions and planning the actions to correct them had to consider the viability of the machine tool's operating routine. Data needed to be collected only at the appropriate times relative to the machining program. As an example, vibration data collection was not taken during a heavy roughing cut, but under more steady-state machining conditions. This meant developing a new operating environment, which linked the software of the DAAS computer to the machine's operating programs – it is known that "synchronisation" is the key to success in diagnostic monitoring. This may be achieved by linking the DAAS computer to either the CNCs or PLCs, so that one can determine the context in which the machine is operating. Thus, it could be stopped, run, begin cutting, or activate a probing cycle, or similar, so that once we know the context of the machine's status, we can incorporate relevant monitoring. If, say, the spindle was running but not in cut then it might be more appropriate to monitor the spindle vibration data.

The DAAS computer runs a "mimic" of the part program in parallel with the actual programmed machining cycle and in this manner, keeps in step ensuring the correct acquisition and analysis of data. This technique permits a very fast reaction to data, indicating when a serious fault condition arises, such as that which is likely to cause tool/workpiece damage. At the machine level, the DAAS software generates indicators of the machine tool's health. Such indicators are interpreted using a ROM-based fast interpreter, taking the form of a simple "logic tree". Using "expert systems" at this level of monitoring/control, was considered appropriate for reasons of size and speed. The "logic trees" are defined by the manufacturing engineer and represent the logic progression from symptoms to identified error states and their associated actions, such as an unscheduled tool change, or operator intervention initiated by the DAAS through the controller link. Other indicators of the cell's status come from the "host" and for this higher level of interpretation an expert system is essential.

This cell's role as a demonstrator of condition monitoring is made operational by means of a simulated material requirements planning (MRP) work plant, with the FTC system integrated into the cell. In summary, this sophisticated FMC will always attempt to fulfil its production task, regardless of conditions. If faults develop, or are introduced, the cell will always attempt recovery by initiating action automatically, where they are within the scope of the control. When this is not possible, it will pass actions on in message form for defined manual intervention. Where recovery is not possible, the cell shuts down under control until such time as the fault is logged as being cleared and at such a time, it will initiate restart automatically and attempt to return to a normal schedule to achieve its original production goal. Where such a goal is no longer achievable, then it generates its "best target", making this information available to the MRP planner. During cell operation, the "host" maintains a graphical mimic of the status and prognosis based on the continuous interrogation of the database – manual intervention is also prompted from the "host" terminal.

Such condition monitoring sophistication is imperative in cells/systems, if a company is to benefit from high productivity, through the minimum of down-time due to error – recovery and maintenance scheduled/unscheduled within the plant. Efficient utilisation is the key element in a truly productive high capital cost plant, so that a company remains competitive, economic and flexible in their manufacturing demands against intense competition from rival manufacturers.

In the following section, we will consider just some of the monitoring systems necessary in order to obtain high quality parts and minimal scrappage, during untended or minimally manned production.

2.5 The Monitoring Systems Necessary for High Part Quality During Untended Machining

As one might expect when machine tools are utilised in the "stand-alone" condition, this invariably infers that an operator is present, whose prime task is to monitor the functions concerned with satisfactory part manufacture. In a typical production situation, the operator will be concerned that the tooling is performed satisfactorily, so will monitor the tools for:

identification
offset measurements
life
breakage detection

In a similar fashion, the operator will monitor/identify workpieces:

identifying the next part to be machined
set up fixturing and arrange clamping for the component
accurately locate the workpiece holding device on the maching tool
position the part in the correct relationship to the part program, by manually adjusting the workpiece, or program, accordingly – unless computerised workholding techniques are in use (see section 3.9, Volume II).

Still other features require the operator's attention, including:

monitoring of the machine tool's cutting efficiency by sight and sound
part program adjustments, as the machine's operating temperature changes, e.g. from cold to its normal operating temperature
speed and feed adjustments, to optimise the best cutting conditions during the running of the part program

2.5.1 Untended Machine Tool Monitoring in an FMC/S

In an FMC/S environment, this implies that the plant is unmanned or, at worst, minimally manned machining occurs. The operator's absence for lengthy periods of time creates a considerable number of manufacturing problems that must be conquered if the machining system is to perform its production functions satisfactorily. These problems occur when attempting to monitor and service the operations normally associated with an experienced operator. Such tasks include monitoring the cutting tool's performance and condition, together with the other human-related

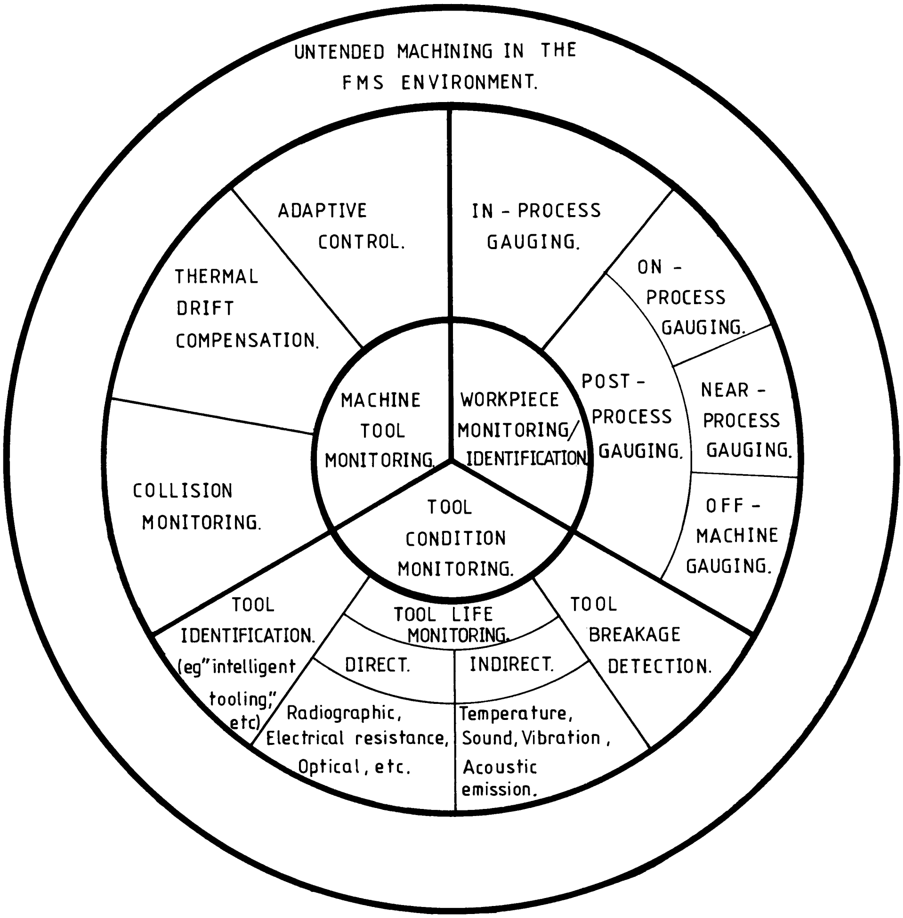


Fig. 2.10. The monitoring systems desirable for successful untended machining in the FMS environment.

tasks. Hence, in the unmanned condition normally associated with FMS plant, the monitoring system provides a degree of artificial intelligence (AI), necessary to mimic operator experience and to a lesser degree, provides instinctive reactions to changes in the plant running normally associated with human involvement.

A considerable array of monitoring systems is necessary to compensate for the lack of human presence on an FMC/S (see Fig. 2.10). In broad terms, they can be classified under three headings – with obvious sub-divisions as shown:

workpiece monitoring
machine tool monitoring
tool condition monitoring

Let us now look at each of these essential monitoring systems found in untended environments in a little more detail.

Workpiece Monitoring

In chapter 3, Volume II a review of workholding techniques was given and here we are primarily concerned with the automatic monitoring of the plant with respect to an FMC/S, although it is quite feasible to use such systems on minimally manned stand-alone machine tools. Essentially, workpiece monitoring is concerned with:

workpiece identification
automatic workpiece set-ups
workpiece gauging

The first requirement prior to machining the parts is to select them from the random mixture as they are either held on pallet stands/pools, or supplied via some other delivery system. With the variety of existing methods available for delivering the parts to the machine, the workpiece monitoring system must cope in an effective manner, such as radio transponders, bar coding, binary pins, etc., for say, machining centre palletised systems. Such indirect workpiece recognition – where the pallet is coded and it is assumed that the correct part/s will be held on this pallet's fixture – uniquely identifies it and calls up the desired part program in the CNC. Having identified the part and its associated part program, the component's orientation needs to be confirmed and this is established by the workpiece/holding monitoring system in the desired relationship and position to this part program. Whilst the machining operation is in progress there are several techniques available to assess part quality (see section 1.8.2, Volume II).

in-process gauging – where information is gathered during the actual machining process – this is difficult to achieve in reality, owing to the practical problems of real-time measurement and control, so offers little potential, but in theory would seem an "ideal" technique

in-cycle gauging – commonly associated with turning and machining centres whether in "stand-alone" or cell form – using the popular touch-trigger probing techniques not only to assess the part quality between operations, but prior to this, to interrogate the fixture for accurate part alignment

near-machine post-process gauging – this technique has found particular favour on turning centre applications, where a receiver gauge is positioned adjacent to the machine tool and a part is automatically loaded and the established feed-back loop to the machine up-dates/corrects as the critical features being assessed change owing to either tool wear, thermal drift, or both. Such gauging equipment might be either contact (LVDT transducers) or non-contact (laser/light path systems), sampling at, say, 10% intervals to 100% inspection

off-machine gauging – using Coordinate Measuring Machines (CMM) coupled to a Statistical Process Control (SPC) package – allows a diverse range of parts to be inspected; alternatively, if short runs are the requirement, then greater flexibility can be accommodated, but at the expense of considerably slower part processing times

Yet another method (strictly speaking outside this discussion on untended monitoring, yet worthy of a mention) is the technique known as "deterministic metrology". This controversial method predicts and corrects for part errors based upon attempting to anticipate any machining errors in real-time and subsequently corrects them. This philosophy assumes that we will always try to cut a good part and as such, eliminates the need for further inspection. Thus a detailed mathematical model is developed in which the error-producing parameters – effects/interactions of machining – are accurately described.

Machine Tool Monitoring

If we ignore the diagnostic sensing devices used in determining the machine's health (previously alluded to in section 2.4) and concentrate on the protection that can be offered to the machine tool as a result of either variations occurring whilst cutting, temperature and protecting against collisions, then three monitoring devices seem necessary:

adaptive control
collision monitoring } both having been described in section 1.8.1, Volume II
thermal drift compensation

If we ignore both adaptive control and collision monitoring systems here as they have been dealt with adequately elsewhere (see section 1.8.1, Volume II) – and concentrate on the latter system of thermal drift compensation, we will gain an appreciation of some of the problems associated with the influence of ambient temperature changes, the variations caused by the machine tool's structural modifications promoted by differential temperature effects and how they influence the part quality.

Whenever a machine tool is used as part of an FMC/S, or in "stand-alone" mode, and subjected to variable conditions of usage at or near its process capability (i.e. "for stable manufacturing process, it is the capacity to reach a certain level of quality" e.g. $C_p < 1.33$) which frequently is the case of late in precision engineering companies, then an uncompensated machine tool is likely to produce some scrap components. Simply, the rise in ambient temperature in the shop plays a significant role in causing the machine's structural elements to move. It has often been the case that the author has visited a company during the heat of the summer and found the ambient room temperature in excess of 30 °C around midday, with this problem being compounded by the fact that direct sunlight is present, further exacerbating the local temperature on the machine tool. In many manufacturing companies with such fluctuating temperature conditions, it seems impossible to maintain a consistent part dimensional quality. Even when the temperature within the workshop is stable and an air-conditioned environment exists, irregular usage of the plant causes differential temperature effects to influence the machine's structure and induce part variations at high relative precision indexes (i.e. $C_p < 1.33$). What often makes matters worse is that the machine tool's calibration – using laser interferometers, or similar methods, probably either occurred some months ago at best, or was undertaken when the machine was cold. Recently, a ball-bar system has become available to obtain a quick check for both turning and machining centres and to a lesser degree, CMMs within the precision manufacturing facility, allowing for speedy and efficient daily re-calibration of a range of geometric and linear features within the volumetric envelope of the machine tool.

Returning to the theme of differential temperature effects produced by irregular usage, typically a turning centre headstock can grow owing to a temperature increase in the bearings/motors by 20 °C. This problem can be minimised by the machine tool builder, with careful design of the structure and incorporating "heat sinks" at "hot spots", controlling thermal growth uniformly at the centreline and away from the spindle nose. However, a more significant thermal problem arises in the differential growth in the ballscrews – often of less temperature magnitude (4 °C) but this affects the positioning accuracy of the machine – particularly for indirect feedback closed-loop monitoring systems (i.e. with rotary encoder/motor designs). On the "C-type" frame typically found on vertical machining centres, the problem of thermal growth on the larger column machines can cause dimensional variations, and thermal sensors are often positioned in the bed, throat (column) and head of the machine tool. In order to obtain a degree of uniformity in controlling the thermal growth, the machine is run in hot/cold and intermittent conditions and plotted values are obtained for each thermal sensor, with software controlling and compensating the machine tool continuously in the X, Y and Z axes. Therefore by the judicious use of thermal sensors positioned at strategic points around the machine's structure, coupled to customised compensation software, it is possible to minimise the effects of thermal growth.

Tool Condition Monitoring

In Volume II we will review the range of monitoring systems used for tool:

identification
life monitoring } in section 1.8.1, Volume II
breakage detection

As we can see from Fig. 2.10, there is a range of monitoring techniques for controlling either the tool management functions of tool tracking, identification, life monitoring and breakage detection, with the express aim of optimising the tool's efficiency both in and out of cut. So, by utilising "intelligent" tooling, discrete data items can be stored on embedded capsules on each tool holder and a range of cutting data can be transferred back-and-forth to the controller/toolholder – in the case of read/write microchip systems – this improves the cutting tool optimisation. Incorporating adaptive control sensing devices – whether of the torque-controlled (TCM), or acoustic emission (AE) varieties – will offer significant improvements in cutting potential over those machines without such monitoring. For example, with TCM, as the main spindle is protected from overload, this in turn prevents damage to either the workpiece, or cutter. As the level of monitoring sensitivity is increased, this has the additional benefits of obtaining optimal stock removal rates under steady-state conditions and utilising a constant cutting power with the cutting/feed forces.

Tool life is improved and the fastest possible feedrate is selected at all times, without over-shooting of power during machining operations. Even more sensitive to minute cutting force/power fluctuations are the acoustic emission (AE) systems, but as they monitor the elastic stress waves created during cutting they are more difficult to isolate from the machine's "noise", particularly when light cutting conditions such as finish machining operations occur.

Much more detail appears in chapter 1, Volume II on tool condition monitoring systems with adequate descriptions of how tool identification, life monitoring and breakage detection are achieved along with the benefits to be gained from such tool/workpiece protection. In the following section we look at just some of the problems that must be overcome when considering the factors that affect part quality in an FMC/S, with particular relevance to the machining centre.

2.5.2 An Overview of the Features Affecting Part Quality in an FMC/S

Regardless of the machine tool that is used for the manufacture of a component, the most important criterion is "will it repeatedly produce a part of satisfactory quality?".

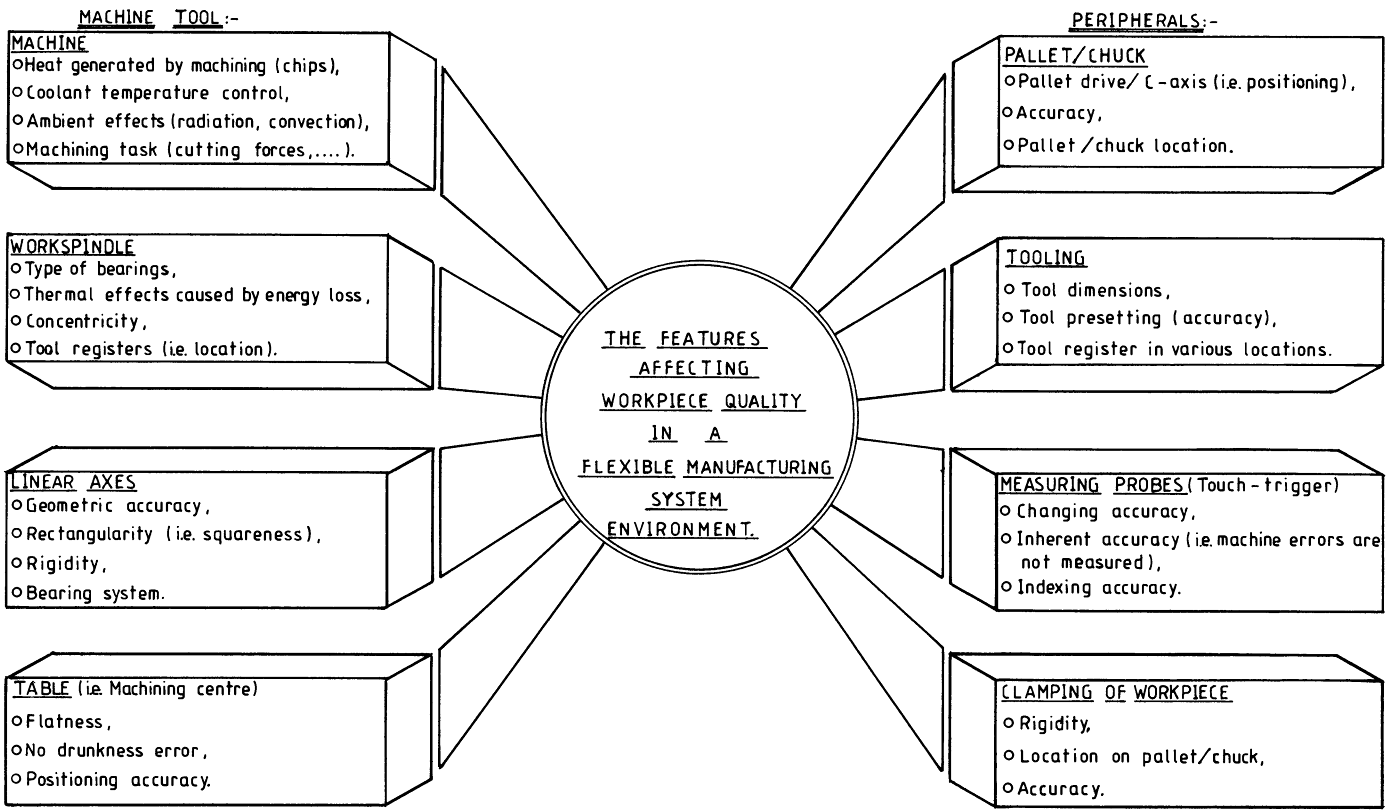


Fig. 2.11. The part quality produced by an FMS depends on the machine tools and peripherals. [Courtesy of Scharmann Machine Ltd.]

There are a number of closely allied factors that influence our ability to manufacture parts, most of which are depicted in Fig. 2.11, in this instance for a machining centre. If we consider the two basic hardware groups, they can be further subdivided as follows:

machine tool:
- machine
- work spindle
- linear axes
- table

peripherals:
- pallet/chuck
- tooling
- measuring probes (touch-trigger)
- clamping of workpiece

Let us now briefly review each of the above in turn beginning with the "machine".

Machine Tool

Machine. On a machining centre, or for that matter any machine tool where large stock removal rates are currently being undertaken, the volume of hot swarf generated must be quickly and efficiently removed from the working envelope and flushed into the swarf conveyor. If swarf is allowed to build up in the cutting vicinity then the hot tempered chips will cause a degree of thermal growth to the machine's structure, locally modifying and distorting the structure, which in turn affects the dimensional characteristics of the part. The same can also be said about coolant temperature control and on many of the larger installations, oil coolers and greater volumes of coolant are used to minimise the heat induced into the coolant during cutting. If this were not the case, then warm coolant during a machining operation might have a significant effect on expansion of the workpiece during its manufacture. As we have seen in section 2.5.1, the ambient room temperature and its fluctuation during the working day can play a role in influencing dimensional characteristics of the part. Yet another influential feature – but this time not a temperature induced one – is how the cutting forces generated can either distort the part, cutter, or both, during machining at high accuracy, particularly where workpiece/cutter rigidity is suspect.

Workspindle. The workspindle's accuracy plays a crucial role in the forming/generating machining tasks employed in the manufacture of parts. Bearings should be designed to allow for thermal growth and alignment modifications during the machine tool's working life. Rigidity must be maintained with bearing wear kept to a minimum and machine tool builders expend considerable effort ensuring that concentricity and alignment are controlled by sophisticated design, lubrication and cooling – often using refrigerated spindles, or heat absorbent materials (heat sinks) at strategic positions around the spindle. However, spindles are not of much use if the tool's location in it is of a small contact région and the tool's adaptor has insufficient register in the taper. As one might expect, the general rule in machine tool building is, the larger the machine the greater its spindle taper. This ensures that with the greater forces generated in larger machine tools during cutting, the spindle nose taper is of sufficient size to accommodate the cutter body whilst machining occurs.

Linear Axis. As with any metrological equipment, machine tools are designed around kinematic motions of translation/rotation, but with extra emphasis upon restraint and location of the moving elements – slideways. The geometric accuracies of one axis with respect to another are crucial when designing a machine tool, as they have a direct effect on the subsequent part quality. A number of geometric features need to be considered by the "builder" – not least of which is the positioning and rigidity of the ways. As moving elements must respond to the motor drive commands issued by the CNC part program during the manufacture of the part, then low-friction rigid and well-spaced ways ensure the smooth transmission of motion. Such geometric features that the construction must account for are:

squareness of the axes with respect to one another
straightness of ways
parallelism of way guides
flatness
other geometric influences: "yaw, pitch and roll" tend to be, in the main, concerned with the moving element upon these ways, as does "backlash" in the ballscrew assembly

Table. Many engineers concerned with the manufacture of components on machine tools rarely consider the fact that even with a new machine the table is not flat. This does not become a problem worthy of consideration unless a company needs to be manufacturing at the highest levels of precision of the machine tool (C_p 1.33). At high relative precision not only is a machining centre table not flat, but as it moves along the ways, either locally or traversing its full axis length, it is subjected to "yaw, pitch and roll". The "yaw" occurs owing to the "crabbing effect" (i.e. sideways movement) in the main, resulting from the positioning of the ballscrew with respect to the ways and any lateral movement within the ways. "Pitch" is present owing to the undulations occurring in the ways, causing the table to rock back-and-forwards as it moves along ways. "Roll" is the twisting motion as the table moves along the ways. Returning to the flatness, it is a well-known fact that once the table has been calibrated – using either the "grid", or "Union Jack" technique – a region of relative flatness normally occurs and this is euphemistically termed "sweet spot" where higher accuracy machining can be achieved. It is worth stating that all the errors described herein will be present on any machine tool to a greater or lesser degree and their influence on part quality can be minimised by calibrating them out – incorporating compensated values into CNC software to override such errors. Lastly, regarding the machine tool's structural elements, we can improve the positional accuracy of the table, or any moving element by using linear direct-feedback scales for each axis. Not only does this minimise "backlash", but improves part quality as it is less influenced by "ballscrew windup" during cutting operations.

Peripherals

Pallet/Chuck. On a vertical machining centre, in particular, when the rotary table for pallets is incorporated the C-axis positioning accuracy will influence the prismatic angularity of the part features. Often a Hirth-coupling is used for location and positional accuracy is achieved through a rotary encoder. Pallet accuracy of the location on the table and working surface must be of a high order, so that when auxiliary workholding equipment is added – chuck, cube, tombstone – the extra height does not induce an accumulated angular or squareness error in situ.

Tooling. As we will see in Volume II, tooling can be classified under three headings: "qualified", "semi-qualified" and "unqualified". With "qualified" tooling we know all about its pertinent dimensions: length and diameter in the case of a new slot/endmill, whereas in "semi-qualified" tooling, we would simply know the drill's diameter with any surety. It follows that "unqualified" tooling is unique and as such, no true dimensional data is known. The point should also be made that at very high accuracy even new "qualified" tooling is made to certain high limits of precision and some companies (e.g. aerospace/optical) regrind their cutters to higher accuracy as a matter of course. Tool presetting plays a vital role in accurately building and setting up tool kits and on milling cutters, if each insert's setting in their respective location pockets is not achieved, then this can influence both the cutting behaviour and the subsequent dimensional characteristics of the workpiece.

Measuring Probes (Touch-Trigger). When in-cycle gauging of critical features is required in an FMC/S environment, the company often relies upon the "probing" accuracy on the machine tool, rather than using up valuable WIP time elsewhere: such is the case when a coordinate measuring machine, or receiver gauge is used. On machining centres the touch-trigger probe is held in the tool magazine and loaded into the spindle nose taper whenever it is decided to assess critical features. This may promote errors into the measurement cycle, as will the machine tool's inherent geometric inaccuracies, although in general they are of the order of micrometres – which may/may not be significant depending upon the level of accuracy demanded.

Clamping of Workpiece. As we will see in Fig. 3.2, Volume II for workholding on turning centres and again, in Fig. 3.16, Volume II for machining centre workholding, the higher accuracy parts occur when using dedicated chucks, or fixtures. The major reason for this is their inherently higher accuracy of manufacture coupled with greater rigidity, which means that workpieces can be located in the required position more accurately and less flexure of the fixturing occurs – at the expense, of course, of more flexibility in accommodating differing part geometries.

As we can appreciate, there are a considerable number of mitigating errors that concern us when manufacturing parts either in a "stand-alone" or "system" mode. Each in itself is not too great a problem, but the significance magnifies as one approaches the process capability of the plant, where a compounding effect can present real problems during the part's manufacture.

2.6 Automated Auxiliary Equipment to Ensure Accurate Quality Assurance in an FMC/S Facility

Automatic Wash Station

Most of the larger "prismatic" machining and "rotational" cells used in industry today have some form of automatic part handling/transfer system incorporated within the facility. Normally, such plant is of high value and accuracy and, as such, many companies feel that using up in-cycle time assessing part quality is something of a waste of valuable productive capability. These companies recognising this point use an integrated and flexible metrology facility on line to assess the occasional preplanned part as deemed necessary by the host computer. Such a flexible metrological facility is a coordinate measuring machine (CMM). However, problems can arise when one tries to deliver this part to be measured straight after the completion of machining. The major problem is residual swarf and coolant adhering to the intricate and inaccessible features, or within the component. So, this usually means that an intermediate cleaning process is necessary, prior to inspection. Obviously, one would not want to manually clean each and every component destined to be inspected, as this would be labour intensive and boring, and not cost effective. Therefore, it is usual to include an automated cleaning facility within the system.

A typical washing station has an AGV loaded double pallet "paddle wheel" cleaning facility controlled through a DNC link to the "host" computer and it is possible to run a range of washing strategies – with any changes in these strategies being effected via a terminal in, for example, the control room. A number of washing/drying strategies can be utilised, such as:

number of paddle wheel stopping positions
paddle wheel position – angle unit
dwell in washing position – seconds
dripping time – seconds
washing time – seconds
blowing time – seconds

As an alternative, a six-axis robot equipped with high-pressure wash/degrease facilities – suitably protected and fully guarded – has proved well up to the task of cleaning components automatically, albeit an expensive but highly flexible solution to the problem.

Once the part has been thoroughly washed and dried, it is in an acceptable state to be loaded onto a CMM for automatic inspection.

An Integrated Coordinate Measuring Machine (CMM)

In the highly productive and flexible manufacturing environment found on FMC/S plant, it is essential to be able to automatically inspect parts on a specified basis, e.g. 5%–100% capability. This means that in a large-scale FMS a washing station should be incorporated prior to inspection of the parts. An AGV can load and unload parts to the CMM via the double-pallet buffer. The CMM with its integral computer is coupled to the "host" via a communications interface. This allows the "host" computer to instigate process strategies appropriate for the parts to be inspected. It also has the ability to inform the CMM as to what measurements are to be undertaken, with this information being based upon statistics previously achieved by measuring results.

If an inspected part exceeds its predefined limits, the "host" receives a feed-back message and the computer then passes this information to the storage/transfer system, making sure that the rejected component is precisely recorded. An operator at the setup station is in the position to make a decision on whether to reject the component, or send it for future re-working.

If such equipment is incorporated from the original feasibility study plan, then it can be an economic method of both cleaning and inspecting parts, without undue delays in work-in-progress (WIP). However, it is essential that when producing our planned integrated FMC/S, such equipment is specified, otherwise undue bottlenecks

Fig. 2.12. One of the most modern factories in Europe, in Worcester, England. A fully integrated CIM facility, producing 100 machines/month by 240 staff on 14.5 acres. [Courtesy of Yamazaki Mazak Ltd.]

in production will arise, upsetting the harmonious flow of production necessary in untended, or minimally manned plant.

The following computer-integrated manufacturing facility has been included as a look at the latest trends in advanced manufacture, whilst giving the reader an appreciation of the type and level of sophistication in an automated factory engaged ironically, in the manufacture of both turning and machining centres – the theme of this book.

2.7 Computer Integrated Manufacture (CIM) in the Automated Factory – a Case Study

It is arguable that the Yamazaki Mazak factory at Worcester, England is the most advanced in Europe. The factory began production in mid-1987 and is based upon Flexible Manufacturing Systems concepts of which it had previous knowledge from several sites outside of Japan, although the original site at Oguchi in Japan was developed some years previously. The UK was chosen because of its English-speaking advantage and the idea of building the factory at the birthplace of the industrial revolution appealed to Mr Teruyki Yamazaki – son of the founder. A green-field site was chosen for the factory (Fig. 2.12) on a 14.5 acre site, with an initial building area of 16 500 square metres. The whole complex was designed to be controlled as a highly advanced CIM system, that is, complete production control ensuring that manufacture is achieved in an optimum time, with minimum inventory. When the site was initially commissioned in 1986, it cost £35 m to build and it was designed to manufacture a range of turning and machining centres – with their own machine tools used to manufacture them. The complete factory has been laid out as a giant shop window, so that visitors (around 3000 per year) can see how the machine tools function within the factory and how the parts are made, tested and assembled.

The plant runs an MRP II system called "Magnet", originally written in Cobol for use in Japan, but heavily modified for the UK factory. The system operates at three distinct levels – using a different computer at each level – for scheduling, process control and specific machine control. An IBM mainframe computer processes any orders entered by the sales department into a sequence of operations involving the purchase of required components and the insertion of the individual order into the master schedule. Twice per day information updates are received from the factory floor and the computer is able to monitor the arrival of the required components and initiate the machining process. It receives data on current progress, distributing instructions based upon product mix optimisation going through the plant via a PC linked to three operational DEC Micro Vax computers – with each Micro Vax having a separate area of responsibility. One is used primarily to control the automatic warehouse, together with movements of four AGVs. A second channels instructions to the three CNC automated machining lines, whilst the third is dedicated to tool management, creating life-cycle maintenance for each tool and scheduling automatic replacements.

The machining activities run as a CIM system with automated delivery to the various machine tool lines from banks of pallets, which have the ability to continue working unmanned for the night shift in a "lights-out' situation. However, it is still cost effective to have a degree of manual operation when painting and welding, and for final assembly, owing to the relatively small volume of work undertaken during such activities. The "host" computer informs the MicroVax responsible for the machining lines when work is to be processed on a particular line, with its respective pallet being delivered to a specific machine according to the dictates of the master schedule. Whilst this is being initiated, the part program is called-up and downloaded to this machine tool, the software being written in Fortran, ready for the machining cycle to commence, once the previous part has been completed. As we have seen in the previous chapter, the part program prescribes not only the cutting sequences and effects the necessary tool changes, it also programs and monitors the feed and speed requirements of the cutting tools to ensure a standard and repeatable performance. It is worth pausing here to discuss the Japanese philosophy to manufacturing, alluded to earlier. They are not concerned with running cycle times at the theoretical 100% efficiency, but more interested in obtaining a longer and more predictable tool life, less stress on the machine tool, fixture and part, whilst enhancing part quality by cutting at around 80% of the capacity. This differs from the manufacturing philosophies adopted by both European and American companies in general and one might wonder how they can achieve such an efficient production throughput? The answer is by exceptional attention to the organisational elements of plant layout, work-in-progress, just-in-time/Kanban philosophies in practice, in a realistic manufacturing environment – this is where the real savings are made. Furthermore, the allocation of discrete functions to different computers working on various levels is the key to a successful CIM implementation, with the old adage to "keep it simple".

Yet another advantage of utilising the CIM strategy using the FMS philosophy is that machine tool building requirements are inherently cyclical in nature – often a high attrition rate occurs where customers might collectively decide to cancel, or postpone new capital goods purchases as recession pressures affect potential orders – allowing the machine tool builder to minimise such unforeseen circumstances. Similarly, CIM strategies can cater for demand peaks, which would otherwise create major problems both in terms of delivery on time and maintaining quality. Thus, using the CIM

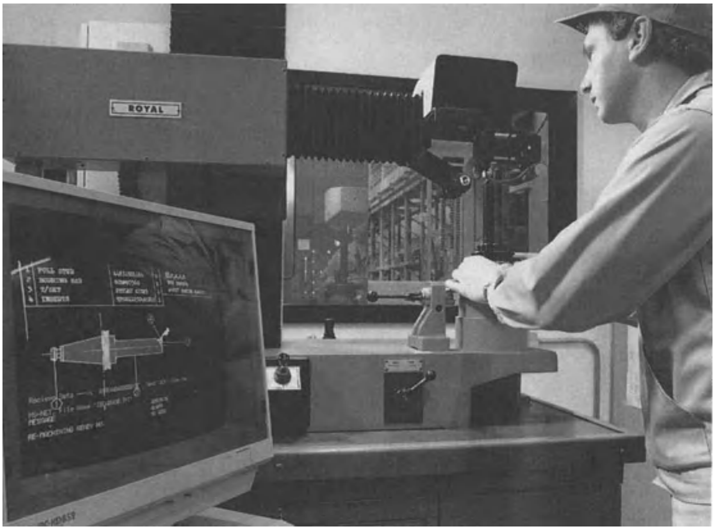


Fig. 2.13. The tool presetting area with on-line tool management/monitoring. [Courtesy of Yamazaki Mazak Ltd.]

approach limits the cyclical consequences of sharp contractions and expansions, by taking advantage of its inherent greater flexibility. Furthermore, as the significant proportion of value-added costs are created by the machinery rather than the labour force, problems of labour shortages, or redundancies are reduced – machines can easily be stopped, or started, without incurring additional costs. However, a more significant benefit is that production lead times can be slashed from the "industry average" of about six months to around eight weeks.

It is essential to maintain short lead times on such an automated facility, as they enable the factory's production schedule to be adjusted with considerable accuracy every month. This point encourages the customer to request the non-standard features – at higher cost – without incurring any additional delays, ensuring that there is no costly and extensive stockpiling of expensive bought-in components.

Prior to a "pictorial tour' around the manufacturing facilities at the Worcester plant, it is worth stating that up to 73% of these machine tools are sourced from European companies, with only the CNC and servo motors coming directly from Japan. Of the total workforce of around 200, about 60 are office and sales staff – with around 15 Japanese workers included in this overall number of employees. The proposed machine tool output is set to rise to about 100 (maximum) machines per month – this being a mixture of a range of turning and machining centres.

Finally, with regard to the working practices within the factory, all employees wear a standard issue overall and the company runs an apprenticeship scheme providing continuity of skills within the plant. Even the managing director must "clock in" using computerised bar-code readers, and all staff have staff status, monthly pay cheques, life insurance/private pension and health-care plans. All employees work a 40 hour week, with the shift workers receiving an additional unsocial hours' allowance, with overtime available to the staff. Not only are the manufacturing facilities clean, bright and exceptionally well laid out, there are some "novel touches" in that visitors can view the whole of the manufacturing facility from an elevated walk-way, running around the factory, but a large range of machines is always on display in the showroom. Just adjacent to the showroom, is a large expansive coffee lounge and informal meeting place, overlooking a traditional Japanese garden. Formal teaching and conference facilities are also present in this vicinity, with specialist engineering and sales staff in attendance at all times, to answer customer enquiries.

This gives the reader an overview of the facility at the Yamazaki Mazak, Worcester, plant; let us now discuss the factory in more detail.

2.7.1 The Layout of the CIM Factory

The manufacturing plant consists of discrete areas such as:

tool presetting and management facility, with automatic tool distribution highway
workpiece fixturing/palletisation
small prismatic line
large prismatic line
rotational parts line
automatic warehouse and delivery systems
sheet metal working and painting
quality control and superfinishing
clean room for precision sub-assembly
final machine tool assembly

Tool Presetting and Management Facility, with Automatic Tool Distribution Highway

A strategically positioned tool presetting facility beside the overhead distribution highway (Fig. 2.13) allows for tooling requirements to be administered via a MicroVax which is on-line to the "host". It organises the entire range of tool management activities including tool offsets, life and replenishment. When present tooling is required the setter has visual confirmation of the tool-build requirement (Fig. 2.13) highlighting the parts necessary and the offsets to be present for the respective cutting edge/s. All tooling is thus "qualified" on the tool presetter and placed into a known position in the "tool hive" pocket, ready for the overhead tool delivery robot to replenish the respective machine tool on demand. When the unmanned night shift arrives, a stock of previously stored preset tooling is buffered in their designated pockets in the "tool hive". This caters for any "sister tooling" – duplicate tools at the end of their tool life – to be replaced in the machine's tool magazine at the appropriate time and in so doing, increasing the tooling capacity to almost infinite lengths, ensuring that tooling is always available. At the end of the night's machining, when the day shift arrives, a stock of worn tools is buffered in identifiable pockets in the "tool hive" and they are broken down and rebuilt as required by the tool management software requirements – in line with production demand.

Obviously, such a complex set of tasks as tool replenishment, distribution and service, across the large tooling library necessary in the FMS lines, needs to be identified by a suitable tool tracking technique. Therefore, each tool holder has an embedded microchip capsule positioned in the end of the pull stud. This microchip carries the information (see section 1.7, Volume II on "intelligent/tagged" tooling concepts) allowing each tool to be identified and tracked around the system and continuously updating the tool life data whilst in-cut by the tool management computer.

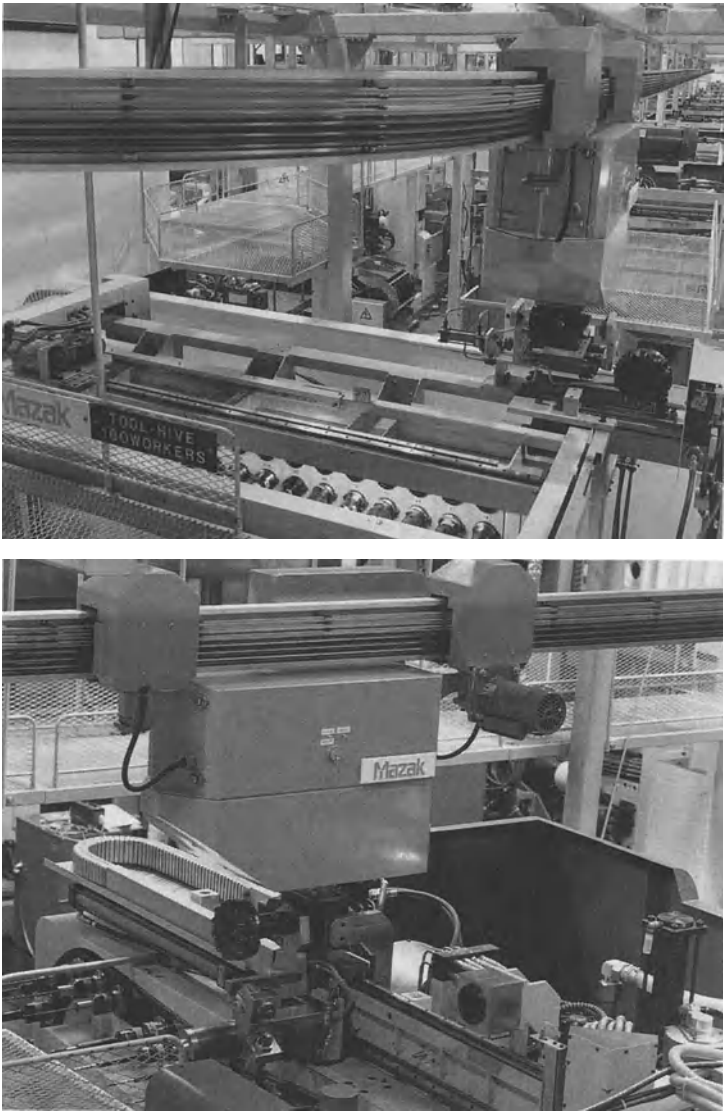


Fig. 2.14. Preset tools are automatically distributed along the U-shaped overhead monorail termed a "tool highway". [Courtesy of Yamazaki Mazak Ltd.]

When the preset life of a tool has been reached, or a new tooling library is needed on one of the machine tools, the tool robot will pick up a replacement from the buffer "tool hive" and transport it to the machine which will unload/load the old/new tool respectively (see Fig. 2.14). This tool highway straddles over both the small and large prismatic lines and is a U-shaped monorail, connected to the tool presetting facility by the adjacent "tool hive". When preset tools are required they are identified by the tool management software on the CPU for selection and delivery via the distribution highway. The highway distributes the tooling demands to the respective machine tools using a random access order and in so doing, optimises its travel along both the highway arms to the respective machining lines. Speed of delivery is not an essential requirement here, as efficient utilisation of resources is all that is needed.

Workpiece Fixturing Palletisation

If all one had to do was load/unload preset "qualified" tooling into the machine tools in their respective FMS lines, then the demands on the micro-computer would be quite small. However, not only must the cutting tools be tracked, assembled/broken down and cutting data determination managed as part of the overall tool management function, but the workpieces require similar attention. This is necessary to ensure that at all times codified pallets can be similarly built up and buffered onto pallet stands, awaiting either return to the pallet assembly area after machining, stored for further machining, or simply awaiting delivery to a machine tool. In Fig. 2.15, we can see an operator accessing information about a pallet build assembly. The isometric assembly mimic present on the screen, informs the operator not only how to assemble the workpiece on the pallet in this visual display, but identifies all the equipment necessary to assemble the fixture and which part should be used, whilst simultaneously noting/storing the pallet's code in the computer.

This workpiece palletisation is undertaken for both the large and small prismatic lines and in an adjacent area an automated palletised facility was built, for some unmanned pallet assembly operations. However, this is still at the proto-type stage of development and may/may not be brought on-line, depending upon the production pressure in the future and it is expected that up to 30% of components could be fixtured in such a manner.

Small Prismatic Line

As mentioned previously, the tool highway serves to load and unload cutting tools, on demand, to these machining centres, whilst palletised workpieces are delivered by a "stacking" RGV to any of the machine tools. This FMS line consists of seven horizontal machining centres of 800 mm pallet size, each equipped with an 80 tool magazine (see Fig. 2.14 for a restricted overhead view of the line). These machines are used, in the main, for the machining of the gearbox components, etc., and are fed components – mainly castings – by two auto-stacking cranes (RGVs) from the two-tier buffer pallet pool running the length of the track. In this manner, a 150 pallet stocker is located beside the RGV rail, with further buffering for 70 pallets, often used during the "lights-out" night shift. Toward the end of this small prismatic line is positioned an automatic wash station where the palletised parts are washed and then transported to a CMM for automatic inspection of critical features as necessary, with feedback of information to and from the "host". In fact, so accurate have the machines in the various FMS lines proved to be that the touch-trigger probing in-cycle has proved, in most cases, to be more than adequate. Probing is used not only for offset updates within the machines, but also for interrogation of the palletised workpieces, undertaken to exactly align the part with respect to the program before machining commences – a desirable check to ensure that dimensional quality is maintained. After machining the pallets are replaced in either the main pallet stocker, or loaded into the buffered stocker.

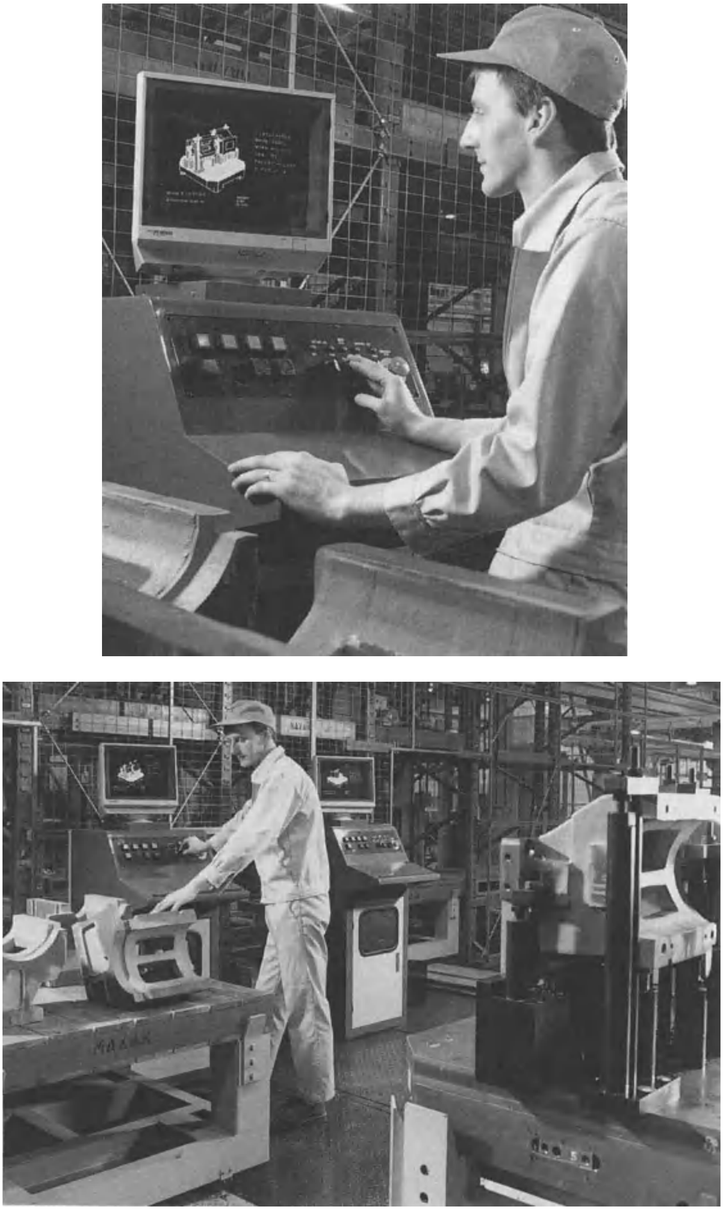


Fig. 2.15. Fixtures are scheduled by the host computer and all of its assembly details are displayed on the screen, allowing the assembler to speedily and accurately build up the part on its fixture. [Courtesy of Yamazaki Mazak Ltd.]

It is worth making the point that each machine tool has in situ a range of condition monitoring equipment: tool breakage/collision devices, tool life monitoring and adaptive control features ensuring that the cutting process is fully monitored during the part/s manufacture.

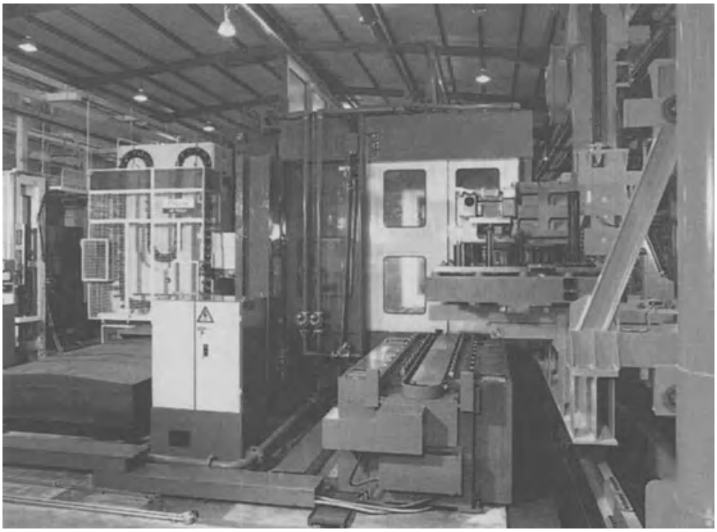


Fig. 2.16. The large prismatic machining line, consisting of travelling column machining centres (three). Pallets are transferred by rail-guided vehicle with "coded" programmable microchip pallet identification. [Courtesy of Yamazaki Mazak Ltd.]

Large Prismatic Line

This FMS line consists of three travelling column horizontal machining centres, with rectangular pallets 3500 mm long by 1600 mm wide. An 80 tool magazine is attached to each machine tool and old/new cutting tools are delivered by the other "arm" of the tool highway – both the small and large FMS lines run parallel to each other. A single auto-stacking crane runs as an RGV, alongside each machining centre and pallets are loaded from a 36 tiered pallet pool (see Fig. 2.16). At the end of this FMS line a large bedway grinder is positioned, and after machining the ways on the castings they can be ground with the minimum of work transportation.

Pallet identification is operated in the same manner as on the small prismatic FMS line, using programmable micro-chip coding systems on each pallet for appropriate identification of workpieces. If, for any reason, a machine tool is taken out of service – for essential/planned maintenance – the "host" tells its respective MicroVax to re-schedule the work destined for this machine to a duplicate machine in the line, with the minimum of disruption to the production schedule, and in this manner, unanticipated or undesired breaks in manufacturing capacity are minimised. Only when manufacturing systems are designed around "rigidly flexible" strategies can they hope to gain some measure of efficiency.

As one might expect with such a large metal cutting facility, the disposal of swarf and coolant control requires particular attention to detail. In fact, a shared underground coolant and chip system was developed carrying 30 tonnes of coolant, with the capacity to handle and dispose of 20 tonnes of swarf per day. This underfloor coolant/chip disposal system carries the used coolant to a collection tank where the swarf is separated and automatically transported outside the building for collection.

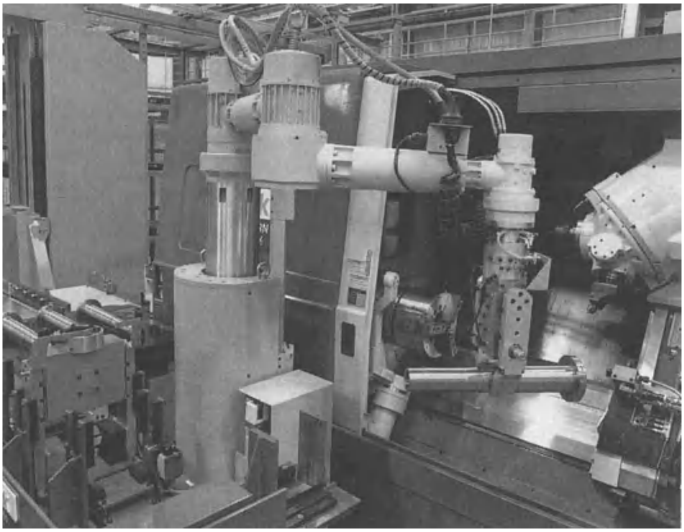


Fig. 2.17. The rotational parts line, consisting of three "mill-centres" fed by robots from stacked pallets. NB: Chucks have an automatic jaw changing facility. [Courtesy of Yamazaki Mazak Ltd.]

Rotational Parts Line

The rotational parts line is somewhat of a misnomer, in that on such machines it is possible to not only turn features, but mill, drill, cut splines, etc., by utilising a fully programmable C-axis and driven tooling. The line consists of three "mill-centre lathes" (turning centres) each with an 80 tool magazine, because a turret has a smaller tooling capacity. A fully programmable robot is situated next to each machine tool and can load parts from a 60 pallet stacking crane RGV (see Fig. 2.17). A novel feature of these turning centres is their ability to automatically change jaws to accommodate a range of part sizes and features. Jaw-changing is achieved by indexing the chuck to the change position and from a position above the headstock, jaws are unloaded and loaded by sliding the jaws out and then indexing the chuck to the jaw-change position. This automated facility increases the versatility of these turning centres considerably, allowing untended turning operations to be continued across a large range of part diameters/geometric features.

Tool presetting and calibration are achieved by utilising the "tool eye" situated on the machine and an automatic recalibration can be programmed when necessary; sister tooling is used so that either when the number of prescribed parts has been machined, or if tool wear has reached a predefined limit, the tool is changed.

This virtually completes our review of the metal-cutting capabilities within the factory, but it is worth stating that apart from a few grinding machines on the shop floor (where, incidentally, the overall temperature throughout the machining/assembly areas is maintained at $\pm 2\frac{1}{2}$°C) there is the jig-boring and super finishing area yet to be described.

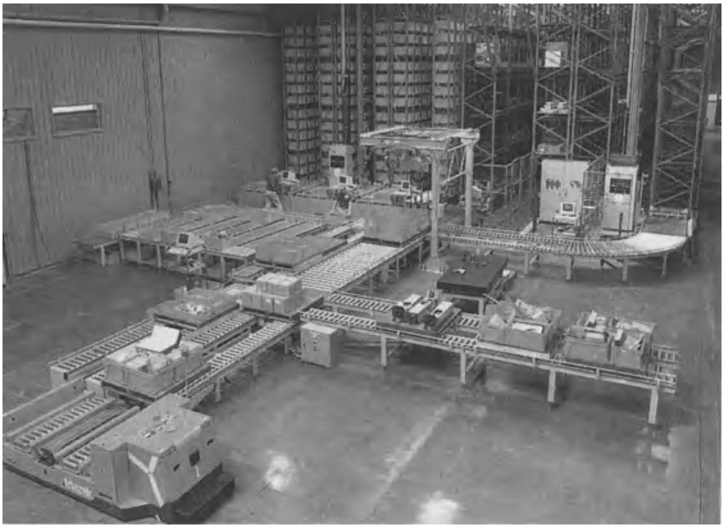


Fig. 2.18. The automatic warehouse under the "host's" control, with two AGVs to distribute parts to assembly areas. [Courtesy of Yamazaki Mazak Ltd.]

Automatic Warehouse and Delivery Systems

Although a limited number of parts are held in stock, the larger castings are sourced on a "just-in-time" (JIT) philosophy so that at any time a relatively small number of major items are carried on the inventory. The parts are held in the automated warehouse (Fig. 2.18) with the parts loading centre controlling the passage of work from the machining to the assembly departments. The "host" controls all the information appertaining to machined parts, purchased goods and assembled units, held in the automated warehouse. As dictated by the "host", they are distributed to their required destinations by two wire-guided AGVs (see Figs. 2.18 and 2.19).

The "host" can easily cope with the 4420 varieties of parts that are held in the factory and can be loaded onto pallets, or held in trays in the vertical stacks and sourced by the automated stacking RGVs (see Fig. 2.18). Two further AGVs of larger size and capacity are used to transport castings/loads up to 1000 kg around the manufacturing facility and are also under the control of the "host" as it processes work according to the dictates of the production schedule.

In Fig. 2.19, we can see one of the AGVs involved in unloading parts at the end of the rotational parts line prior to stacking in the tiered buffer, awaiting delivery to the turning centres by RGV and subsequent loading into the machine by the robot (Fig. 2.17).

Sheet Metal Working and Painting

As anticipated by the reader, the sheet metal working facility is fully computer-controlled. Sheet metal working is performed in approximately half the time it takes in a conventional factory. This speed of production of sheet metal parts is achieved using

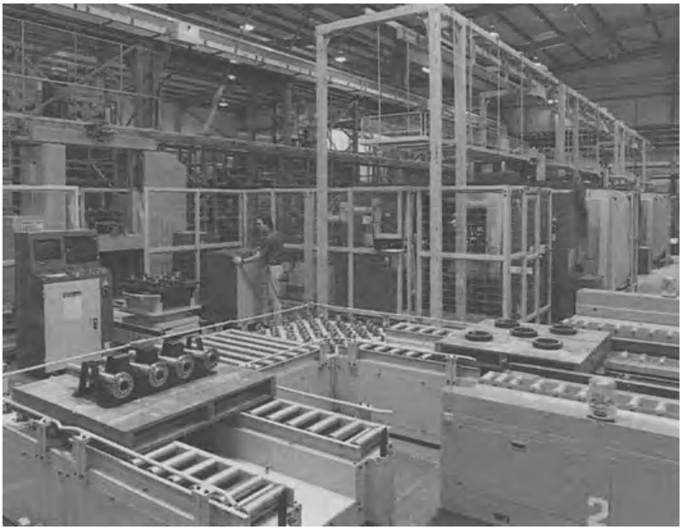


Fig. 2.19. An AGV delivering parts ready for palletising into pallet store for the rotational parts line. [Courtesy of Yamazaki Mazak Ltd.]

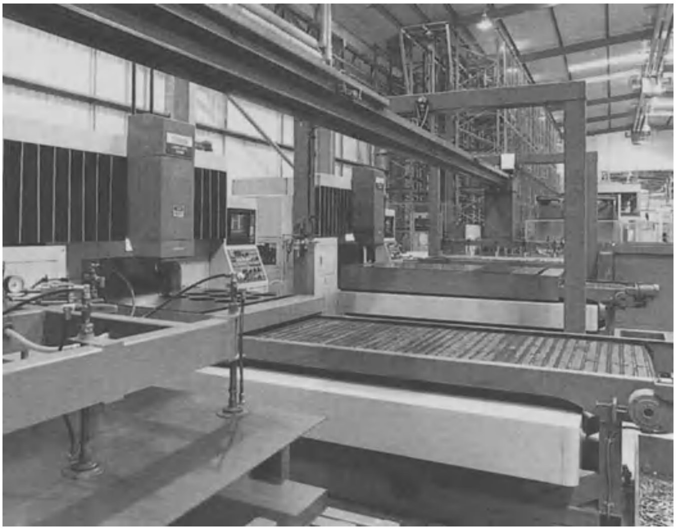


Fig. 2.20. Sheet metal working – laser path cutting machines, CNC folding and bending machines, together with automatic welding machines. [Courtesy of Yamazaki Mazak Ltd.]

two laser path cutting machines, CNC folding and bending machines, automatic welding machines and a storage facility for 180 part varieties. The laser path cutting machines have the sheets loaded automatically from stacks onto their beds and the parts are cut out accordingly (Fig. 2.20). However, if some buffering of stock is required, then the laser leaves the parts attached to the parent sheet at prescribed intervals, by less than 1 mm, allowing for flat stacking – fully cut out (like a jig-saw

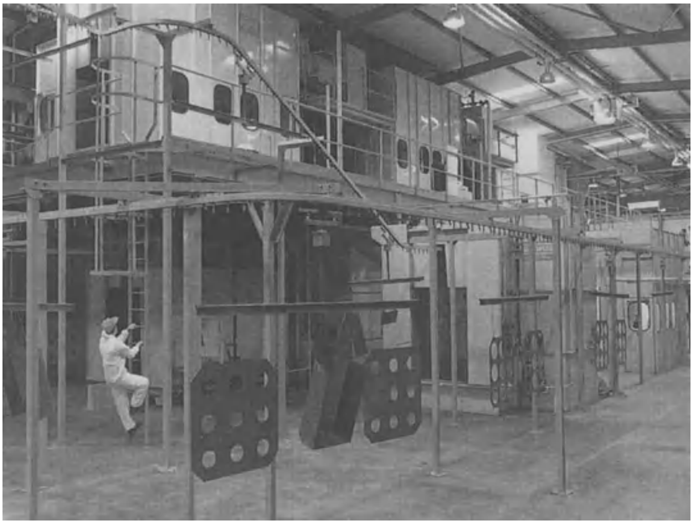


Fig. 2.21. Automated transportation of parts to either one of two painting systems, one for cast components and the other for sheet metalwork. [Courtesy of Yamazaki Mazak Ltd.]

puzzle) – then broken out when needed. In this manner, the area needed to hold any buffer stock is kept to a minimum.

At the end of the sheet metal facility is the painting bay, where two systems are provided: one for cast iron and heavy products and another for sheet metal spraying (Fig. 2.21). Both systems are automated and the transport of parts through the spraying booths and drying stages is fully controlled, but unlike automotive factories where robotic spraying and dipping are used, the actual spraying is completed manually. Once again, it is worth pausing here for a moment to discuss the reasons for this manual spraying operation. With such a diverse range of parts to be sprayed – of relatively low volume – it would be unwise to expend great amounts of money and effort in fully automating a robotic spraying facility of this type. Such plant would be hard to justify in terms of equipment, capital and effort. Furthermore, with the well-proven Japanese philosophy of "keeping it simple", manual spraying will produce a satisfactory quality and at minimum expense. The final point of being able to know when, why and by how much, to automate, is why the Japanese have become so successful in terms of both production throughput and quality.

Quality Control and Superfinishing

The superfinishing/jigboring facility on the shop floor has had special attention paid to it in terms of the installation of the machine tools. Not only are the foundations extra deep, they are isolated from the remainder of the shop floor to minimise vibrations. The special-housed machines are in a closely controlled-temperature environment, to within $\pm 1\,°C$, as this ensures that the precision can be maintained to within $0.5\,\mu m$ tolerances, where applicable. The machine tools range from high accuracy surface and cylindrical grinders to two of the Yamazaki Mazak's Jig Centre ATC machines. Such equipment is essential when high accuracy roundness, dimensional and geometrical tolerances are to be consistently held.

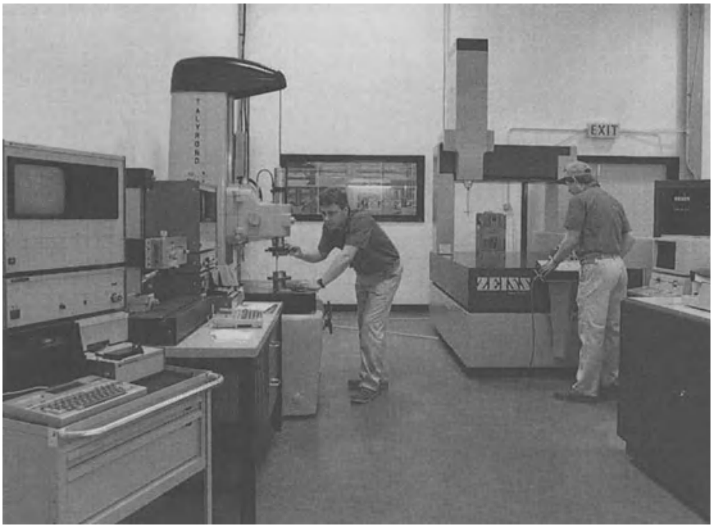


Fig. 2.22. The quality control of parts – temperature-controlled environment with a comprehensive range of metrology equipment. [Courtesy of Yamazaki Mazak Ltd.]

The quality control of high precision parts is assessed in the metrology laboratory adjacent to the superfinishing facility. Here (Fig. 2.22) in the temperature-controlled room, spindles, bearings, housings, etc. are inspected for roundness, surface finish, dimensional/geometrical features on a range of high accuracy equipment: Talyrond (roundness) and Talysurf (surface finish) instruments, Zeiss CMM (linear and geometric features on prismatic/rotational parts) and other metrological equipment. The quality information is fed back to the respective MicroVax for logging of data and quality control action.

Clean Room for Precision Sub-assembly

Not only is it essential in a "clean room" (Fig. 2.23) to maintain high accuracy and stability of temperature, but in order to avoid ingression of dust/debris particles in the air, contaminating the precision surfaces, it is important to purify the air to "class 10 000", i.e. as clean as the air above the middle of the Pacific Ocean. The workforce in the clean room wear special overalls and it is in here where assembly of the spindles and headstocks for turning centres and spindle cartridges for machining centres occurs. All sub-assemblies are then continuously tested/monitored on programmed "trial runs", to ensure that the spindles/cartridges within their housings are operating satisfactorily.

Final Machine Tool Assembly

The assembly hall (not shown) is where the sub-assemblies, machine beds and bought-in components are all delivered via the large AGVs. Typical machine assemblies include: spindle units, tool magazines, control units, etc., which are all subjected to exhaustive run and test procedures for 24 hours, prior to final assembly. The results

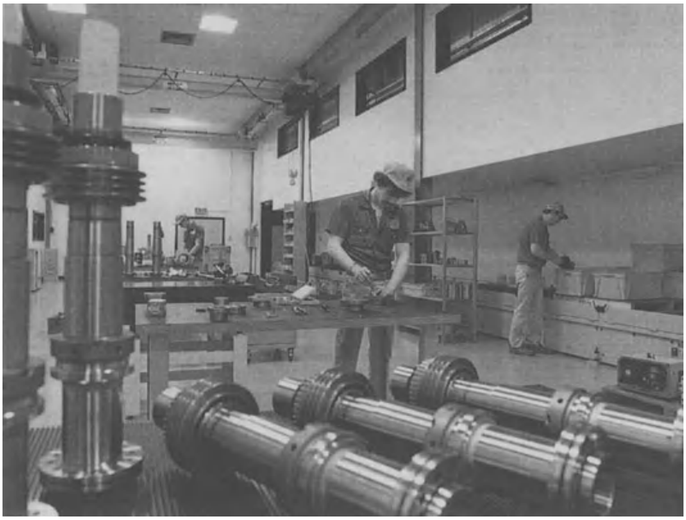


Fig. 2.23. The clean room and sub-assembly area for critical parts, such as spindles and headstocks (turning centres), also spindle cartridges (machining centres) prior to complete machine tool assembly. [Courtesy of Yamazaki Mazak Ltd.]

are continuously monitored and recorded. Machines thus assembled can be directly despatched, or moved, to customer "prove-out" areas where fixturing and tooling are fitted by the user, if necessary.

This completes our tour of the manufacturing facility at Yamazaki Mazak's CIM factory and it is worth concluding with some final comments on total quality management (TQM). TQM within the factory not only relates to every aspect of quality – not just one of the machines and its mechanical components – but also, the quality of the people and procedures adopted in maintaining/improving quality levels. In 1989, this factory produced about 1000 machine tools, worth then around £70 m, giving a theoretical turnover per employee (180 production people) of just under £400 000. Not only this, but in a recent survey conducted by a consultancy company, they were the top company in terms of automation, productivity, quality and ideas.

Such a technological approach to the manufacture of goods must surely be a lesson to us all, in that there are no mystical thoughts/philosophies in reaching these levels of production, only well-proven ideas that are efficiently carried out in a practical common-sense manner. Many companies can achieve similar productive potential within their existing plants – obviously to a lesser degree – with a clearly defined strategy of implementation, improvement and capital expenditure. If this is not the case, then more energetic and expansive companies will steadily, but surely, take over a staid and complacent competitor.

2.8 Present and Future Trends in Turning and Machining Centre Development

Increasingly, as companies are approaching the process capability of their machines, machine tool builders are being asked to improve their products, offering the customer still higher accuracy/precision. This will entail a range of modifications to current production machine tools. They will need to be able to resolve axes to higher levels than currently available, whilst monitoring the performance in real-time and correcting errors present during machining. In essence, the major problems to be addressed when attempting to improve production machine tools falls into several categories:

improving the machine's linear resolution
speedy recalibration of volumetric envelope
the increasing importance of condition monitoring
improving inertial response of slideway motion
thermal drift and damping improvements
ultra-high speeds for non-ferrous/metallic machining operations

The objective in high precision production machine tools is to produce a "zero defect" part, which no longer depends upon the skills and capabilities of the operator. We know that even with CNC performing a programmed sequence to faithfully manufacture parts with dimensional precision, it is still not possible to build the perfect machine tool. Every production machine today has varying degrees of inaccuracy present and adverse physical effects will, of course, be inevitable. In the following section we will look at the means by which these errors can be minimised, in a commercial sense, and attempt to describe how one might re-engineer machine tools for almost sub-micron accuracy and precision.

2.8.1 Approaching Sub-micron Levels of Accuracy and Precision on Turning and Machining Centres

It is well known that "direct" feedback monitoring systems, utilising linear scales, offer much greater axis resolution than their open/closed-loop "indirect" feedback counterparts. Even here, resolution of the latest scales can only be maintained with any predictable determination over small linear ranges, when approaching micron levels of precision. The major reason for this is the structural changes in-cycle, promoted by differential thermal expansion of the structure influencing the attached linear axis scales. This non-uniform thermal growth can be minimised by attaching laser interferometers coupled with suitable optics for each slideway. Such high resolution, around 40 nanometres (10^{-9} m), has already been incorporated onto diamond turning lathes in production environments and it is only a matter of time before they are incorporated onto commercially available ultra-high accuracy machine tools.

Laser transducers offer high resolution and are less influenced by thermal growth characteristics, as thermal and humidity sensors can compensate, to some extent, for non-linearity of axes and differential thermal growth. The major problem that exists on such machine tools when used at ultra-high accuracy/precision, is that the machine tool's structure will have present, in greater or lesser degrees, the following errors, axes and geometric misalignments:

straightness
flatness
parallelism
positional accuracy
angular: yaw, pitch and roll

repeatability
backlash – to some extent, even with ballscrews
velocity – promoted by feedrate (inertial and CNC interpolation errors)

All these errors can combine to influence the volumetric envelope of the machine tools. It is, however, possible to reduce these interactive elements by incorporating an "adaptive error compensation" unit. This equipment minutely adjusts the axes in "real-time" and the axes/geometric errors are minimised. In such a system, sensors monitor changes in the machine tool structure and software algorithms developed during the machine's initial calibration – via a total error-mapping of the volumetric envelope – can be used to modify each axis motion independently during workpiece machining.

Yet another contributor to errors on machine tools is the product of vibrations promoted during machining and to a lesser extent the machine tool's damping characteristics. Recently, to improve both the thermal growth and damping effects during machining for highly accurate machine tools, "Granitan" has found much favour. This is the product of crushed granite and thermosetting resins bonded to improve thermal expansion by five times and damping by ten times, although such advantages mean a more expensive and heavy machine tool structure.

2.8.2 Ultra-high Speed Cutting Operations on Machining Centres

One of the first questions one might ask is, "Why do we need to machine at ultra-high speeds?". There are a number of important production benefits that can be gained by such an approach:

increased productivity
minimal changes in material properties
distortion of workpiece reduced
burr-free improved finish
thin-section machining potential
tool life improvements
reduction in cutting tool varieties
fixturing of simpler design

Prior to a discussion on these important benefits, it is worth making the point that the term ultra-high speed machining refers to peripheral speeds in excess of 1500 m/min.

Increased Productivity

Obviously it is necessary to optimise the feed to this increase in rotational speed to obtain greater productivity. Typical cutting data might be a spindle speed of 20 000 r.p.m. with a roughing feedrate of 12 m/min, giving a saving in machining time three times greater than that found using conventional spindles.

Minimal Changes in Material Properties

Conventionally machined workpieces at and near the surface exhibit a degree of hardening, promoted by rupture of the slip planes as chip formation occurs causing higher temperatures and heat transfer to the workpiece owing to the action of cutting, inducing sub/surface residual stresses. The research has shown that once we obtain ultra-high speeds, the chip's deformation and its compression approach zero; it follows that minimal heat transfer into the workpiece occurs causing little in the way of work hardening at the surface. During cutting trials it has been demonstrated that the workpiece's temperature rise is normally less than 3 °C above ambient, when ultra-high speed machining. Furthermore, when "ramping" into a surface close to its underside – feeding down whilst simultaneously traversing along – this thin section does not "burn" as is often the case during conventional cutting operations.

Burr Free and Improved Finish

With more energy efficient and "cleaner" machining available from ultra-high spindle speeds, improvements in both surface finish (arithmetical mean roughness) together with burr-free edges occur. Burrs always present problems during the production of parts, as in many cases costly hand finishing becomes the only real alternative with larger components. Such extra manual intervention adds value to the part whilst increasing lead times.

Thin-section Machining Potential

By utilising ultra-high rotational speeds, the cutter forces are reduced significantly, which allows very thin wall and base sections to be machined. Typically a part feature might be a deep pocket to be machined from solid at ultra-high speed: roughing out using a 25 mm diameter slot drill and finish machined with a 12 mm diameter endmill in a very fast time, having a wall thickness of 1 mm and height of 33 mm. However, thickness can be down to 0.3 mm wide and of greater heights than the machined part just mentioned typically an 18:1 ratio (i.e. depth: cutter ratio), which would be impossible, in terms of geometric/linear tolerances, when using conventional milling rotational speeds.

Tool Life Improvements

The improvement in machining efficiency results in much lower cutting forces on the tool and, consequently, less wear occurs. Such wear reduction at ultra-high speeds is quite considerable and the in-cut machining improvements, between either regrinds or replacement, can be up to 80%.

Reduction in Cutting Tool Varieties

The improvement in efficiency of the cutting process means that we can dispense with a large tooling inventory held in the magazine. Often just one slot drill might be used for roughing, with possibly two endmills needed for finishing – this being dependent upon the part's corner radii, etc. Other cutters might be needed to produce features such as angles on the part, or barrel milling cutters may be required to machine contours, minimising cusp height effects. The ultra-high speed machining action ejects the swarf from the cutting vicinity, when tooling is correctly designed, and, in so doing, eliminates any secondary cutting promoted by trapped chips. Therefore, the need to be continuously changing to different diameter cutters, to provide better swarf clearance, is reduced, improving in-cut and tool changing times.

Fixturing of Simpler Design

The many benefits of ultra-high speed machining (force reduction, lower workpiece distortion and so on) combine to allow simpler and cheaper fixturing. Often all that is necessary are simple base plates for component location and restraint, with the need for costly fixturing only being necessary very occasionally.

It follows that if these are the benefits to be gained when ultra-high speed machining, then there must also be some problems that must be addressed when utilising this technique for milling/drilling on machining centres.

Problems Associated with Ultra-high Speed Milling

In order to gain the significant benefits when milling at ultra-high speed, several problems not associated with conventional rotational speeds must be overcome:

machine tool's accuracy and rigidity
cutting spindle performance
tool holder and cutter design
axis drive control capability
controller processing speed

Machine Tool's Accuracy and Rigidity

With the higher acceleration/deceleration and speed requirements needed to obtain the optimum performance when ultra-high speed milling, there are considerably greater stresses induced into the machine tool's structure. Therefore the machine must be designed to overcome stick/slip problems – giving high acceleration/deceleration response – coupled with higher rigidity and damping capabilities.

Cutting Spindle Performance

Possibly the greatest design problems are naturally associated with the spindle, with these high rotational speeds being fundamental to the success for ultra-high speed milling operations – more will be said on this topic shortly. However, for now it is worth mentioning that the spindle needs to maintain performance for extended times at high speed and critical to its operation is the design of bearings, their pre-load, lubrication, etc. Such a spindle needs to be able to accelerate/decelerate quickly, otherwise the savings will be lost for short cycle operations, whilst transmitting high power, not just at high speed but lower in the range for either drilling/tapping, or face milling operations. Bearings must be such that when they are transmitting high power, the heat generated does not cause thermal instability, which would not only reduce bearing life but influence machining accuracies.

Tool Holder and Cutter Design

As the rotational speed increases the spindle nose taper must be reduced in order to overcome the high cantilevered rotational masses and the centrifugal forces influencing cutter/holder stability. Therefore at just over 20 000 r.p.m. the 40 International (or its equivalent) taper is satisfactory, but when over 30 000 r.p.m. the 30 international taper is preferred and so on; it needs to be of short length whenever possible. Both spindle nose and tool adaptor tapers are made to a tolerance, which in turn can cause a radial out-of-balance, owing to the cutting forces, to occur. Not only will it be necessary to minimise radial out-of-balance effects, but axial balance, along the tool's and adaptor's length, needs to be addressed similarly if the cutting action is not to be de-stabilised during machining. At present, most companies machining at these speeds have only been "single-plane" balancing – for radial balance – whereas "dual-plane" dynamic balancing is the requirement. Such "dual-plane" balanced tooling is very difficult to achieve at present and further work on high-speed dynamic balancing, prior to use on these machines is necessary if their full cutting potential is to be realised. As an example of radial out-of-balance, if a cutter/holder is to be rotated at about 25 000 r.p.m., then only several micrometres of radial motion can be tolerated, otherwise it becomes unbalanced. Yet another problem occurs at high rotational speeds – the spindle nose taper swells owing to centrifugal force and Z-axis positioning is influenced as the cutter body is pulled back by the draw-bar. Not only is out-of-balance a product of rotational speed, cutter balancing and its fit in the spindle nose, but it is also affected by driving dog design, when present. However, this is outside the remit of the current discussion.

Axis Drive Control Capability

We have seen in section 1.5, Volume III on "High speed milling fundamentals", that servo-lag can cause geometric and linear errors in our workpiece. These are not too great a problem for general machining tolerances at conventional speeds, but become very significant as part accuracy increases and are further exacerbated by fast feedrates associated with ultra-high speed machining applications. Block "look-ahead" capabilities approaching 64 blocks are desirable here to maintain appropriate control.

Controller Processing Speed

What was said about ultra-high speed milling in the previous statement is equally true for processing speed when machining with fast feedrates (see section 1.5, Volume II).

Not only should the "look-ahead" capability of the controller be enhanced, but the processing speed should ideally be in the region of 2–8 ms in order to minimise potential "data starvation", which causes hesitation in cutter/slideway response.

By now the reader should have gained an appreciation of not only the benefits to be gained from utilising machine tools equipped for ultra-high speed milling applications, but some of the problems that need to be addressed by both the builder and

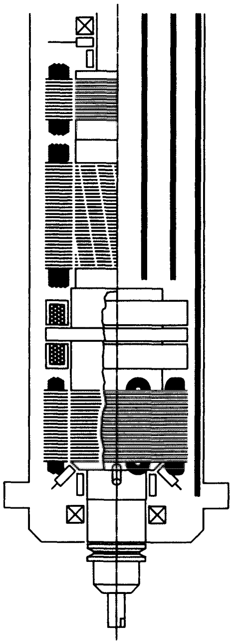


Fig. 2.24. Ultra-fast high-frequency spindles with "active" magnetic bearings. 80 000 min^{-1}, 10 kW, SKI 25; 60 000 min^{-1}, 20 kW, SKI 30; 40 000 min^{-1}, 40 kW, SKI 40. [Courtesy of Rudolfe Carne Ltd/IBAG.]

tooling supplier. In the following pages, let us look at two potential direct-drive spindles currently available, that could be fitted for such work:

magnetic "active" spindles
pneumatic spindles

Magnetic "Active" Spindles

Once ball bearings reach an upper velocity of 80 m/s they tend to lose contact with the journal's wall and begin to skid, which means they rapidly wear out, owing to a combination of factors: centrifugal force, frictional effects and roundness modifications. Under such high rotational speeds, magnetic bearings become a viable alternative, as not only can they be used at ultra-high rotations, but, owing to their design, the power is available for lower speed milling applications. A typical magnetic bearing spindle is shown in Fig. 2.24 and has a speed range of 4000–40 000 r.p.m., delivering 40 kW continuous power, with a peak power of 52 kW, being assembled into a 200 mm diameter housing. The spindle was jointly developed between the company and Zurich University and has two radial and one bi-directional axial magnetic type bearings, with the high-frequency motor located about midway along the spindle housing. The bearing system is active, with the spindle position being maintained within 1 μm maximum run-out by digital control of the current to the magnets – initiated by radial and axial sensors which monitor position 10 000 times a second.

Under normal operation, the bearing control centralises the shaft prior to rotation, then continues to compute the necessary magnet current values until rotation ceases.

Table 2.3.

Machining data	Conventional spindle	Active magnetic bearing HF spindle
Rev/min (max)	6 000	40 000
Feedrate (mm/min)	2 400	10 000
Stock removal (cm^3/min)	480	2 000
	Costs (in $)	
CNC machine	600 000	600 000
Additional spindle	–	150 000
Labour costs (5 years): 10 000 h @ $50/h	500 000	500 000
Machine + labour cost	1 100 000	1 250 000
Cost per hour	110	125
Amortisation cost for 1000 cm^3 stock removal ($)	3.82	1.04
Overall saving	–	72.8%

In the event of a malfunction, two small angular contact "catch" bearings – 0.2 mm clear of the shaft – provide emergency support. To maintain control of the spindle at all times requires an: electrical/electronic frequency converter for the high-frequency spindle drive; water tanks, pumps and heat exchanger for spindle jacket cooling, pneumatic filter regulator for hydropneumatic tool clamping; spray coolant and filtration system and finally, a separate electronic regulation and computer unit.

In order to minimise the tool balancing problem (alluded to earlier) at high rotational speed, a taper/contact face system was developed. This tool holding system utilises a Belleville spring tensioned drawbolt which engages the holder bringing it into the taper and, as it does so, a small elastic distortion of the spindle nose housing allows the toolholder shoulder contact.

Although these spindles cost approximately double the conventional ball bearing models, the real savings can be appreciated in Table 2.3 for a comparison of milling aluminium with a solid carbide cutter, 20 mm diameter having two flutes, with a depth of cut 10 mm and a feed per tooth of 0.2 mm.

Pneumatic Spindles

The air-lubricated bearing has been with us for some time and new applications are being identified as these bearings become more widely known and understood. In principle, the nature of an aerostatic bearing consists of a cylindrical bush having two rows of gas feed holes spaced evenly around the bearing circumference. The bearing is surrounded by a reservoir, into which gas is fed at pressure. The bearing carries a cylindrical shaft and, in operation, gas flows from the reservoir through the feed holes into an angular space between the shaft and bushing. From here, it flows axially (see Fig. 2.25b), escaping to atmosphere from the ends of the bearing. The pressure falls as the gas flows through the feed holes and enters the bearing clearance. It falls still further, as the gas flows towards the ends of the bearing, before finally exhausting to air. If we assume the condition of a weightless shaft occurs, then it will float concentrically within the bearing and all pressure forces will balance.

When a load is applied to the shaft, then the clearance between the shaft and the bushing diminishes in the direction of the load. The effect of this change in clearance is to increase the resistance to air flow at the zone of smallest clearance, resulting in an increase in air pressure. Conversely, where the clearance has increased, then the resistance to flow is diminished and the pressure falls. Thus a new equilibrium position is established, where the pressure difference across the shaft balances the applied load.

The aerodynamic bearing is capable of generating the necessary load balancing forces within itself, by virtue of rotation alone, enabling the bearing system to operate without the need for an external pressure supply, thus offering the potential for air-lubricated bearings without external air supply.

The hybrid bearing is basically an aerostatic bearing where advantage is taken of the inherent self-generating load capacity of the aerodynamic bearing. Therefore, we thus have an aerostatic bearing which, when operating at the design speed, can have between two to three times the static load capacity. Such characteristics are of particular significance if they are to be used for ultra-high speed machining spindles.

Typically, in Fig. 2.25a, can be seen an aerodynamic thrust bearing with spiral grooves and a commercially available spindle might offer the following benefits:

high rotational speeds – 10 000–30 000 r.p.m.

powerful electric motor – 15.5 kW at 30 000 r.p.m.

large bearing load capacities – these increase dramatically with speed for high table feed rates

low vibration and high bearing stiffness, offering excellent surface finish

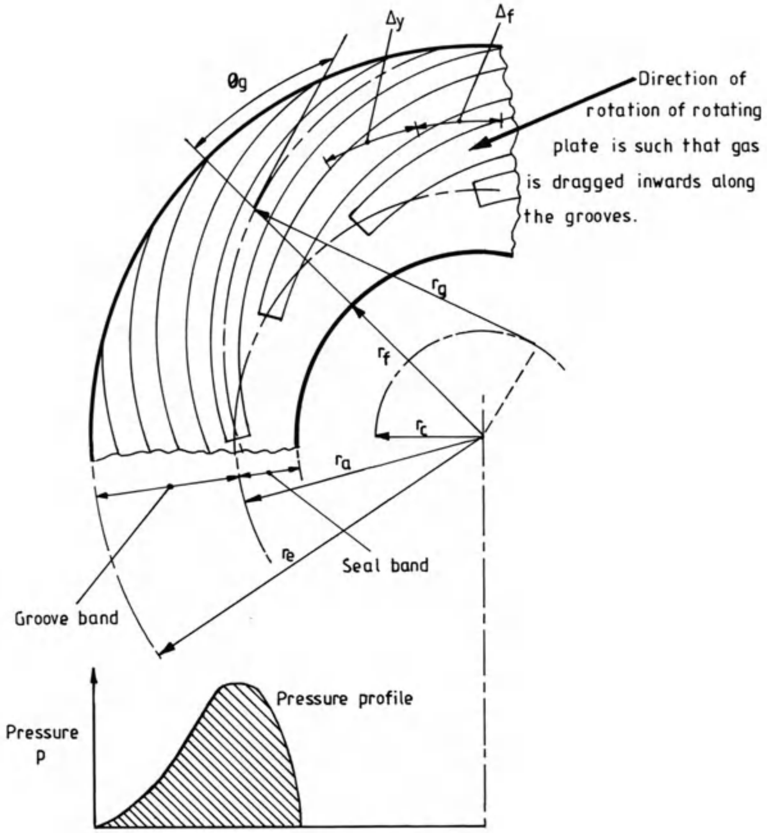
minimal maintenance and indefinite working life – owing to non-contacting rotational parts

The future of ultra-high speed machining will allow us to approach the theoretical optimum cutting volume for, say, high-grade aluminium. This means that it should be possible to remove stock up to 120 cm^3/min/kW. Currently, the best machine tools can mill at around 73 cm^3/kW and shortly one Japanese machine tool manufacturer will be achieving stock removal rates of 80 cm^3/kW at 40 000 r.p.m. So, in summary, we can say that "true" high speed machining is now a practical reality for machining non-ferrous and many non-metallic materials and work is continuing in the development of cutting steels and more exotic materials for the aerospace industries.

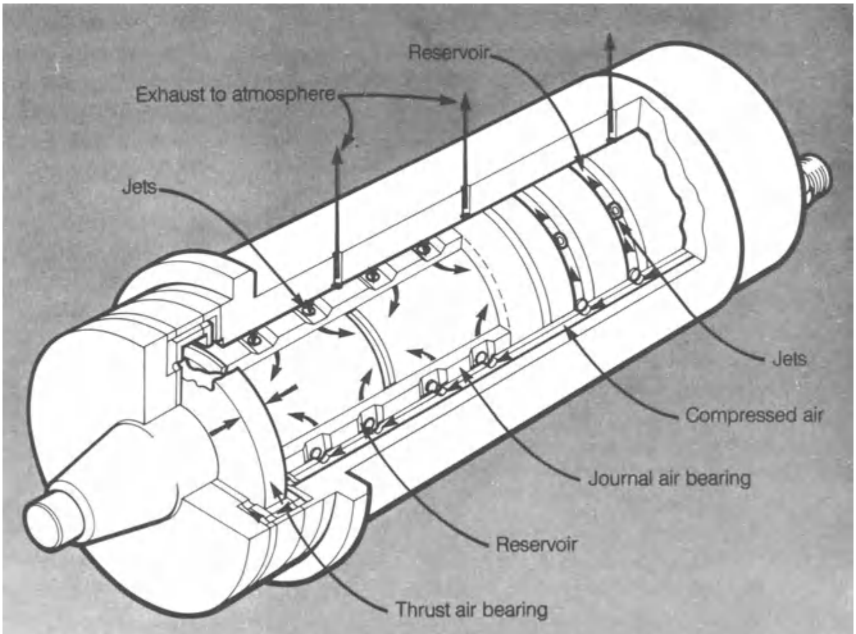
2.8.3 Higher Accuracy on Turning Centres Using Direct Drive Spindles

With the continuing development in machining centre spindles, for greater speed, accuracy, thermal stability, damping capacity and so on, there has been a similar advance in the latest turning centre headstocks. Direct-driven headstocks are now beginning to appear on the more advanced machines (typical of such a headstock is that depicted in Fig. 2.26a) as their belt-driven cousins are now beginning to "show their age". Just why these direct-drive headstocks are replacing the traditional belt-driven varieties can be seen in Fig. 2.26b, where the combination of spindle motor plus drive (belts) cause an undulating and irregular harmonic rotational motion. The influence of this irregular harmonic belt-driven rotation can be appreciated by the schematic representation in Fig. 2.26c, where a tumbling three-lobed-harmonic-shape is reproduced on the workpiece by the action of the headstock's rotation and the linear motion of the cutting tool.

In Fig. 2.26d, there is virtually no harmonic influence on the workpiece using a direct-drive spindle and a much more consistent part results, in terms of both its geometrical and linear dimensions. Yet other benefits accrue when using direct-drive



a



Showing the basic principles of an air lubricated bearing indicating the airflow.

c

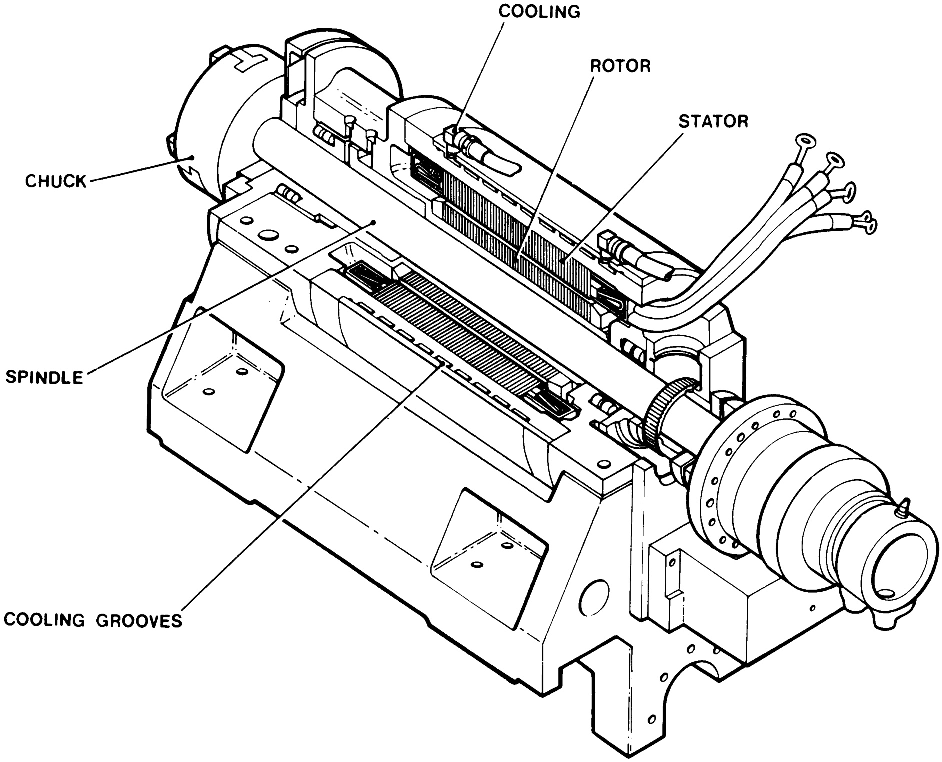
Fig. 2.25. Details of air-driven high-speed spindles used in milling applications. **a** A typical aerodynamic thrust bearing with spiral grooves. Air is dragged into the grooves by virtue of the relative motion of the plates and a pressure rise is caused by the restriction of the sealing band with consequent load generation. **b** A cutaway diagram of an air-driven spindle. **c** An ultra-high speed milling operation on an aluminium component. [Courtesy of Westwind Air Bearings Ltd.]

spindles, which include lower maintenance (no belt-tensioning problems and a more uniform load on the bearings), better thermal growth characteristics, higher spindle accuracy and improved damping.

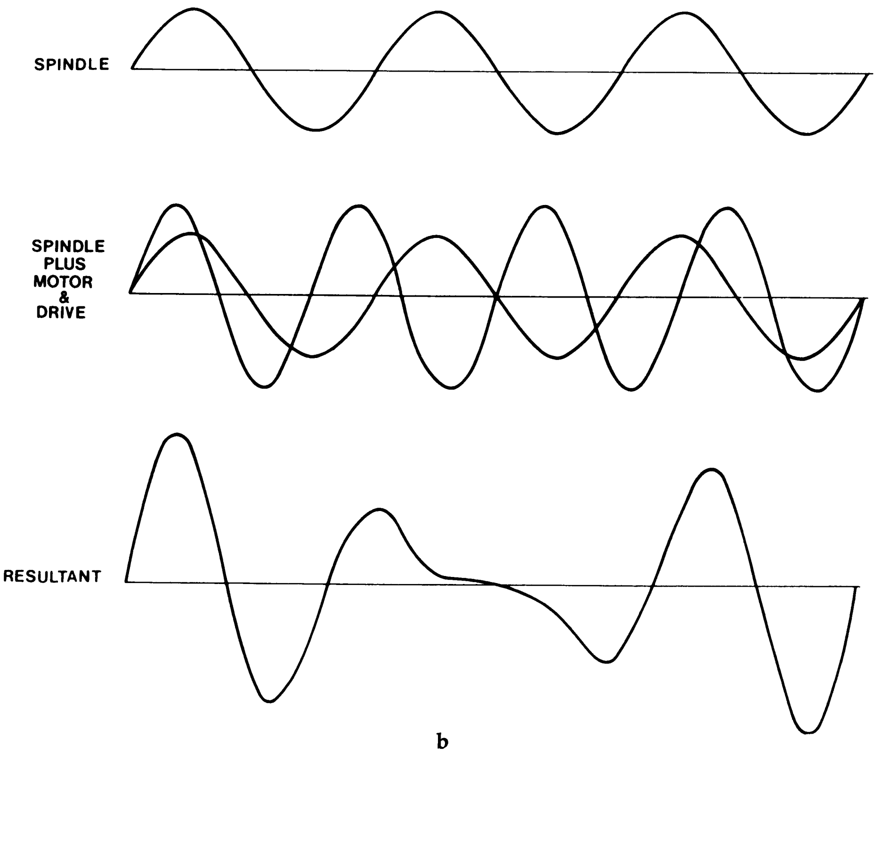
2.8.4 Diamond Turning and Machining – for Ultra-high Accuracy, Precision and Surface Finish

In recent years there has been pressure to achieve not only consistent dimensional and geometrical tolerances on high precision parts, but also superior surface finishes. Probably the "driving force" behind this development has been the optical industry, where diamond-lapped surface configurations used to take days, if not months, for the large monolithic mirrors used in the optical industry, or for astronomical telescopes. With the advent of diamond machining techniques, such large removal of stock, via coarse lapping, has been virtually eliminated, as these machine tools can generate a very close approximation to the tenths of wavelengths of light configurations needed in the final optical product. Hence, finish lapping with micron/submicron diamond pastes is all that is required to complete the product to its best optical configuration.

Not only is the optical industry in need of faster methods of production, but other exacting precision parts (of diverse shape, size and complexity) requiring superior finishes are being demanded by industry.


COOLING
ROTOR
STATOR
CHUCK
SPINDLE
COOLING GROOVES

a


SPINDLE
SPINDLE PLUS MOTOR & DRIVE
RESULTANT

b

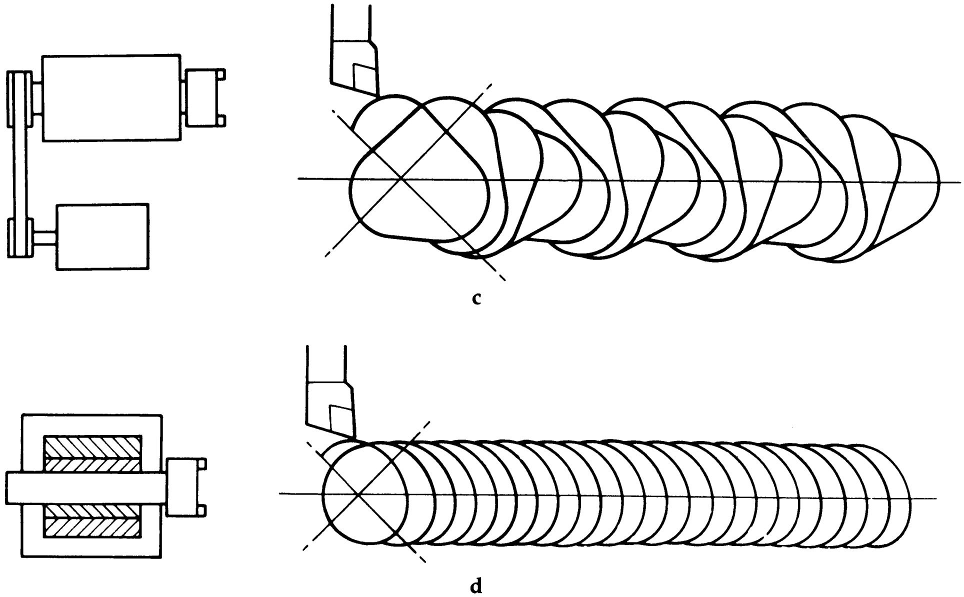


Fig. 2.26. The component quality is improved by using direct-drive spindles, rather than belt-driven headstocks on turning centres. **a** Direct-drive spindle cartridge for a turning centre. **b** The sinusoidal influence of component elements on a belt-driven headstock. **c** The harmonic effect of a belt-driven headstock on a turned component. **d** The harmonics virtually disappear on the component when direct-drive spindles are utilised. [Courtesy of Yamazaki Mazak Ltd.]

Diamond Turning Machines

The inherent hardness of many of the components machined on diamond turning lathes has, in the past, meant that natural industrial diamond tooling had to be used. Such tooling meant that the machine tool had to be inherently very rigid, with no play in the bearings, whilst offering high damping capacity, otherwise the tooling would easily fracture along its planes of weakness. Such "build philosophy" has been carried over to the latest diamond turning machines, despite the fact that often synthetic polycrystalline diamond (PCD) tooling can be utilised.

In a typical example where chucking tends to be simple, the part is often held in situ by pneumatic application. This type of machine has relatively unsophisticated tooling requirements and the main attention is placed upon a very high precision headstock and rigid bed, coupled with high resolution axes control. Obviously, a CNC controller is used to generate the necessary tool vectors for machining the part and a "direct" closed-loop laser-controlled positional feedback system is fitted to accurately monitor axis slideway motion.

Recently, a cutting tool company in Indianapolis, USA, has been producing some of the most accurate tool nose geometries, based upon chemically machining synthetic diamond cutting tools. In the past, most diamond tooling has been abraded away to form the correct tool geometry, and this was acceptable when one was prepared to spend time diamond lapping the surface profile to the correct configuration. However, as companies are demanding faster production and throughput of diamond machined parts, this has meant that post-machining operations must be kept to a minimum. The

Fig. 2.27. Possibly the most accurate and advanced diamond turning/grinding centre at present available. [Courtesy of CUPE Ltd.]

problem with conventionally abrading the diamond tooling to obtain the desired geometry, has meant that the irregular form of the tool nose radius has, when cutting, produced scratches in the surface of the component that need to be polished out later. The technique of chemically machining the edge away – by automatically removing the tool's surface atom-by-atom exposing an ultra-smooth planar face that is substantially co-planer with the naturally occurring crystal plane within the crystalline structure of the diamond – produces a super-smooth cutting tool edge which, when magnified optically ×10 000 still looks smooth. When machining this molecular-level chemically machined tool profile, significant savings in post-machining finishing are offered and will become more important as diamond machining applications expand.

Fig. 2.27 shows possibly the ultimate in advanced machine tool design in terms of diamond turning and grinding capacity currently available today. Let us look in some detail at what makes this machine tool so special. It has a three-axis CNC controller, using a "T-type" base and bridge construction, providing high loop stiffness between the tool and workpiece. The "T-base" is constructed from Granitan S100, giving excellent stiffness and high damping characteristics. Vibrations are minimised by supporting the base on a three point, self-levelling pneumatic vibration isolation system. The work spindle is built into the bridge carriage, which moves at 90° to the spindle axis and the toolpost is mounted on a separate carriage moving parallel to the spindle axis.

Carriage ways utilise hydrostatic bearings providing smooth motion with good damping, high stiffness and load carrying capacity, with freedom from "slip-stick" – essential requirements when servo positioning slides down to 1.2 nm. Oil temperature is controlled to 0.01 °C, ensuring thermal stability of the machine. The drive systems to both carriages incorporate direct drive frameless d.c. torque motor/tachogenerators mounted directly. Linear displacement for each axis is via laser interferometry (based upon heterodyne interferometry) with He–Ne lasers and the total system has been designed to minimise Abbé offset errors. The environmental effects on the laser path are corrected by an optical wavelength compensator, built into the system.

The workspindle is an oil hydrostatic bearing type, designed for high stiffness and low error motion. Once again, thermal stability is maintained through careful material selection and construction, coupled with oil temperature control to ±0.1 °C. The spindle is driven by a high performance brushless d.c. motor, directly mounted onto the spindle, with rotary encoder for fast tool servo applications; a stepless variable speed with bi-directional motion, having dynamic balancing capacity, vacuum work-holding and a temperature-controlled drive motor is utilised.

The B-axis rotary table allows the cutting tool tip to always be at a tangent to the surface being cut, i.e. normal to the cutting surface. Having the tool at such an orientation to the part eliminates errors due to tool tip irregularities. To maximise tool life, the B-axis can present an unused portion of the tool tip (by a small angular offset), furthermore, permitting versatility when machining Fresnel optics, as well as allowing the table to be indexed for the fly-cutting of optical polygons. The table is supported by hydrostatic bearings and a direct-drive frameless d.c. torque motor/tachogenerator is mounted directly onto the table with a rotary encoder.

A critical element on a diamond turning machine is the toolholder, with the tools having an 8 × 8 mm cross-section tool shank, closely supported to minimise tool overhang and improve rigidity. Tool setting is by a "station" located to the right-hand side of the workhead and utilises two air-bearing Linear Variable Differential Transformers (LVDT) gauge heads – one to determine the X-offset and the other the Z-offset for height adjustment. Tool setting is a fully automated function under CNC control and can be initiated at any time during machining. Later, a non-contacting optical tool setting station will be available for this machine tool.

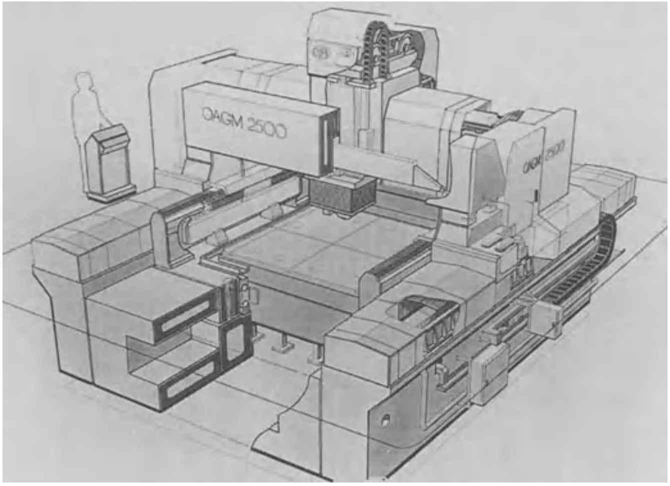
The machine utilises one of the most advanced CNC systems with its "electronic gearbox" capability, ensuring "zero following error" performance. The controller offers exceptional tool path accuracy by virtue of its unique high resolution, fast feed forward techniques – eliminating servo following errors. Yet another unusual feature of this controller is its on-line cubic spline interpolation facility. This allows data of the path definition to be input by either the equation of shape for the component surface – entered at the operator's control panel, or via a personal computer – or using the minimum number of datapoints. Both techniques eliminate the need for conventional post-processing of data. Other features available with this CNC include:

software error compensation
- tool error mapping
- error compensation for: B-axis, rotary motion and scale error
- volumetric error compensation for: cubic lattice and parametric errors

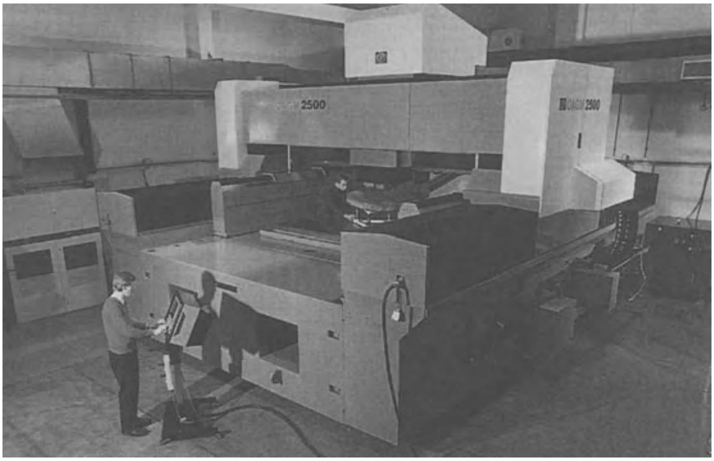
dynamic error compensation
- thermal growth, e.g. in spindle
- refractive index. e.g. laser interferometry
- fast tool servos
- metrology frame methods (see final section in book)

diagnostics
- fault indication
- performance monitoring for safety

Finally, let us turn our attention to possibly the most expensive and accurate machine tool ever made, utilising the latest trends in machine tool technology.



a



b

Fig. 2.28. The most sophisticated machine tool currently available with the ability to machine optical curvatures on large monolithic mirror blanks. There is an in-situ interferometric probe used adjacent to the spindle for surface evaluation. **a** A sectional diagram illustrating the major elements in the 3-axis machine tool. **b** The large Granitan structure with ultra-precise straight edge ways. The machine incorporates laser-controlled slideways and hydrostatic bearings. [Courtesy of CUPE Ltd.]

Diamond Machining for Optical Components

In recent years, the design trends in large optics – the most accurate/precise components currently manufactured – have progressed towards systems incorporating large, off-axis, aspheric optical elements. Such segments can be used in groups forming a single large parent optical surface. These segmented mirrors have found applications in space where it is possible to launch a folded mirror array, then deploying it providing a reflector larger than the diameter of its launch vehicle.

The machine tool shown schematically in Fig. 2.28a and actually in Fig. 2.28b, has been designed and built in the UK to generate and measure off-axis elements prior to final polishing. This machine tool weighs approximately 130 tonnes, having a component capacity of 2.5 m × 2.5 m × 0.6 m, but its overall length being 8 m × 6 m × 5 m. An advanced three-axis CNC controller is used together with an in-situ probe; also incorporated is a multiple path laser interferometer system to achieve the required component quality.

This machine tool incorporates polystyrene cores surrounded by Granitan S100 structure, suitably supported by light steel weldments, offering high stability and internal damping. The base is made in four sections, each weighing approximately 17 tonnes, with outer guideway members mounted on either side of the two centre spacing sections. To ensure precise re-assembly in the USA (Kodak), the base unit mounting faces were scraped flat. A 2.5 m × 2.5 m cast iron worktable was kinematically mounted onto the base structure in such a manner that any deflections caused by gantry motions did not produce table distortion. Weight relieving systems were fitted to minimise excessive loading on the kinematic location positions. The surrounding metrology frame was kinematically connected to the worktable – with its own weight relieving systems. The table and metrology frame were designed to compensate for thermal changes in the structure and were closely linked to the fabricated optical reference flats (Corning ULE 7971 titanium silicate material) in the metrology frame; each reference flat being 2.75 m × 0.3 m × 0.1 m. The travelling gantry – Granitan filled weldments – carried the spindle and in-situ metrology system.

Torque motor DC drives on the X and Y axes were by traction–friction, with each drive unit being mounted directly, driving a "vee" roller which in turn operated against a rigid circular section drive bar. Sagging of the drive bar was prevented by spring-loaded devices positioned at intervals along its length. Slippage of the gantry (caused by machining forces or acceleration) was prevented using a preloaded roller, providing sufficient force to maintain the drive rollers in contact with each traction bar at all times. The shorter Z-axis was controlled via the conventional ballscrew system, but with a backlash-free non-influencing nut. The ballscrew had a directly mounted d.c. torque motor which was mechanically counterbalanced.

To obtain the desired accuracy and resolution for each axis motion, the reference measurement system was via the "metrology frame concept" – this being utilised in the past on a number of high-precision machines. The basic reference frame is by three precision glass reference bars, principally for the control of the Z-axis. In practice, two reference bars are mounted either side of the worktable in the X-direction, which are nominally parallel and coplanar to the table. The third reference bar is mounted above and at right angles to the "X-bars", forming the reference for motions in the Y-direction, but all are mounted at the "Airy points", providing, in this case, the "points of minimum deflection" required for straight edges. In order to control the machine to the desired accuracy/precision, a built-in multi-path laser interferometer system is provided. Using three lasers and associated optics, the output beam is split three ways providing a comprehensive monitoring system for each axis. Furthermore, if any changes in environmental conditions occur such as temperature/humidity, these are immediately detected and compensation is actioned automatically. The laser resolution is to 2.5 nm across the volumetric envelope of the machine tool.

The in-situ gauging head alluded to earlier, can be used for the in-process inspection of any large three-dimensional optical elements. The form of the surface profile can be determined from the vertically acting measuring probe mounted adjacent to the spindle. The workpiece's optical surface can be completely scanned, providing a global evaluation of the machined surface. Surface data can be analysed using proprietary interferometry evaluation software developed by Kodak. The retractable probe can be sealed in a protective housing during machining operations. The probe's contact stylus is manufactured from "Zerodur" – having virtually a zero coefficient of linear expansion – which minimises errors caused by thermal changes. This probe's spindle is carried in an externally pressurised air-bearing, with a suitable counter-balance system providing a low and adjustable contact force. A retro-reflector referencing the Y-references straight-edge in conjunction with suitable optics, performs the vertical (Z) displacement measurement function. In order that the Z-axis can stay within the small stroke of the probe, the Z-axis slideway is under servo-control and caused to operate such that the null-seeking feedback device built into the probe is kept centralised. Additionally, small movements of the stylus (up to 4 mm) can be performed by means of bias coils, electrically operated and built into the probe body.

Owing to the high loads carried by the larger moving members of this machine tool, they have their carriage bearings of fluid film – X and Y axes utilise hydrostatic bearings fed by temperature controlled oil, whereas the Z-axis bearings are aerostatic. The collection and return of the exhaust oil from the bearings is filtered and temperature controlled to ±0.1 °C, prior to recycling back to the hydrostatic bearings. Total oil flow is very low for the X and Y axes (1.6 l/min with nominal separation gaps being 25 nm). Typical vertical stiffness of each X-axis guideway is 9500 N/μm and horizontaly 8000 N/μm, with the Y-axis values being approximately half those of "X".

At present this machine tool utilises an air-bearing grinding spindle, operating at 3000 r.p.m. (electrically powered), but it would be quite feasible to use PCD rotating tooling on such a machine in a similar fashion to that described for the diamond turning lathe (Fig. 2.27).

What the reader should be able to appreciate by now, is that machine tools are approaching the absolute limits of accuracy/precision available either today, or for some considerable time in the future. They are operating in cutting environments which until recently were the domain of metrology instruments – in terms of workpiece resolution; meaning that not only are the part's qualities (dimensional and geometric features) influenced by the design, build and calibration procedures adopted on the machine (frequent calibration) but also its operating environment: temperature/humidity control, together with isolated and deep foundations. The general approach today is for greater and more consistent part quality on turning and machining centres in industry and this book has attempted to follow the latest trends in terms of advances in machine tools, cutting tool technology, workholding technology and cutting fluids.

Appendix

National and International Machine Tool Standards

Determination of Accuracy and Repeatability of Positioning of CNC Machine Tools

Date of issue	*Standard*	*Country of origin*
1972	NMTBA	USA
1977	VDI/DGQ 3441	Germany
1985	BS 4656: PART 16	Great Britain
1987	BS 4656: PART 16 (AMENDED)	Great Britain
1988	ISO 230-2	International
1991	BS 3800: PART 2	Great Britain

BS3800: General Tests for Machine Tools

PART 1: 1990 Code of practice for testing geometric accuracy of machines operating under no load, or finishing operations;
- geometric and practical test methods,
- definitions,
- use of checking instruments,
- explanation of tolerances,
- description of preliminary checking operations,
- description of accuracy of instruments required.

PART 2: 1991 Statistical methods for determination of accuracy and repeatability of machine tool;
- linear and rotary positioning errors applied to CNC machine tools,
- angular (pitch, yaw and roll) and straightness positioning errors applied to CNC and manually controlled machine tools.

PART 3: 1990 Method of testing performance of machines operating under loaded conditions in respect of thermal distortions;
- thermal distortion of structure,
- thermal drift of axis drives.

Glossary of Terms

A

A AXIS – The axis of rotary motion of a machine tool member or slide about the X axis.

ABSOLUTE ACCURACY – Accuracy as measured from a reference which must be specified.

ABSOLUTE DIMENSION – A dimension expressed with respect to the initial zero point of a coordinate axis.

ABSOLUTE POINT (Robots) – Equivalent to absolute coordinates in NC machines. The coordinates of a data point are defined in relation to an absolute zero.

ABSOLUTE PROGRAMMING – Programming using words indicating absolute dimensions.

ABSOLUTE READOUT – A display of the true slide position as derived from the position commands within the control system.

ABSOLUTE SYSTEM – NC system in which all positional dimensions, both input and feedback, are measured from a fixed point of origin.

ACCANDEC – (Acceleration and deceleration) Acceleration and deceleration in feedrate; it provides smooth starts and stops when operating under NC and when changing from one feedrate value to another.

ACCEPTANCE TEST – A series of tests which evaluate the performance and capabilities of both software and hardware.

ACCESS TIME – The time interval between the instant at which information is: 1. called for from storage and the instant at which delivery is completed, i.e., the read time; 2. ready for storage and the instant at which storage is completed, i.e., the write time.

ACCUMULATOR – A part of the logical arithmetic unit for a computer. It may be used for intermediate storage to form algebraic sums, or for other intermediate operations.

ACCURACY – 1. Measured by the difference between the actual position of the machine slide and the position demanded. 2. Conformity of an indicated value to a true value, i.e., an actual or an accepted standard value. The accuracy of a control system is expressed as the deviation or difference between the ultimately controlled variable and its ideal value, usually in the steady state or at sampled instants.

ACTIVE CONTROL – A technique of automatically adjusting feeds and/or speeds to an optimum by sensing cutting conditions and acting upon them.

ACTIVE STORAGE – That part of the control logic which holds the information while it is being transformed into motion.

ADDRESS – A character or group of characters at the beginning of a word which identifies the data allowed in the word.

ADDRESS BLOCK FORMAT – A block format in which each word contains an address.

ALGOL – (Algorithmic Language) Language used to develop computer programs by algorithm.

ALGORITHM – A rule or procedure for solving a mathematical problem that frequently involves repetition of an operation.

ALPHANUMERIC or ALPHAMERIC – A system in which the characters used are letters A to Z, and numerals 0 to 9.

ALPHANUMERIC DISPLAY – Equipment, such as a CRT, which is capable of displaying only letters, digits and special characters.

AMPLIFIER – A signal gain device whose output is a function of its input.

AMPLITUDE – Term used to describe the magnitude of a simple wave or simple part of a complex. The largest or crest value measured from zero.

ANALOG – In NC the term applies to a system which utilises electrical voltage magnitudes or ratios to represent physical axis positions.

ANALOG DATA – The information content of an analog signal as conveyed by the value of magnitude of some characteristics of the signal such as the amplitude, phase, or frequency of a voltage, the amplitude or duration of a pulse, the angular position of a shaft, or the pressure of a fluid.

ANALOG SIGNALS – Physical variables (e.g., distance, rotation) represented by electrical signals.

ANALOG-TO-DIGITAL (A/D) CONVERTER – A device that changes physical motion or electrical voltage into digital factors.

AND – A logical operator which has the property such that if X and Y are two logic variables, then the function "X and Y" is defined by the following table:

X	Y	X and Y
0	0	0
0	1	0
1	0	0
1	1	1

The AND operator is usually represented in electrical rotation by a centred dot "·", and in FORTRAN programming notation by an asterisk "*" within a Boolean expression.

AND-GATE – A signal circuit with two or more inputs. The output produces a signal only if all inputs received coincident signals.

APPLICATION PROGRAMS – Computer programs designed and written to value a specific problem.

APT – (Automatically Programmed Tools) A universal computer-assisted program system for multi-axis contouring programming. APT III – Provides for five axes of machine tool motion.

ARC CLOCKWISE – An arc generated by the coordinated motion of two axes in which curvature of the path of the tool with respect to the workpiece is clockwise, when viewing the plane of motion from the positive ddirection of the perpendicular axis.

ARC COUNTERCLOCKWISE – (Substitute "Counterclockwise" for "Clockwise" in "Arc Clockwise" definition.)

ARCHITECTURE – Operating characteristics of a control system, or control unit, or computer.

ASCII – (American Standard Code for Information Interchange) A data transmission code which has been established as an American Standard by the American Standards Association. It is a code in which 7 bits are used to represent each character. (Also USASCII.)

ASSEMBLY – The fitting together of a number of parts to create a complete unit.

ASSEMBLY DRAWING – The drawing of a number of parts which shows how they fit together to construct a complete unit.

ASYNCHRONOUS – Without any regular time relationship.

ASYNCHRONOUS TRANSMISSION – The transmission of information in irregular sections, with the time interval of each transmission varying and each section being identified by a stop and start signal.

ATTRIBUTE – A quality that is characteristic of a subject.

AUTOMATED ASSEMBLY – The application of automation to assembly.

AUTOMATION – The technique of making a process or system automatic. Automatically controlled operation of an apparatus, process, or system, especially by electronic devices. In present day terminology, usually used in relation to a system whereby the electronic device controlling an apparatus or process also is interfaced to and communicates with a computer.

AUXILIARY FUNCTION – A function of a machine other than the control of the coordinates of a workpiece or cutter – usually on–off type operations.

AXIS – 1. A principal direction along which a movement of the tool or workpiece occurs. 2. One of the reference lines of a coordinate system.

AXIS (Robots) – A moving element of a robot or manipulator.

AXIS INHIBIT – Prevents movement of the selected slides with the power on.

AXIS INTERCHANGE – The capability of inputting the information concerning one axis into the storage of another axis.

AXIS INVERSION – The reversal of normal plus and minus values along an axis which makes possible the machining of a left-handed part from right-handed programming or vice-versa. Same as mirror image.

B

B AXIS – The axis of rotary motion of a machine tool member or slide about the Y axis.

BACKGROUND – In computing the execution of low priority work when higher priority work is not using the computer.

BACKGROUND PROCESSING – The automatic execution of computer programs in background.

BACKLASH – A relative movement between interacting mechanical parts, resulting from looseness.

BAND – The range of frequencies between two defined limits.

BASE – A number base. A quantity used implicitly to define some system of representing numbers by positional notation. Radix.

BATCH – A number of items being dealt with as a group.

BATCH PROCESSING – A manufacturing operation in which a specified quantity of material is subject to a series of treatment steps. Also, a mode of computer operations in which each program is completed before the next is started.

BAUD – A unit of signalling speed equal to the number of discrete conditions or signal events per second; 1 bit per second in a train of binary signals, and 3 bits per second in an octal train of signals.

BEHIND THE TAPE READER – A means of inputting data directly into a machine tool control unit from an external source connected behind the tape reader.

BENCHMARK – A standard example against which measurements may be made.

BILL OF MATERIALS – A listing of all the parts that constitute an assembled product.

BINARY – A numbering system based on 2. Only the digits 0 and 1 are used when written.

BINARY CIRCUIT – A circuit which operates in the manner of a switch, that is, it is either "on" or "off".

BINARY CODED DECIMAL (BCD) – A number code in which individual decimal digits are each represented by a group of binary digits; in the 8-4-2-1 BCD notation, each decimal digit is represented by a four-place binary number, weighted in sequence as 8, 4, 2 and 1.

BINARY DIGIT (BIT) – A character used to represent one of the two digits in the binary number system, and the basic unit of information or data storage in a two-state device.

BLOCK – A set of words, characters, digits, or other elements handled as a unit. On a punched tape, it consists of one or more characters or rows across the tape that collectively provide enough information for an operation. A "word" or group of words considered as a unit separated from other such units by an "end of block" character (EOB).

BLOCK DELETE – Permits selected blocks of tape to be ignored by the control system at discretion of the operator with permission of the programmer.

BLOCK DIAGRAM – A chart setting forth the particular sequence of operations to be performed for handling a particular application.

BLOCK FORMAT – The arrangement of the words, characters and data in a block.

BODE DIAGRAM – A plot of log amplitude ratio and phase angle as functions of log frequency, representing a transfer function.

BOOLEAN ALGEBRA – An algebra named after George Boole. This algebra is similar in form to ordinary algebra, but with classes, propositions, yes/no criteria, etc., for variables rather than numeric quantities, it includes the operator's AND, OR, NOT, EXCEPT, IF THEN.

BOOTSTRAP – A short sequence of instructions, which when entered into the computer's programmable memory will operate a device to load the programmable memory with a larger, more sophisticated program – usually a loader program.

BUFFER STORAGE – 1. A place for storing information in a control for anticipated transference to active storage. It enables control system to act immediately on stored information without waiting for the tape reader. 2. A register used for intermediate storage of information in the transfer sequence between the computer's accumulators and a peripheral device.

BUG – An error or mistake.

BULK MEMORY – A high capacity auxiliary data storage device such as a disk or drum.

BUS – A conductor used for transmitting signals or power between elements.

BYTE – A sequence of adjacent bits, usually less than a word, operated on as a unit.

C

C AXIS – The axis of rotary motion of a machine tool member or slide about the Z axis.

CALIBRATION – Adjustment of a device, such that the output is within a specified tolerance for particular values of the input.

CANCEL – A command which will discontinue any canned cycles or sequence commands.

CANNED CYCLE – A preset sequence of events initiated by a single NC command, e.g., G84 for NC tap cycle. Also fixed cycle.

CANONICAL FORM – A standard numerical representation of data.

CATHODE RAY TUBE (CRT) – A display device in which controlled electron beams are used to present alphanumeric or graphical data on a luminescent screen.

CENTRAL PROCESSING UNIT (CPU) – The portion of a computer system consisting of the arithmetic and control units and the working memory.

CHANNEL – A communication path.

CHARACTER – One of a set of symbols. The general term to include all symbols such as alphabetic letters, numerals, punctuation marks, mathematic operators, etc. Also, the coded representation of such symbols.

CHIP – A single piece of silicon which has been cut from a slice by scribing and breaking. It can contain one or more circuits but is packaged as a unit.

CIRCULAR INTERPOLATION – 1. Capability of generating up to 90 degrees of arc using one block of information as defined by EIA. 2. A mode of contouring control which uses the information contained in a single block to produce an arc of a circle.

CLDATA – Cutter location data (see CLFILE).

CLEAR – To erase the contents of a storage device by replacing the contents with blanks or zeros.

CLEARANCE DISTANCE – The distance between the tool and the workpiece when the change is made from rapid approach to feed movement to avoid tool breakage.

CLFILE – Cutter location file (see CLDATA).

CLOCK – A device which generates periodic synchronisation signals.

CLOSED LOOP – A signal path in which outputs are fed back for comparison with desired values to regulate system behaviour.

CNC – Computer (Computerised) Numerical Control – A numerical control system wherein a dedicated, stored program computer is used to perform some or all of the basic numerical control functions.

COMMAND – An operative order which initiates a movement or a function.

COMPATIBILITY – The interchangeability of items.

COMPILER – A program which translates from high-level problem-oriented computer languages to machine-oriented instructions.

COMPONENT – One of the parts of which an entity is composed.

COMPUTER – A device capable of accepting information in the form of signals or symbols, performing prescribed operations on the information, and providing results as outputs.

COMPUTER-AIDED DESIGN (CAD) – A process which uses a computer in the creation or modification of a design.

COMPUTER-AIDED DESIGN/COMPUTER-AIDED MANUFACTURE (CADCAM) – The integration of computer-aided design with computer-aided manufacture.

COMPUTER-AIDED ENGINEERING (CAE) – The use of computing facilities in the integration of all aspects of design and manufacture to create an integrated engineering facility.

COMPUTER-AIDED MANUFACTURE (CAM) – A process which uses a computer in the management, control or operation of a manufacturing facility.

COMPUTER PART PROGRAMMING – The preparation of a part program to obtain a machine program using a computer and appropriate processor and part processor.

CONFIGURATION – The manner in which items are arranged.

CONTINUOUS PATH OPERATION – An operation in which rate and direction of relative movement of machine members is under continuous numerical control. There is no pause for data reading.

CONTOURING – An operation in which simultaneous control of more than one axis is accomplished.

CONTOURING CONTROL SYSTEM – An NC system for controlling a machine (milling, drafting, etc.) in a path resulting from the coordinated, simultaneous motion of 2 or more axes.

CONTROLLED PATH (Robots) – The straight line motion of a defined offset tool point between programmed points. All robot axes are interpolated through the programmed span.

CONTROL TAPE – A tape on which a machine program is recorded.

COORDINATE DIMENSIONING – A system of dimensioning based on a common starting point.

COORDINATE DIMENSIONING WORD – 1. A word in a block of machining information that provides instruction for one of the machine's axes. 2. A word defining an absolute dimension.

CORE MEMORY – A high-speed random access data storage device utilising arrays of magnetic ferrite cores, usually employed as a working computer memory.

CORE RESIDENT – Pivotal programs permanently stored in core memory for frequent execution.

COUNTER – A device or memory location whose value or contents can be incremented or decremented in response to an input signal.

CURSOR – Visual movable pointer used on a CRT by an operator to indicate where corrections or additions are to be made.

CUTTER DIAMETER COMPENSATION – A system in which the programmed path may be altered to allow for the difference between actual and programmed cutter diameters.

CUTTER OFFSET – 1. The distance from the part surface to the axial centre of a cutter. 2. An NC feature which allows an operator to use an oversized or undersized cutter.

CUTTER PATH – The path described by the centre of a cutter.

CYCLE – 1. A sequence of operations that is repeated regularly. 2. The time it takes for one such sequence to occur.

CYCLE TIME – The period required for a complete action. In particular, the interval required for a read and a write operation in working memory, usually taken as a measure of computer speed.

CYCLING CONTROL – A fundamental level machine control which programs the machine through dial or plugboard input.

D

DAMPING – A characteristic built into electrical circuits and mechanical systems to prevent rapid or excessive corrections which might lead to instability or oscillatory conditions.

DATA – Facts or information prepared for processing by, or issued by, a computer.

DATABASE – Comprehensive files of information having a specific structure such that they are suitable for communication, interpretation and processing by both human and automatic means.

DATA POINT – A programmed point which contains tool plant coordinate data and functional information.

DEAD BAND – The range through which an input can be varied without initiating response, usually expressed in percentage of span.

DEAD TIME – The interval between initiation of a stimulus change and the start of the resulting response.

DEAD ZONE – A range of inputs for which no change in output occurs.

DEBUG – To detect, locate, and remove mistakes from computer software or hardware.

DECADE – A group of assembly of ten units.

DECADE SWITCHING – Use of a series of switches each with ten positions with values of 0 to 9, in which adjacent switches have a ratio of value of 10:1.

DECIMAL CODE – A code in which each allowable position has one of 10 possible states. (The conventional decimal number system is a decimal code.)

DECODER – A circuit arrangement which receives and converts digital information from one form to another.

DEDICATED – Devoted to a particular function or purpose.

DEVIATION – The error or difference between the instantaneous value of the controlled variable and the setpoint.

DIAGNOSTIC ROUTINE – A program which locates malfunctions in hardware or software.

DIGITAL – Representation of data in discrete or numerical form.

DIGITAL COMPUTER – A computer that operates on symbols representing data, by performing arithmetic and logic operations.

DIGITAL-TO-ANALOG (D-A) CONVERSION – Production of an analog signal, whose instantaneous magnitude is proportional to the value of a digital input.

DIGITISE – To obtain the digital representation of a measured quantity or continuous signal.

DIRECTOR – A term used to designate an NC control unit.

DISCRETE – State of being separate or distinct, as opposed to a continuously varying state or condition.

DISCRETE COMPONENT CIRCUIT – An electrical circuit, implemented with individual transistors, resistors, diodes, capacitors, or other components.

DISK – A device on which information is stored.

DISK MEMORY – A non-programmable, bulk storage, random access memory consisting of a magnetisable coating on one or both sides of a rotating thin circular plate.

DISPLAY – Lights, annunciators, numerical indicators, or other operator output devices at consoles or remote stations.

DISTRIBUTED COMPUTER NETWORK – A collection of computers which can communicate with each other.

DISTRIBUTED PROCESSING – The processing of information on a distributed computer network in such a manner as to improve the overall efficiency of the task.

DITHER – An electrical oscillatory signal of low amplitude and of a predetermined frequency imparted to a servo valve to keep the spool from sticking.

DNC – (Direct Numerical Control) Numerical control of machining or processing by a computer.

DOCUMENTATION – The group of techniques necessarily used to organise, present, and communicate recorded specialised knowledge.

DOUBLE PRECISION – The use of two computer words to represent a number.

DOWNTIME – The interval during which a device is inoperative.

DRIFT – An undesired change in output over a period of time, which is unrelated to input, operating conditions, or load.

DRIVER – A program or routine that controls external peripheral devices or executes other programs.

DUMP – To copy the present contents of a memory onto a printout or auxiliary storage.

DWELL – A timed delay of programmed or established duration, not cyclic or sequential, i.e., not an interlock or hold.

DYNAMIC GAIN – The magnitude ratio of a steady-state output to a sinusoidal input signal.

E

EBCDIC – Extended binary coded decimal interchange code.

EDIT – To modify a program, or alter stored data prior to output.

EDITOR – A computer program which provides the ability to edit.

EIA STANDARD CODE – Any one of the Electronics Industries Association standard codes for positioning, straight-cut, and contouring control systems.

ELECTROMAGNETIC INTERFERENCE (EMI) – Unwanted electrical energy or noise induced in the circuits of a device, owing to the presence of electromagnetic fields.

EMULATOR – A device or program which behaves like another system, and produces identical results.

ENCODER – An electromechanical transducer which produces a serial or parallel digital indication of mechanical angle or displacement.

END EFFECTOR (Robots) – The general term used to describe a gripper or other tool used on a robot.

END OF BLOCK CHARACTER – 1. A character indicating the end of a block of tape information. Used to stop the tape reader after a block has been read. 2. The typewriter function of the carriage return when preparing machine control tapes.

END OF PROGRAM – **A miscellaneous function (M02)** indicating completion of a workpiece. (Stops spindle, coolant, and feed after completion of all commands in the block. Used to reset control and/or machine.)

END OF TAPE – **A miscellaneous function (M30)** which stops spindle, coolant and feed after completion of all commands in the block. (Used to reset control and/or machine.)

END POINT – An extremity of a span.

ERROR – The difference between the indicated and desired values of a measured signal.

ERROR DETECTING – A data code in which each acceptable term conforms to certain rules, such that if transmission or processing errors occur, false results can be detected.

ERROR SIGNAL – Difference between the output and input signals in a servo system.

EXCLUSIVE OR – A logical operator, which has the property such that if X and Y are two logic variables, then the function is defined by the following table:

X	**Y**	**Function**
0	0	0
0	1	1
1	0	1
1	1	0

The logical operator is usually represented in electrical notation by an encircled plus sign "+". There is no equivalent FORTRAN symbol.

EXECUTE – To carry out an instruction or to run a program.

EXECUTIVE – Software which controls the execution of programs in the computer, based on established priorities and real-time or demand requirements.

EXTENDED ARITHMETIC ELEMENT – A CPU logic element, which provides hardware implemented multiply, divide, and normalise functions.

F

FEEDBACK – The signal or data fed back to a commanding unit from a controlled machine or process to denote its response to the command signal. The signal representing the difference between actual response and desired response that is used by the commanding unit to improve performance of the controlled machine or process.

FEEDBACK CONTROL – Action in which a measured variable is compared to its desired value, with a function of the resulting error signal used as a corrective command.

FEEDBACK DEVICE – An element of a control system which converts linear or rotary motion to an electrical signal for comparison to the input signal, e.g., resolver, encoder, inductosyn.

FEEDBACK LOOP – A closed signal path, in which outputs are compared with desired values to obtain corrective commands.

FEEDBACK RESOLUTION – The smallest increment of dimension that the feedback device can distinguish and reproduce as an electrical output.

FEEDBACK SIGNAL – The measurement signal indicating the value of a directly controlled variable, which is compared with a setpoint to generate a correction command.

FEED ENGAGE POINT – The point where the motion of the Z axis changes from rapid traverse to a programmed feed (usually referred to as the "R" dimension).

FEEDFORWARD (ANTICIPATORY) CONTROL – Action in which information concerning upstream conditions is converted into corrective commands to minimise the effect of the disturbances.

FEED FUNCTION – The relative motion between the tool or instrument and the work due to motion of the programmed axis or axes.

FEEDRATE BY-PASS – A function directing the control system to ignore programmed feedrate and substitute selected operational rate.

FEEDRATE NUMBER – A coded number read from the tape which describes the feedrate function. Usually denoted as the "F" word.

FEEDRATE OVERRIDE – A variable manual control function directing the control system to reduce or increase the programmed feedrate.

FINAL CONTROL ELEMENT – A valve, motor, or other device which directly changes the value of the manipulated variable.

FIRMWARE – Programs or instructions stored in read only memories.

FIRST GENERATION – 1. In the NC industry, the period of technology associated with vacuum tubes and stepping switches. 2. The period of technology in computer design utilising vacuum tubes, electronics, off-line storage on drum or disk, and programming in machine language.

FIXED BLOCK FORMAT – A format in which the number and sequence of **words** and **characters** appearing in successive **blocks** is constant.

FIXED HEADS – Rigidly mounted reading and writing transducers on bulk memory devices.

FIXED SEQUENCE FORMAT – A means of identifying a word by its location in a block of information. Words must be presented in a specific order and all possible words preceding the last desired word must be present in the block.

FLIP FLOP – A bi-stable device. A device capable of assuming two stable states. A bistable device which may assume a given stable state depending upon the pulse history of one or more input points and having one or more output points. The device is capable of storing a bit of information; controlling gates; etc. A toggle.

FLOPPY DISK – A flexible disk used for storing information.

FLOW CHART – A graphical representation of a problem or system in which interconnected symbols are used to represent operations, data, flow, and equipment.

FLUIDICS – The technique of control that uses only a fluid as the controlling medium. All control is performed without moving elements.

FOREGROUND PROCESSING – Execution of real-time or high priority programs, which can pre-empt the use of computing facilities.

FORMAT – The arrangement of data.

FORMAT CLASSIFICATION – A means, usually in an abbreviated notation, by which the motions, dimensional data, type of control system, number of digits, **auxiliary functions**, etc. for a particular system can be denoted.

FORMAT DETAIL – Describes specifically which words of what length are used by a specific system in the **format classification**.

FORTRAN – Acronym for Formula Translator, an algebraic procedure oriented computer language designed to solve arithmetic and logical programs.

FOURTH GENERATION – In the NC industry, the change in technology of control logic to include computer architecture.

FREQUENCY RESPONSE ANALYSIS – A method of analysing systems based on introducing cyclic inputs and measuring the resulting output at various frequencies.

FREQUENCY RESPONSE CHARACTERISTIC – The amplitude and phase relation between steady-state sinusoidal inputs and the resulting sinusoidal outputs.

FULL DUPLEX – Allows the simultaneous transmission of information in both directions.

FULL PROPORTIONAL SERVO – A system with complete proportionality between output and input.

FULL RANGE FLOATING ZERO – A characteristic of a numerical machine tool control permitting the zero point on an axis to be shifted readily over a specified range. The control retains information on the location of "permanent" zero.

G

G CODE – A word addressed by the letter G and followed by a numerical code defining preparatory functions or cycle types in a numerical control system.

GAIN – The ratio of the magnitude of the output of a system with respect to that of the input (the conditions of operation and measurements must be specified, e.g., voltage, current or power).

GATE – A device which blocks or passes a signal depending on the presence or absence of specified input signals.

GAUGE HEIGHT – A predetermined partial retraction point along the Z axis to which the cutter retreats from time to time to allow safe X–Y table travel.

GENERAL PURPOSE COMPUTER – A computer designed and capable of carrying out a wide range of tasks.

GENERAL PURPOSE PROCESSOR – A computer program which carries out computations on the part program and prepares the author location data for a particular part without reference to machines on which it might be made.

GRAPHICS – The use of a computer to interactively create a drawing displayed on a terminal.

GRAY CODE – A binary code, in which successive values differ in one place only.

GROUP TECHNOLOGY – The grouping of machines and of parts based on similarities in production requirements such that the parts may be produced more efficiently.

H

HALF DUPLEX – Allows the transmission of information one way at a time.

HARD COPY – Any form of computer-produced printed document. Also, sometimes punched cards or paper tape.

HARDWARE – Physical equipment.

HEAD – A device, usually a small electromagnet on a storage medium such as magnetic tape or a magnetic drum, that reads, records, or erases information on that medium. The block assembly and perforating or reading fingers used for punching or reading holes in paper tape.

HOUSEKEEPING – The general organisation of programs stored to ensure efficient system response.

HYSTERESIS – The difference between the response of a system to increasing and decreasing signals.

I

IC – Integrated circuit.

INCREMENTAL DIMENSION – A dimension expressed with respect to the preceding point in a sequence of points.

INCREMENTAL FEED – A manual or automatic input of present motion command for a machine axis.

INCREMENTAL PROGRAMMING – Programming using words indicating incremental dimensions.

INCREMENTAL SYSTEM – Control system in which each coordinate or positional dimension is taken from the last position.

INDEXING – Movement of one axis at a time to a precise point from numeric commands.

INDUCTOSYN SCALE – A precision data element for the accurate measurement and control of angles or linear distances, utilising the inductive coupling between conductors separated by a small air gap.

INHIBIT – To prevent an action or acceptance of data by applying an appropriate signal to the appropriate input.

INITIALISE – To cause a program or hardware circuit to return a program, a system, or a hardware device to an original state or to selected points with a computer program.

INPUT – A dependent variable applied to a control unit or system.

INPUT RESOLUTION – The smallest increment of dimension that can be programmed as input to the system.

INSTABILITY – The state or property of a system where there is an output for which there is not corresponding input.

INSTRUCTION – A statement that specifies an operation and the values or locations of its operands.

INSTRUCTION SET – The list of machine language instructions which a computer can perform.

INTEGRATED CIRCUIT (IC) – A combination of interconnected passive and active circuit elements incorporated on a continuous substrate.

INTEGRATOR – A device which integrates an input signal, usually with respect to time.

INTELLIGENT TERMINAL – A terminal which has its own local processing power.

INTERACTIVE GRAPHICS – Ability to carry out graphics tasks with immediate response from the computer.

INTERFACE – 1. A hardware component or circuit for linking two pieces of electrical equipment having separate functions, e.g., tape reader to data processor or control system to machine. 2. A hardware component or circuit for linking the computer to external I/O device.

INTERFEROMETER – An instrument that uses light interference phenomena for determination of wavelength, spectral fine structure, indices of refraction, and very small linear displacements.

INTERLOCK – To arrange the control of machines or devices so that their operation is interdependent in order to assure their proper coordination.

INTERLOCK BY-PASS – A command to temporarily circumvent a normally provided interlock.

INTERPOLATION – 1. The insertion of intermediate information based on assumed order or computation. 2. A function of a control whereby data points are generated between given coordinate positions to allow simultaneous movement of two or more axes of motion in a defined geometric pattern, e.g., linear, circular and parabolic.

INTERPOLATOR – A device which is part of a numerical control system and performs interpolation.

INTERRUPT – A break in the execution of a sequential program or routine, to permit processing of high priority data.

I/O – (Input/Output) Input or output or both.

ITERATION – A set of repetitive computations, in which the output of each step is the input to the next step.

J

JCL – Job control program

JOB – An amount of work to be completed.

JOG – A control function which provides for the momentary operation of a drive for the purpose of accomplishing a small movement of the driven machine.

K

KEYBOARD – The keys of a teletype-writer which have the capability of transmitting information to a computer but not receiving information.

L

LAG – Delay caused by conditions such as capacitance, inertia, resistance or dead time.

LANGUAGE – A set of representations and rules used to convey information.

LAYOUT – A visual representation of a complete physical entity usually to scale.

LEVEL – 1. Formerly a channel of punched tape. 2. The average amplitude of a variable quantity applying particularly to sound or electronic signals expressed in decibels, volts, amperes, or watts. 3. The degree of subordination in a hierarchy.

LIGHT PEN – A photo sensing device similar to an ordinary fountain pen which is used to instruct CRT displays by means of light sensing optics.

LINEAR INTERPOLATION – A function of a control whereby data points are generated between given coordinate positions to allow simultaneous movement of two or more axes of motion in a linear (straight line) path.

LINE PRINTER – A printing device that can print an entire line of characters all at once.

LINKAGE – A means of communicating information from one routine to another.

LOCKOUT SWITCH – A switch provided with a memory, which protects the contents of designated segments from alteration.

LOG – A detailed record of actions for a period of time.

LOG OFF – The completion of a terminal session.

LOG ON – The beginning of a terminal session.

LOGIC – 1. Electronic devices used to govern a particular sequence of operations in a given system. 2. Interrelation or sequence of facts or events when seen as inevitable or predictable.

LOGIC LEVEL – The voltage magnitude associated with signal pulses representing ONES and ZEROS in binary computation.

LOOP TAPE – A short piece of tape, containing a complete program of operation, with the ends joined.

LSI – Large Scale Integration – A large number of interconnected integrated circuits manufactured simultaneously on a single slice of semi-conductor material.

M

MACHINE LANGUAGE – A language written in a series of bits which are understandable by, and therefore instruct, a computer. The "first level" computer language, as compared to a "second level" assembly language or a "third level" compiler language.

MACHINE PROGRAM – An ordered set of instructions in automatic control language and format recorded on appropriate input media and sufficiently complete to effect the direct operation of an automatic control system.

MACHINING CENTRE – A machine tool, usually numerically controlled, capable of automatically drilling, reaming, tapping, milling and boring multiple faces of a part and often equipped with a system for automatically changing cutting tools.

MACRO – A source language instruction from which many machine language instructions can be generated (see compiler language).

MAGNETIC CORE – An element for switching or storing information on magnetic memory elements for later use by a computer.

MAGNETIC CORE STORAGE – The process of storing information on magnet memory elements for later use by a computer.

MAGNETIC DISK STORAGE – A storage device or system consisting of magnetically coated metal disks.

MAINFRAME – See central processing unit.

MANAGEMENT INFORMATION SERVICE (MIS) – An information feedback system from the machine to management and implemented by a computer.

MANUAL DATA INPUT (MDI) – A means of inserting data manually into the control system.

MANUAL FEEDRATE OVERRIDE – Device enabling operator to reduce or increase the feedrate.

MANUAL PART PROGRAMMING – The manual preparation of a manuscript in machine control language and format to define a sequence of commands for use on an NC machine.

MANUSCRIPT – Form used by a part programmer for listing detailed manual or computer part programming instructions.

MEMORY – A device or media used to store information in a form that can be understood by the computer hardware.

MEMORY, BULK – Any non-programmable large memory, i.e., drum, disk.

MEMORY CYCLE TIME – The minimum time between two successive data accesses from a memory.

MEMORY PROTECT – A technique of protecting stored data from alteration, using a guard bit to inhibit the execution of any modification instruction.

MICROPROCESSOR – A single integrated circuit which forms the basic element of a computer.

MICROPROGRAMMING – A programming technique in which multiple instruction operations can be combined for greater speed and more efficient memory use.

MICROSECOND – One millionth of a second.

MILLISECOND – One thousandth of a second.

MISCELLANEOUS FUNCTION – An off–on function of a machine such as Clamp or Coolant on. (See Auxiliary Function).

MNEMONIC – An alphanumeric designation, designed to aid in remembering a memory location or computer operation.

MODEM – A contraction of modulator demodulator. The term may be used with two different meanings: 1. The modulator and the demodulator of a modem are associated at the same end of a circuit. 2. The modulator and the demodulator of a modem are associated at the opposite ends of a circuit to form a channel.

MODULE – An independent unit which may be used on its own or in conjunction with other units to form a complete entity.

MONITOR – A device used for observing or testing the operations of a system.

MOVABLE HEADS – Reading and writing transducers on bulk memory devices which can be positioned over the data locations.

MSI – Medium Scale Integration. (See LSI.) Smaller than LSI, but having at least 12 gates or basic circuits with at least 100 circuit elements.

MULTIPLEXER – A hardware device which handles multiple signals over a single channel.

N

NAND – A combination of the Boolean logic functions NOT and AND.

NAND GATE – A component which implements the NAND function.

NANOSECOND – One thousandth of one microsecond.

NEGATIVE LOGIC – Logic in which the more negative voltage represents the one (1) state; the less negative voltage represents the zero (0) state.

NIXIE LIGHT OR TUBE – A glow lamp which converts a combination of electrical impulses into a visible number.

NOISE – An extraneous signal in an electrical circuit capable of interfering with the desired signal. Loosely, any disturbance tending to interfere with the normal operation of a device or system.

NOR GATE – A component which implements the NOR function.

NOT – A logic operator having property that if P is a logic quantity then quantity "NOT P" assumes values as defined in the following table:

P	**NOT P**
0	1
1	0

The NOT operator is represented in electrical notation by an overline, e.g., $\overline{P}$ and in FORTRAN by a minus sign "–" in a Boolean expression.

NUMERICAL CONTROL (NC) – A technique of operating machine tools or similar equipment, in which motion is developed in response to numerically coded commands.

NUMERICAL DATA – Data in which information is expressed by a set of numbers that can only assume discrete values.

O

OBJECT PROGRAM – The coded output of an assembler or compiler.

OCTAL – A characteristic of a system in which there are eight elements, such as a numbering system with a radix of eight.

OFF-LINE – Operating software or hardware not under the direct control of a central processor, or operations performed while a computer is not monitoring or controlling processes or equipment.

OFFSET – The steady-state deviation of the controlled variable from a fixed setpoint.

ON-LINE – A condition in which equipment or programs are under direct control of a central processor.

ONE – One of the two symbols normally employed in binary arithmetic and logic, indicating binary one and the true condition, respectively.

OPEN LOOP – A signal path without feedback.

OPEN LOOP SYSTEM – A control system that has no means of comparing the output with the input for control purposes (no feedback).

OPERATING SYSTEM – Software which controls the execution of computer programs and the movement of information between peripheral devices.

OPTIMISATION – A process whose object is to make one or more variables assume, in the best possible manner, the value best suited to the operation in hand, dependent on the values of certain other variables which may be either predetermined or sensed during the operation.

OPTIMISE – To establish control parameters which maximise or minimise the value of performance.

OPTIONAL STOP – A Miscellaneous Function command similar to "Program Stop" except that the control ignores the command unless the operator has previously pushed a button to validate the command (M01).

OR – A logic operator having the property that if P and Q are logic quantities then the quantity "P or Q" assumes values as defined by the following table:

P	**Q**	**P OR Q**
0	0	0
0	1	1
1	0	1
1	1	1

The OR operator is represented in both electrical and FORTRAN terminology by a "+", i.e., P + Q.

OR GATE – A device which implements the OR function.

ORIENTATION (Robots) – The angular position of the wrist axes.

OUTPUT – Dependent variable signal produced by a transmitter, control unit or other device.

OUTPUT IMPEDANCE – The impedance presented by a device to the load.

OUTPUT SIGNAL – A signal delivered by a device, element, or system.

OVERLAY – A technique of repeatedly using the same area of computer store when actioning different stages of a problem.

OVERSHOOT – The amount that a controlled variable exceeds its desired value after a change of input.

P

PARABOLA – A plane curve generated by a point moving so that its distance from a fixed second point is equal to its distance from a fixed line.

PARABOLIC INTERPOLATION – Control of cutter path by interpolation between three (3) fixed points by assuming the intermediate points are on a parabola.

PARALLEL – The simultaneous transfer and processing of all bits in a unit of information.

PARAMETER – A characteristic of a system or device, the value of which serves to distinguish various specific states.

PARITY CHECK – A test of whether the number of ONES or ZEROS in an array of binary digits is odd or even to detect errors in a group of bits.

PART PROGRAM – An ordered set of instructions in a language and in a format required to cause operations to be effected under automatic control, which is either written in the form of a machine program on an input media or prepared as input data for processing in a computer to obtain a machine program.

PART PROGRAMMER – A person who prepares the planned sequence of events for the operation of a numerically controlled machine tool.

PASSWORD – A word the operator must supply in order to meet the security requirements and gain access to the computer.

PATCH – Temporary coding used to correct or alter a routine, or a term used in CAD.

PERIPHERAL – Auxiliary equipment used for entering data into or receiving data from a computer.

PERIPHERAL EQUIPMENT – The auxiliary machines and storage devices which may be placed under control of the central computer and may be used on-line or off-line, e.g., card reader and punches, magnetic tape feeds, high speed printers, CRTs and magnetic drums or disks.

PICOSECOND – One millionth of one microsecond.

PITCH (Robots) – A rotation of the payload or tool about a horizontal axis on the end of a robot arm which is perpendicular to the longitudinal axis of the arm.

PLANNING SHEET – A list of operations for the manufacture of a part, prepared before the part program.

PLOTTER – A device used to make a drawing of a display.

POINT-TO-POINT CONTROL SYSTEM – An NC system which controls motion only to reach a given end point but exercises no path control during the transition from one end point to the next.

POLAR AXES – The fixed lines from which the angles made by radius vectors are measured in a polar coordinates system.

POLAR COORDINATES – A mathematical system for locating a point in a plane by the length of its radius vector and the angle this vector makes with a fixed line.

POSITION READOUT – A display of absolute slide position as derived from a position feedback device (transducer usually) normally attached to the lead screw of the machine. (See Command Readout.)

POSITION SENSOR – A device for measuring a position, and converting this measurement into a form convenient for transmission.

POSITION STORAGE – The storage media in an NC system containing the coordinate positions read from tape.

POSITIVE LOGIC – Logic in which the more positive voltage represents the one (1) state.

POST-PROCESSOR – A computer program which adapts the output of a processor into a machine program for the production of a part on a particular combination of machine tool and controller.

PRECISION – The degree of discrimination with which a quantity is stated, e.g., a three-digit numeral discriminates among 1000 possibilities. Precision is contrasted with accuracy, i.e., a quantity expressed with 10 decimal digits of precision may only have one digit of accuracy.

PREPARATORY FUNCTION – An NC command on the input tape changing the mode of operation of the control. (Generally noted at the beginning of a block by "G" plus two digits.)

PREPROCESSOR – A computer program which prepares information for processing.

PREVENTATIVE MAINTENANCE – Maintenance specifically designed to identify potential faults before they occur.

PRINTED CIRCUIT – A circuit for electronic components made by depositing conductive material in continuous paths from terminal to terminal on an insulating surface.

PROCESSOR – A computer program which processes information.

PROGRAM – A plan for the solution of a problem. A complete program includes plans for the transcription of data, coding for the computer, and plans for the absorption of the results into the system. The list of coded instructions is called a routine. To plan a computation or process from the asking of a question to the delivery of the results, including the integration of the operation into an existing system. Thus, programming consists of planning and coding, including numerical analysis, systems analysis, specification of printing formats, and any other functions necessary to the integration of a computer in a system.

PROGRAMMABLE – Capable of being set to operate in a specified manner, or of accepting remote setpoint or other commands.

PROGRAMMED ACCELERATION – A controlled velocity increase to the programmed feedrate of an NC machine.

PROGRAMMED DWELL – The capability of commanding delays in program execution for a programmable length of time.

PROGRAM STOP – A **Miscellaneous Function** (M00) command to stop the spindle, coolant and feed after completion of the dimensional move commanded in the **block**. To continue with the remainder of the program, the operator must initiate a restart.

PROTOCOL – Set of rules governing message exchange between two devices.

PUNCHED PAPER TAPE – A strip of paper on which characters are represented by combinations of holes.

PULSE – A short duration change in the level of a variable.

Q

QUADRANT – Any of the four parts into which a plane is divided by rectangular coordinate axes lying in that plane.

QUADRATURE – Displaced 90 degrees in phase angle.

R

R DIMENSION – (See Feed Engage Point).

RANDOM ACCESS MEMORY (RAM) – A storage unit in which direct access is provided to information, independent of memory location.

RASTER DISPLAY – A display in which the entire display surface is scanned at a constant refresh rate.

RASTER SCAN – Line-by-line sweep across the entire display surface to generate elements of a display image.

READ – To acquire data from a source. To copy, usually from one form of storage to another, particularly from external or secondary storage to internal storage. To sense the meaning of arrangements of hardware. To sense the presence of information on a recording medium.

READER – A device capable of sensing information stored in off-line memory media (cards, paper tape, magnetic tape) and generating equivalent information in an on-line memory device (register, memory locations).

READ ONLY MEMORY (ROM) – A storage device generally used for control program, whose content is not alterable by normal operating procedures.

REAL TIME CLOCK – The circuitry which maintains time for use in program execution and event initiation.

REAL TIME OPERATION – Computer monitoring, control, or processing functions performed at a rate compatible with the operation of physical equipment or processes.

REFERENCE BLOCK – A block within an NC program identified by an "O" or "H" in place of the word address "N" and containing sufficient data to enable resumption of the program following an interruption. (This block should be located at a convenient point in the program which enables the operator to reset and resume operation.)

REFRESH – CRT display technology which requires continuous restroking of the display image.

RELOCATABLE POINT/SEQUENCE OF POINT (Robots) – A point or sequence in a robot which can be relocated in space.

REPAINT – Redraws a display on a CRT to reflect its current status.

REPEATABILITY – The closeness of agreement among multiple measurements of an output, for the same value of the measured signal under the same operating conditions, approaching from the same direction, for full range traverses.

REPRODUCIBILITY – The closeness of agreement among repeated measurements of the output for the same value of input, made under the same operating conditions over a period of time, approaching from either direction.

RESOLUTION – 1. The smallest distinguishable increment into which a signal or picture, etc. is divided in a device or system. 2. The minimum positioning motion which can be specified.

RESOLVER – 1. A mechanical to electrical transducer (see Transducer) whose input is a vector quantity and whose outputs are components of the vector. 2. A transformer whose coupling may be varied by rotating one set of windings relative to another. It consists of a stator and rotor, each having two distributed windings 90 electrical degrees apart.

RETROFIT – Work done to an existing machine tool from simply adding special jigs or fixtures to the complete re-engineering and manufacturing, and often involving the addition of a numerical control system.

ROBOT – An automatic device which performs functions ordinarily ascribed to human beings.

ROLL (Robots) – A rotation of the payload or tool about the longitudinal axis of the wrist.

ROUTINE – A series of computer instructions which performs a specified task.

RUN – The execution of a program on a computer.

S

SAMPLE AND HOLD – A circuit used to increase the interval during which a sampled signal is available, by maintaining an output equal to the most recent input sample.

SAMPLES DATA – Data in which the information content can be, or is, ascertained only at discrete intervals of time. (Can be analog or digital.)

SAMPLING PERIOD – The interval between observations in a periodic sampling control system.

SCALE – To change a quantity by a given factor, to bring its range within prescribed limits.

SCALE FACTOR – A coefficient used to multiply or divide quantities in order to convert them to a given magnitude.

SCHEDULE – A programme or timetable of planned events or of work.

SECOND GENERATION – 1. In the NC industry, the period of technology associated with transistors (solid state). 2. The period of technology in computer design utilising solid-state circuits, off-line storage, and significant development in software, the assembler.

SECURITY – Prevention of unauthorised access to information or programs.

SENSITIVITY – The ratio of a change in steady state output to the corresponding change of input, often measured in percentage of span.

SENSOR – A unit which is actuated by a physical quantity and which gives a signal representing the value of that physical quantity.

SEQUENCE (Robots) – Part of a robot program which consists of a point or series of points the performance of which will be dependent on defined input/flag conditions existing.

SEQUENCE CONTROL – A system of control in which a series of machine movements occurs in a devised order, the completion of one movement initiating the next, and in which the extent of the movements is not specified by numeric data.

SERIAL – The transfer and processing of each bit in a unit of information, one at a time.

SERVO AMPLIFIER – The part of the servo system which increases the error signal and provides the power to drive the machine slides or the servo valve controlling a hydraulic drive.

SETPOINT – The position established by an operator as the starting point for the program on an NC machine.

SIGN – The symbol or bit which distinguishes positive from negative numbers.

SIGNAL – Information conveyed between points in a transmission or control system, usually as a continuous variable.

SIGNIFICANT DIGIT – A digit that contributes to the precision of a numeral. The number of significant digits is counted beginning with the digit contributing the most value, called the most significant digit, and ending with the one contributing the least value, called the least significant digit.

SIMULATOR – A device or computer program that performs simulation.

SKEWING – Refers to time delay or offset between any two signals in relation to each other.

SOFTWARE – The collection of programs, routines, and documents associated with a computer.

SOURCE IMPEDANCE – The impedance presented to the input of a device by the source.

SOURCE LANGUAGE – The symbolic language comprising statements and formulas used to specify computer processing. It is translated into object language by an assembler or compiler, and is more powerful than an assembly language in that it translates one statement into many items (see macro).

STABILITY – Freedom from undesirable deviation, used as a measure of process controllability.

STANDBY POWER SUPPLY – An energy generation or storage system that can permit equipment to operate temporarily or shut down in an orderly manner.

STATIC GAIN – The ratio of steady-state output to input change.

STEADY STATE – A characteristic or condition exhibiting only negligible change over an arbitrarily long period of time.

STEPPING MOTOR – A bi-directional permanent magnet motor which turns in finite steps.

STEP RESPONSE – The time response of an instrument subjected to an instantaneous change in input.

STEP RESPONSE TIME – The time required for an element output to change from an initial value to a specified percentage of a steady state, either before or in the absence of overshoot, after an input step change.

STORAGE – A memory device in which data can be entered and held, and from which it can be retrieved.

STORAGE TUBE – A CRT which retains an image for a considerable period of time without redrawing.

STRAIGHT CUT SYSTEM – A system which has feedrate control only along the axes and can control cutting action only along a path parallel to the linear (or circular) machine ways.

SUB PROGRAM – A segment of a machine program which can be called into effect by the appropriate machine control command.

SUBROUTINE – A series of computer instructions to perform a specific task for many other routines. It is distinguishable from a main routine in that it requires, as one of its parameters, a location specifying where to return to the main program after its function has been accomplished.

SUMMING POINT – A point at which signals are added algebraically.

SYNCHRO – A transformer having a polyphase primary winding and single phase secondary winding which can be rotated. The voltage induced into the secondary may be controlled in phase by turning the secondary coil.

SYNCHRONOUS – A fixed rate transmission of information synchronised by a clock for both receiver and sender.

SYNTAX – The rules which govern the structure of words and expressions in a language.

T

TABLET – An input device which allows digitised coordinates to be indicated by stylus position.

TACHOMETER – A speed measuring instrument generally used to determine revolutions per minute. In NC it is used as a velocity feedback device.

TAPE – A magnetic or perforated paper medium for storing information.

TAPE LEADER – The front or lead portion of a tape.

TAPE PREPARATION – The act of translating command information into punched or magnetic tape.

TAPE TRAILER – The trailing end portion of a tape.

TASK – A unit of work.

TEACH (Robots) – The mode by which a robot is driven to required points in space for programming.

TERMINAL – A device by which information may be entered or extracted from a system or communication network.

THIRD GENERATION – 1. In the NC industry, the period of technology associated with integrated circuits. 2. The period of technology in computer design utilising integrated circuits, core memory, advanced subroutines, time sharing, and fast core access.

THRESHOLD – The minimum value of a signal required for detection.

TIME CONSTANT – For a first order system, the time required for the output to complete 63.2% of the total rise or decay as a result of a step change of the input.

TIME SHARING – The interleaved use of a sequential device, to provide apparently simultaneous service to a number of users.

TOGGLE – A flip-flop or two-position switch.

TOOL CENTRE POINT (Robots) – The real or imaginary offset point defined in relation to the tool mounting plate of a robot which moves in a straight line between programmed points and at the programmed velocity in controlled path machines.

TOOL FUNCTION – A tape command identifying a tool and calling for its selection. The address is normally a "T" word.

TOOL LENGTH COMPENSATION – A manual input means which eliminates the need for preset tooling and allows programmer to program all tools as if they are of equal length.

TOOL OFFSET – 1. A correction for tool position parallel to a controlled axis. 2. The ability to reset tool position manually to compensate for tool wear, finish cuts and tool exchange.

TOOLPATH – The geometry of the path a tool will follow to machine a component.

TOOLPATH FEEDRATE – The velocity, relative to the workpace, of the tool reference point along the author path, usually expressed in units of length per minute or per revolution.

TRACK – The portion of a moving storage medium, such as the drum, tape or disc, that is accessible to a given reading head position.

TRANSFER FUNCTION – An expression relating the output of a linear system to the input.

TRUNCATE – To terminate a computational process in accordance with some rule, e.g., to end the evaluation of a power series at a specified term.

TRUTH TABLE – A matrix that describes a logic function by listing all possible combinations of inputs, and indicating the outputs for each combination.

TUNING – The adjustment of coefficients governing the various modes of control.

TURNING CENTRE – A lathe type numerically controlled machine tool capable of automatically boring, turning outer and inner diameters, threading, facing multiple diameters and faces of a part and often equipped with a system for automatically changing or indexing cutting tools.

TURN KEY SYSTEM – A term applied to an agreement whereby a supplier will install an NC or computer system so that he has total responsibility for building, installing, and testing the system.

V

VARIABLE (Robots) – An ability to count events.

VARIABLE BLOCK FORMAT – Tape format which allows the number of words in successive blocks to vary.

VECTOR – A quantity that has magnitude, direction and sense and that is commonly represented by a directed line segment whose length represents the magnitude and whose orientation in space represents the direction.

VECTOR FEEDRATE – The resultant feedrate which a cutter or tool moves with respect to the work surface. The individual slides may move slower or faster than the programmed rate; but the resultant movement is equal to the programmed rate.

VOLATILE STORAGE – A memory in which data can only be retained while power is being applied.

W

WINDUP – Lost motion in a mechanical system which is proportional to the force or torque applied.

WIRE-FRAME – A 3-dimensional drawing created by the projection of the points of intersection of the geometry.

WORD ADDRESS FORMAT – Addressing each word in a block by one or more characters which identify the meaning of the word.

WORD LENGTH – The number of bits or characters in a word.

WORLD COORDINATES (Robots) – The coordinate system by which a point in space is defined in three cartesian coordinates and three orientation or polar coordinates.

WRIST (Robots) – The element of a robot which applies orientation to a tool.

X

X AXIS – Axis of motion that is always horizontal and parallel to the work-holding surface.

Y

Y AXIS – Axis of motion that is perpendicular to both the X and Z axes.

YAW (Robots) – A rotation of a payload or tool about a vertical axis that is perpendicular to the pitch axis of the wrist.

Z

Z AXIS – Axis of motion that is always parallel to the principal spindle of the machine.

ZERO – One of the two symbols normally employed in binary arithmetic and logic, indicating the value zero and the false condition, respectively.

ZERO OFFSET – A characteristic of a numerical machine tool control permitting the zero point on an axis to be shifted readily over a specified range. (The control retains information on the location of the "permanent" zero.)

ZERO SHIFT – A characteristic of a numerical machine tool control permitting the zero point on an axis to be shifted readily over a specified range. (The control does **not** retain information on the location of the "permanent" zero.)

ZERO SUPPRESSION – The elimination of non-significant zeros to the left of significant digits usually before printing.

ZERO SYNCHRONISATION – A technique which permits automatic recovery of a precise position after the machine axis has been approximately positioned by manual control.

[COURTESY OF THE NUMERICAL ENGINEERING SOCIETY (UK)]

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Networking Production (monthly)
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Wear (seven/annum) (Elsevier Sequoia)

Company Addresses

UK Head Office	*International Head Office*
William Asquith (1981) Ltd Highroad Well Works Gibbet Street Halifax W. Yorks HX2 OAP Tel: 0422 367771	
Boko Machine Tools (UK) Ltd Kingfield Industrial Estate Kingfield Road Coventry West Midlands CV1 4DW Tel: 0203 228447/8	**Bohner & Kohle** GmbH & Co Maschinenfabrik Weilstrasse 4–10 D-7300 Esslingen/Neckar Postfach 67 Germany Tel: 0711-3901-0
Bostomatic UK Ltd 7 Prospect Way Butler's Leap Rugby CV21 3UU Tel: 0788 73865	**Boston Digital Corp** Granite Park Milford MA 01757 USA Tel: (508) 473–4561
Bridgeport Machines Ltd PO Box 22 Forest Road Leicester LE5 OFJ Tel: 0533 531122	**Bridgeport Machines Inc** 500 Lindley Street Bridgeport CT 06606 USA
Butler Newall Ltd (Electronic Accuracy Systems) Westholme Road Halifax HX1 4JR Tel: 0422 331144	

UK Head Office / *International Head Office*

BYG Systems Ltd
Highfields Science Park
University Boulevard
Nottingham
NG7 2QP
Tel: 0602 252221

Carne (UFM) Ltd
Swan Works
416–418 London Road
Isleworth
Middlesex
TW7 5AE
Tel: 081 5601182

Ibag Zürich AG
Glattalstrasse 138
CH-8052 Zürich
Switzerland
Tel: 01 301 0020

Centreline Machine Tool Co. Ltd
Newton Road
Hinckley
Leics
LE10 3DS
Tel: 0455 618012

Cimcool Division Head Office
Cincinnati Milacron Ltd
Maybrook Road
Castle Vale Industrial Estate
Sutton Coldfield
West Midlands
B76 8BB
Tel: 021 351 1891

Cimcool Industrial Products
PO Box 463
3130 Al-Vlaardingen
Netherlands
460 0660

The Cimulation Centre
Avon House
PO Box 46
Chippenham
Wiltshire
SN15 1JH
Tel: 0249 650316

Cincinnati Milacron UK Ltd
PO Box No. 505
Kingsbury Road
Birmingham
B24 0QU
Tel: 021 351 3821

Cincinnati Head Quarters
Oakley Complex
4701 Marburg Avenue
Cincinnati
Ohio 45209
USA
Tel: 513 841 8100

Cranfield Precision Engineering Ltd (CUPE)
Cranfield Institute of Technology
Cranfield
Bedford
MK43 0AL
Tel: 0234 752789

Crawford Collets Ltd
Tower Hill Works
Witney
Oxfordshire
OX8 5DS
Tel: 0993 703931

UK Head Office

Dean Smith & Grace Ltd
Keighley
West Yorkshire
BD1 4PG
Tel: 0535 605261

International Head Office

Monarch M/C Tool Co
615 North Oak Street
PO Box 668
Sidney
Ohio 45365
USA
Tel: 513 492 4111

DeBeers Industrial Diamond Division Ltd
Charters
Sunninghill
Ascot
Berks
SL5 9PX
Tel: 0990 23456

Devlieg Microbore Tooling Co
Leicester Road
Lutterworth
Leics
LE17 4HE
Tel: 0455 553030

Eclipse Magnetics Ltd
Vulcan Road
Sheffield
S9 1EW
Tel: 0742 560600

Federal-Mogul
Westwind Air Bearings Ltd
Trading Park
Holton Heath
Poole
Dorset
BH16 6LN
Tel: 0202 622565

Ferranti Industrial Electronics Ltd
Dunsinane Avenue
Dundee
DD2 3PN
Tel: 0382 89311

Flexible Manufacturing Technology Ltd (FMT)
Carden Avenue
Hollingbury
Brighton
BN1 8AU
Tel: 0273 507255

GE Fanuc Automation
1 Fairways
Pitfield
Kiln Farm
Milton Keynes
MK11 3EE
Tel: 0908 260200

GE Fanuc Automation Europe SA
Zone Industrielle Echternach
Grand-Duche de Luxembourg
Tel: 728372

UK Head Office	*International Head Office*
Gildemeister (UK) Ltd Unitool House Camford Way Sundon Park Luton LU3 3AN Tel: 0582 570661	**Gildemeister Aktiengesellschaft** Morsestrasse 1 D-4800 Bielefeld 11 Germany Tel: 05205 7510
Hahn & Kolb (GB) Ltd 6 Forum Drive Leicester Road Rugby Warks CV21 1NY Tel: 0788 577288	**Hahn & Kolb GmbH & Co** Bei Angabe Des Postfach 106018 W-7000 Stuttgart 10 Germany Tel: 49 711 945-0
Iscar Tools Ltd Woodgate Business Park 156 Clapgate Lane Bartley Green Birmingham B32 3DE Tel: 021 422 4070	**Iscar Limited** Box 11 Tefen 24959 Israel Tel: 0109724970311
AT & T Istel Industrial Systems Ltd Highfield House Headless Cross Drive Redditch Worcs B97 5EG Tel: 0527 550330	
Jones & Shipman PLC Narborough Road South PO Box 89 Leicester LE3 2LF Tel: 0533 896222	
Kennametal Europe PO Box 29 Kingswinford West Midlands DY6 7NP Tel: 0384 408010	**Kennametal Inc International** PO Box 231 Latrobe PA 15650 USA Tel: 412 539 4700
Krupp Widia UK Ltd 5 The Valley Centre Goron Road High Wycombe Bucks Tel: 0494 451845	**Krupp Widia GmbH** Münchener Strasse 90 D-4300 Essen 1 Germany Tel: 0201 725 0
KT-Swasey Ltd Stafford Park 2 Telford Shropshire TF3 3BO Tel: 0952 290200	**KT-Swasey** 11000 W. Theodore Trecker Way Milwaukee Wisconsin 53214-0277 USA Tel: 414 476 8300

UK Head Office	*International Head Office*
LK Tool Company Ltd East Midlands Airport Castle Donnington Derby DE7 2SA Tel: 0332 811349	
McDonnell Douglas Information Systems Ltd Boundary Way Hemel Hempstead Herts HP2 7HU Tel: 0442 232424	**McDonnell Douglas** Information Systems International 18881 Von Karman Suite 1800 Irvine California 92715 USA Tel: 714 724 5600
Micro Aided Engineering Ltd Bolton Business Centre 44 Lower Bridgeman Street Bolton Greater Manchester BL2 1DG Tel: 0204 396500	
NC Engineering Ltd 1 Park Avenue, Bushey Watford Herts WD2 2DG Tel: 0923 243962	
NCMT Ltd (Makino) Ferry Works Thames Ditton Surrey KT7 0QQ Tel: 081 398 3402	
P-E Information Systems Ltd (Hocus) Park House Egham Surrey TW20 0HW Tel: 0784 34411	
Rank Taylor Hobson Ltd PO Box 36 New Star Road Leicester LE4 7JQ Tel: 0533 763771	
Renishaw Metrology Plc New Mills Wotton-under-Edge Gloucs GL12 8JR Tel: 0453 844211	

UK Head Office

International Head Office

Renishaw Transducer Systems Ltd
Old Town
Wotton-under-Edge
Gloucs
GL12 7DH
Tel: 0453 844302

Ringspan (UK) Ltd
3 Napier Road
Bedford
MK41 0QS
Tel: 0234 42511

Ringspan GmbH
Schaberweg 30–34
6380 Bad Homburg
Germany
Tel: 06172 275-0

Röhm (GB) Ltd
The Albany Boat House
Lower Ham Road
Kingston-upon-Thames
Surrey
KT2 5BB
Tel: 081 549 6647

Sandvik Coromant UK
Manor Way
Halesowen
West Midlands
B62 8QZ
Tel: 021 550 4700

Sandvik AB
81181 Sandviken
Sweden
Tel: 026 260000

Scharmann Machine Ltd
Cannon House
2255 Coventry Road
Sheldon
Birmingham
B26 3NX
Tel: 021 742 4216

Dörries Scharmann GmbH
D-4050 Mönchengladbach 2
Hugo-Junkers Strasses 12–32
Germany
Tel: 02166 454-0

Seco Tools (UK) Ltd
Kinwarton Farm Road
Alcester
Warks
B49 6EL
Tel: 0789 764341

Seco Tools AB
77301 Fabest
Sweden
Tel: 022-340000

Siemens PLC
Sir William Siemens House
Princess Road
Manchester
M20 8UR
Tel: 061 446 5740

Siemens Aktiengesellschaft
Power Engineering & Automation Group
Numerical Controls & Drives For Machine Tools Division
PO Box 4848
8500 Nuemberg 1
Germany

SMG Ltd
Industrial House
River Dee Business Park
River Lane
Saltney
Chester
CH4 8QY
Tel: 0244 681206

SMT Machine Company AB
PO Box 800
S-721 22 Västeras
Sweden
Tel: +46 (0)21-805120

UK Head Office	*International Head Office*
Stellram Ltd Hercules Way Bowerhill Industrial Estate Melksham Wiltshire SN12 6TS Tel: 0225 706882	**Stellram SA** 1260 Nyon Switzerland Tel: 022-613101
System 3R (UK) Ltd 2 Duke Street Princes Risborough Bucks HP17 0AT Tel: 08444 4339	**System 3R International AB** Sorterargatan S-162 26 Vallingby Sweden Tel: 46(8)6202000
Tecnomagnetica UK Ltd 18 Riverside Estate Sir Thomas Longley Road Frindsbury Rochester Kent ME2 4DP Tel: 0634 715802	**Tecnomagnete SPA** Via Dei Cignoli 9 20151 Milano Italy
Thame Engineering Co. Ltd Field End Thame Road Long Crendon Aylesbury Bucks HP18 9EJ Tel: 0844 208050	
Walter Cutters & Grinders Ltd Walker Road North Moons Industrial Estate Redditch Worcs B98 9HE Tel: 0527 60281	**Walter AG** Postfach 2049 W-7400 Tuzbingen Germany Tel: 497071 7010
WDS Wharton LTD Marlco Works Hagden Lane Watford WD1 8NA Tel: 0923 226606	
Wix & Royd Ltd 77–81 Brighton Road Redhill Surrey RH1 6PS Tel: 0727 768823	
Yamazaki Mazak UK Ltd Badgeworth Drive Worcester WR4 9NF Tel: 0905 755755	

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