



COLLEGE OF AERONAUTICS

(Proposed Cranfield Institute of Technology)

DEPARTMENT OF PRODUCTION ENGINEERING

DESIGN PROJECT 1967/8

THE DESIGN OF A NUMERICALLY CONTROLLED
PRECISION TURNING / MILLING MACHINE



MANAGEMENT REPORT

Prepared by: N. Powell

Staff Advisor: C. J. Charnley

SUMMARY

This report outlines the design of a precision turning machine with a limited milling facility which incorporates a fluidic numerical control system. It contains an introduction to the project together with summaries of the reports of the Technical Survey, Concept and Configuration, Design, and Control committees.

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1.0 INTRODUCTION

Production Technology Course

The aims of the course are to provide a comprehensive education in modern production engineering and to present problems to the student in both technology and management such that decision making becomes accepted practice.

The students specialize in one of the related fields of production engineering, such as machines and automation, fluid and fluidic systems or precision engineering.

The course is comprised of a series of lecture courses, a group design project and an individual research thesis. The research thesis, which is normally chosen in consultation with the Company sponsoring the student, forms the main basis of the specialisation which is supplemented by the choice of lectures and activities in the group project.

The Group Design Project

The project has the following aims:-

- 1) To act as a unifying link to the various lectures attended and to provide practical examples for the application of theories developed.
- 2) To give experience in the working as a member of group on an industrial design problem.
- 3) To provide a platform for the integration of teaching and research in the development of new automatic production systems.

The method of operation involves the formation of a project board which comprises both staff and students, and also requires the formation of specialist committees to meet the particular design needs. Each committee is responsible for arranging its own meetings and conducting its affairs, has to consider the design requirements, and make recommendations to the board concerning its chosen area of activity.

At the meetings of the project board, which are held weekly, each student takes it in turn to act as secretary. He then prepares the minutes of that meeting and an agenda for the next one, at which he acts as chairman to the board. The student members of the project group have all had industrial experience and in many cases are sponsored by firms; the position held with each firm is shown at the end of this report.

For the session 1967/8 the initial terms of reference were "the design of a linear path system", the underlying philosophy being the combination of machine and control unit into an integrated system, with the linear movements under controlled feedrate. After exhaustive discussion, during which various machines were considered, it was decided to concentrate on "the design of a precision turning machine with limited milling facilities". Detailed layout drawings were produced of the final machine design, together with a scale model, photographs of which are shown in fig. 1. The machine has been designed from a functional viewpoint and was based upon a specification derived from a technical survey, which is described later. The following advantages are claimed:-

- 1) The arrangement used provides for conventional turning operations together with limited milling operations, such as cutting keyways or drilling radial holes on turned components at one setting, thus eliminating the need for second or subsequent operations.
- 2) The use of inclined slideways makes for a compact machine and eliminates the build up of swarf in the machining area, an important consideration in a machine designed for high utilisation.
- 3) The use of a moving headstock separates the linear motions, reduces compound slide errors and improves the accuracy which should be maintained for an extended period because of the provision of hydrostatic slideways.
- 4) The control system is implemented with fluidic elements to achieve low cost and high reliability.
- 5) The design incorporates a box type structure for maximum strength and rigidity.

A summary of the reports of the various committees follows and describes in greater detail the above mentioned features. The full reports of the various committees references 2, 3, 4 and 5 together with other published information concerning the research activities of the department are available on request.

2.0 OUTLINE OF DESIGN

The final design solution resulted in a machine with a number of interesting if not unique features.

The machine frame has a box type structure which houses all moving parts and is inclined at an angle to the base to save floor space. In place of the conventional headstock, the M.E.L. hydrostatic spindle drive is used and the work moves past the tool slide under

the action of an hydraulic ram. Hydraulic rams and hydrostatic slideways are used for headstock, tailstock, tool slide and tool magazine movements whilst hydraulic actuation is employed for all tool rotation and toolpost and magazine indexing.

The sliding headstock gives separate movements of the X and Y axes and thus eliminates some of the errors encountered in compound slides.

The technical survey showed that the number of turning tools, drills and milling cutters required per set-up could be as many as twelve and as a result a tool magazine housing sixteen tools was designed to cater for this and also provide spare tool stations. This would enable all tools required, to complete the machining operation on a given component, to be pre-loaded into the magazine.

A low cost fluidic control system has been designed and is compatible with the rest of the machine tool system. Although initially the fluidic system presents immediate development costs, it was considered that it would result in a cheaper system in the future.

The overall cost of the machine was considered and it was concluded that the manufacturing cost would be about £4,500 plus about £2,000 for the control system resulting in a probable selling price of about £8,000. However when considering the heavy development cost a more realistic price, initially, would be about £12,000.

3.0 TECHNICAL SURVEY

The function of the technical survey committee was to conduct a survey the results of which could be used to establish a basic specification for the machine.

A questionnaire was compiled and sent to 500 firms, one hundred to each of the following groups of industries (the figures in brackets indicate the percentage returns received).

Aircraft and Accessories (28); Motor Car and Accessories (13)
Electronics and Computing (10); Machine Tools and Accessories (7)
Precision Equipment and Instruments (18).

The information supplied against each question was analysed and histograms plotted, thus enabling maximum zone areas to be identified and a machine specification to be compiled.

It should be made clear that because of the limited scope of the survey the results can only be taken as a general guide. However, it was considered that the results were sufficiently useful to compile the following specification for the design project.

Specification

The specification was chosen from an inspection of the shape of the histograms so as to include a minimum of 75% of the components surveyed.

a) COMPONENTS

		<u>Percentage included</u>
Maximum Length	8 in (200 mm)	87
Maximum Diameter	4 in (100 mm)	86
Tolerance on Length	± 0.001 in (± 0.02 mm)	95
Tolerance on Diameter	± 0.001 in (± 0.02 mm)	91
Tolerance on Milling	± 0.001 in (± 0.02 mm)	98

b) TOOLING (Magazine requirements)

		<u>Percentage included</u>
Number of Turning Tools	8	100
Number of Drills	4	76
Number of Milling Tools	4	96

4.0 CONCEPT AND CONFIGURATION

It was decided to consider as wide a range of machines as possible which would satisfy the terms of reference viz.: "The Design of a Linear Path System". Five types of machines were listed and these were:-

- 1) Precision turning, (2) Jig boring, (3) Inspection, (4) Milling, 5) Welding.

In discussions that followed the initial survey it was decided that the type of machine which would probably satisfy the largest demand from the machine tools market, would be either a precision turning machine or a milling machine or a combination of the two. Three concept committees were formed to examine these and prepare line diagrams of their solution.

Concept Committee "A"

This committee submitted two designs, the first was for a "short-bed precision turning machine" and the second was for the same type of machine but included provision for limited milling facilities. In the case of the first design it was intended that this machine would produce components whose ratio of work length to diameter was 1:1 and that it would be influenced in its design by the results of a survey made by Dr. H. H. Moll and presented in his paper "A Users Viewpoint of the Machine Tool of the Future".

The machine would have a short bed length and would be compact in size. The machine bed and saddle would be inclined and so provide easy work loading, tool setting and swarf removal.

Cutting tools would be carried in a hexagonal turret which would accept both turning tools and drills, the power to the drills being provided by a hydraulic motor mounted on the turret. This arrangement would enable the drilling of axial and radial holes. The drive to the work spindle would be by hydraulic motor and the actuation to both saddle and cross-slide would be by hydraulic rams. The position of these two slides would be determined by linear transducers.

Work would be programmed on to punched paper tape, and the tape reader and associated control equipment would be contained in a console alongside the machine.

With the second design many of the above features were included with the addition of provision for fitting milling cutters such as end mills and tee slotters into the turret which would enable milling operations to be performed.

Concept Committee "B"

This committee considered that the study of a milling machine would offer a number of advantages over that of a turning machine, and as a result submitted three designs of a milling machine.

All the designs had a number of common features in that the machine should accept a maximum workpiece size of 12 x 12 x 8 in (300 x 300 x 200 mm), a rotary table which could be indexed to cater for overlapping of machining and loading operations, and a control system that used fluidic elements with a provision for manual data input.

In the first design, all machining motions were performed by the tool, the table merely indexed from one station to the next, in the next design the tool head performed two machining motions and the traverse motion was performed by the table. This resulted in a better slideway design for the tool head. In the third design,

again all machining motions are performed by the tool head, the table has three stations and the motor and slides can be removed as a sub-assembly for easy maintenance. Provision is made for swarf removal by including a disposal chute under the table and sloping to the rear of the machine. The third design was proposed by this committee.

Concept Committee "C"

This committee submitted a machine design which was a combination turning-milling machine. Three tool drums were included which supplied tools to three machining stations, this enabled both turning and milling operations to be performed at either station.

The design enabled work to be gripped at either end so that components could be machined from both ends, thus eliminating the need for a second operation machine. It would be necessary for the control system to provide controlled feedrate in three axes on four units.

Configuration Committee

The designs submitted by the three concept committees were considered by the board and it was decided to proceed with a machine design which would include many of the features shown in the designs submitted by committees A and C. The brief of this committee was therefore to prepare a configuration which incorporated these features and should basically be a short bed machine to handle components in which the length was approximately equal to the diameter.

Basic Requirements

A turning machine with facilities for milling defines a certain relationship between the workpiece and cutting tool, and also governs the type of cutting tools used on the machine.

It is a requirement that the work is provided with a rotational movement and the turning tools move with respect to the work, either by moving the tools along the axis of the work or by moving the rotating work past the tools. The turning tools must also be provided with a cross-slide movement so that they can pass across the face of work. The milling cutters must be provided with rotational movement and also with movement along the axis of the work and across its face.

The maximum size of the work used on the machine will govern the size and length of the slideways which in turn will govern the overall size of the machine.

Design Solution

Cutting Tools and Tool Loading

The cutting tools to be used were divided into two types - turning tools, single point and form tools and rotational tools - drills, end mills etc. The basic relationship between workpiece and cutting tools is shown in fig. 2a in which is shown that the work must have rotational movement and the turning tools must move axially along the work and at right angles to the work axis. Drills must have the same basic movements and also rotate about their axes. Finally the tailstock centre must have movement along the work axis. The various methods by which these relationships can be obtained are shown in figures 2b,c,d and e.

In the last arrangement only one tool is held in the tool-post station at any one time all others are stored in a magazine. When a tool change is required the tool-post indexes to face the magazine, the tool is discharged into the magazine, which then indexes to present a new tool. It was considered that this arrangement had more to offer than any of the others, and would be particularly suitable for inclusion in a numerically controlled machine.

Machine Frame and Slideways

The initial machine configuration fig. 3 shows an arrangement where all the sliding elements of the machine move on slideways contained within a box type structure.

The three moving elements, headstock, tool-post and tailstock are all powered by hydraulic rams, and the measuring systems for headstock and tool-post are contained within the ram spindle. All three rams are actuated on the centre line of the work, so that actuation and measurement are co-axial.

In this design the headstock moves past the cutting tools and the tool-post moves at right angles to the work axis. With this arrangement the normal movements of the tool slide are separated, so that errors normally associated with compound slides are reduced.

All moving parts are supported on hydrostatic bearings, resulting in low co-efficient of friction and high stiffness; desirable features in any machine tool intended for precision work and operated by numerical control.

5.0 MACHINE DESIGN

The task of the Design Committee was to design a machine to produce work which is normally produced on a centre lathe, but with the added feature that it should also perform other operations which would normally require the use of a milling machine.

The combination of turning with limited milling facility necessitated a departure from conventional design, resulting in a machine having a moving headstock, cradled between the slideways of a box type structure frame, and a tool-post, which moves at right angles to the work axis, contained in the lower part of the machine. A tool magazine to store the many tools required for the different machining operations, and which could present them to the tool-post station when required, was also included.

All machine movements are controlled by data stored on punched paper tape, and various mechanisms had to be designed in order that the machine could respond to these signals.

The work of each sub-committee is shown, together with sketches and design drawings where applicable, but it should be realised that this represents only a precis of the actual work done, and that for a full understanding, reference should be made to the final reports.

5.1 Headstock

It was a requirement that the headstock move relative to the machine frame, and this resulted in a headstock which is a compact, self-contained unit, which moves along the machine slideways on hydrostatic bearings. To accommodate both turning and milling operations the spindle has been provided with a variable speed drive over a wide range.

Automatic work loading, which was a subject covered by this sub-committee, has been investigated and the design of a cheap but effective device is included; it was considered that this should be offered as an accessory to the machine.

Design Solution

Headstock Assembly

A survey into headstock drives revealed that a hydraulic motor which met the design requirements, had been developed by the National Engineering Laboratory (N.E.L.) for application to machine tool drives, and with suitable modification could be incorporated into this machine.

This motor is of the axial piston variable displacement type. Speed control is achieved by varying the swash plate angle, in conjunction with a variable displacement pump thus providing a speed range up to 2,000 rev/min. The headstock motor used has been based on this design, and is capable of operating up to 3,000 rev/min. A layout drawing of the headstock assembly is shown in fig. 4 from which it can be seen that the motor shaft has been extended to become the machine spindle and is supported on two hydrostatic journal bearings.

The front bearing is a double conical one and will take both radial and axial loads, while the rear bearing is of parallel design and will take radial loads only. The conical bearing consists of two rows of six equally spaced pads of recessed design set at 30° to the spindle axis, while the rear bearing consists of one row of six equally spaced recessed pads. Calculations were carried out to evaluate the design parameters of the spindle bearings.

This type of motor has the ability to act as a very effective brake, and as a result can be used to stop the machine almost instantaneously from a very high speed, but in addition a disc brake is used to hold machine spindle rigid when machining with a drill or end mill. The headstock motor casing has been designed to incorporate the hydrostatic slideways. Calculations for these bearings have been evaluated and a three pad configuration chosen. Provision has been made for securing the actuation cylinders to the motor casing, and these cylinders control the forward movement of the headstock under controlled feedrate and also the rapid advance from the drilling to the turning position.

At the rear of the headstock is a unit which houses the rotary encoder and the disc brake. The encoder is used to monitor the angular spindle position during operations such as drilling radial holes in a flange or milling a helix. A removable cover provides easy access for inspection and maintenance.

The type of chuck selected had to be one which could be operated by remote control and for use with a numerically controlled machine, the type of control available could be pneumatic, electric or hydraulic. Pneumatic and hydraulic are more common and both sources of power are available on the machine.

The chucking requirements were met by an 8 in (200 mm) dia. three jaw high-speed power chuck having an aluminium body fitted with steel jaw-ways carrying hard top jaws. It has a wedge type gripping operation and its action is controlled by a draw bar, passing through the centre of the spindle, and coupled to a hydraulic cylinder mounted at the rear of the spindle. This will operate up to a speed of 3,100 rev/min.

Work Loading Mechanism

This consists of three units, a loading drum, a transfer channel and a transfer arm. Work is loaded into the drum, which will accept up to 20 components, and elevated in the channel; the transfer arm will then feed the work to the chuck through an aperture at the rear of the machine. When machining operations are complete the component will be removed from the chuck and transferred back to the drum for removal by the operator. The work loading mechanism will be a free standing unit positioned at the rear of the machine, and its operations will be controlled by data on the punched paper tape.

5.2 Tool-Post and Tool-Loading

The design problem confronting the tool-post and tool-loading sub-committee was two fold, first to examine the requirements of a tool-post station which would locate and clamp both turning and rotational tools as well as providing a drive for the latter, and also present to the work specified cutting tools.

The second was to consider the best arrangement of a magazine which could store a total of sixteen cutting tools, and present any one of them to the tool-post station when required.

With such a large number of tools, each one being selected by command signals from punched paper tape, it meant that either all tools would have to be contained in a multi-station turret mounted on the machine and indexed into position when required or stored in a magazine of some form and presented to a tool-station when required by some transfer mechanism. The latter was considered to be more suitable and the design study was based upon this arrangement.

Basic Requirements

Tool-post station - This is required to accept from the magazine, single point and form tools and rotational tools such as drills and end mills and to present these to the work at the start of a machining operation and to rigidly support these tools so that they withstand the action of the cutting forces.

It should be possible to index the station so that machining operations can be performed along the axis of the work and also at right angles to it. The loading and unloading of the tools to and from the tool station should be automatic and the indexed position of the station should be known at all times.

Tool magazine - This is required to store sixteen tools made up of both turning and rotational tools. It should be possible to pre-load the tools into the magazine and then position it on the machine suitably indexed so that it adopts its correct orientation. The magazine should be capable of indexing station by station and also be able to present to the tool station any tool stored in the magazine. The position of the various tools stored in the magazine must be known, so that some form of rotary encoder should be an integral part of the assembly. A drive should be provided for the rotational tools either from the machine drive system or by a separate power pack mounted on the tool station.

Design solution

Tool-post station - Consideration was given to the possibility of fitting both turning and rotational tools into the same tool-station

socket, but this idea was abandoned in view of the large cutting forces encountered in turning as these forces would have to be borne by the bearings supporting the rotary cutter spindle and would no doubt shorten the life of the bearings.

It was therefore decided to have separate sockets to house the turning and rotational tools, (refer to fig. 5) positioned at 180° to each other, as this gives a compact unit as well as providing maximum clearance from both headstock and tailstock.

Rotational tools can be fitted into either a collet chuck or a taper sleeve, the shank on both of these fittings is common and is a quick tool-change device known as the ACTERA. This is of Swiss origin and enables tools to be easily and quickly fitted into a driving socket; in position the tool shank is securely held by two locking balls secured by a mechanical latch which ensures a very positive drive. It would be impossible for these balls to be depressed and so release the tool shank during a machining operation.

The indexing of the tool-post station is performed by a pneumatic cylinder which is mounted underneath the housing; the piston ram operates through a rack and pinion. At the indexing positions the housing is accurately located by a cylinder operated vee register; this ensures that the tools take up the correct position for turning and drilling operations and also for the rejection and acceptance of new tools from the magazine. Following each indexing operation the housing is locked to the cross-slide by a hydraulic clamp; this ensures that the housing is rigidly held during machining operations.

The drive for the rotational tools will be a hydraulic gear type motor which is mounted on top of the tool-post housing. This motor will have a number of selected speeds up to 2000 rev/min and a rating of 2 horse power.

The tool-post station is mounted on a hydrostatically supported cross-slide which moves at right angles to the work axis and is constrained in all other axes. The slide is actuated on by a hydraulic cylinder mounted underneath, and the piston ram moves at a controlled feedrate over the length of its stroke.

- 5.3 Tool magazine - The magazine fig. 6 is a circular drum which can store a total of sixteen cutting tools, nine being rotational and seven turning tools. The rotational tools cover drills up to 1 in (25 mm) dia. and 8 in (200 mm) in length, end mills, reamers, tee cutters and slotting mills. All tools are fitted into the magazine with the shank facing outwards so that the longest tool governs the size of the magazine.

The magazine which is of aluminium alloy, can be pre-loaded with tools away from the machine, and therefore the total number of

tools required to completely machine a component can be loaded at one setting. Each tool position is identified so that on a command signal from the tape any tool can be indexed into position ready for loading into the tool-post.

The magazine, when loaded into the machine is keyed to a drive shaft and this in turn is coupled to a rotary encoder, so that the position of the magazine is known at all times by the control unit. The sensing head is attached to the slide on which the magazine moves. The slide moves on crossed rollers on one side and on plain rollers on the other, to ensure a smooth motion for the magazine.

A description of the sequencing of the magazine for tool loading and unloading, together the fluidic control circuitry is contained in the main report.

- 5.4 Tailstock and machine facilities - The work of the Tailstock and machine facilities sub-committee was to prepare a design for a tailstock, to determine the best method of applying the cutting fluid and to consider the range of fluids available, and to also examine the methods of swarf removal and to design a system for swarf removal.

Design solution

Tailstock - The tailstock body comprises a casting which incorporates hydrostatic bearing pads. The tailstock movement is controlled by a hydraulic cylinder, the ram of which is coupled to the underside of the tailstock and the cylinder body to the machine frame.

With a machine of this design where the work travels past the cutting tools, it means that the tailstock must also move in conjunction with the work; this is achieved by connecting the tailstock cylinder with suitable control valves to the cylinder actuating the headstock, so that movement of the headstock is accompanied by a corresponding movement of the tailstock. The variation of force that is exerted by the tailstock on the work is controlled by a relief valve fitted in the hydraulic supply line to the cylinder. This would need to be set by the operator during the setting up procedure.

Cutting Fluid System - The ideal method of applying a cutting fluid is by the use of jets operating at high pressure directed at the cutting edge of the tool, in conjunction with a copious flow of fluid operating at low pressure to flood the tool and workpiece.

The "Hi-jet" system chosen involves the projection of small jets of special neat oil at high pressure, aimed directly at the cutting edge from below; in addition an overhead flood of oil is provided to reduce the fumes. The increased tool life is attributed to improvements in both lubrication and cooling at the cutting edge of

the tool. At normal cutting speeds the increase in tool life can be as high as eight times, while at the higher speeds improvements of up to twenty and thirty times have been obtained.

Swarf Removal - The design of the machine makes the problem of swarf removal a little easier, in that the angled frame and slides enable the swarf to fall into space, where it can be ducted and conveyed away from the machine. This system has been achieved by fitting a deflector plate below the machining position which discharges the swarf out of the back of the machine. An intermittent blast of air assists the motion of the swarf down the chute. At the rear of the machine the swarf is conveyed away to a refuse centre.

5.5 Aesthetic and Ergonomic Design

The role of the Aesthetic and Ergonomic Design sub-committee was to consider the aesthetic and ergonomic aspects of the machine and also to construct a model of the final machine design.

Because of the influence of fashion and ergonomics, machine tools can no longer be designed on functional grounds alone. Fashion dictates that the machine should be pleasing to the eye and therefore such things as colour, size and outline should be considered. However aesthetics cannot be considered in isolation, as it must complement basic design requirements. The general ergonomic considerations are that an operator should be able to set up and control the machine rapidly, safely and with the minimum amount of fatigue. This covers the adoption of standards concerning the arrangements and direction of movement of operating handles, knobs etc. Also unnecessary movements and fatigue can be reduced if the layout of levers and control panels be adapted to the geometry of the human body.

5.6 Frame and Slideways

The design of the machine frame and slideways posed two problems; the first was that the frame would have to be a very stiff structure, and the second, that the slideways would have to provide exact alignment for the moving parts and a sliding surface with a low co-efficient of friction. Both are important considerations for a machine capable of precision turning as well as limited milling operations.

Means of protecting the slideways from abrasion have been investigated and a section dealing with this is included.

Design solution

The solution to the design of the frame depended to a large extent upon the arrangement of the various machine elements within the frame and a total of six different arrangements were prepared.

In the final solution fig. 7 a box type structure is used to support and guide the moving headstock and tailstock, which is inclined at an angle to the base of the machine. The tool-post station moves at right angles to the headstock movement, and thus its movement is within the well of the machine. The slideways for the tool-post station form the backbone for the frame and this in conjunction with the box type arrangement results in a very rigid machine frame. The top half of the box section is separated from the frame on the centre line of the work at an angle of 30° to the horizontal; this enables the bearing faces to be machined in each half of the frame and the headstock and tailstock to be assembled prior to the bolting together for the final assembly.

All moving parts are supported on kinematically arranged hydrostatic bearings which have been chosen for the slideways as they offer features unattainable with conventional cast-iron slideways with oil film separation. High stiffness values together with very low values of co-efficient of friction are inherent features of hydrostatic bearings, so that they are particularly suitable for inclusion on a numerically controlled machine tool. The runners for the headstock are cast integral with the motor casing, and as this is the moving member, the hydrostatic pads are machined in the runners. The male portion of the vee is on the sliding element and the female on the frame, this will provide the best arrangement as well as being the easiest to manufacture. The slideway design for the tool-post station is similar to that for the headstock, the main difference being that the hydrostatic vee is inverted so as to absorb the downward forces resulting from the cutting action. The slideway design for the tailstock is again similar to that for the headstock except that the span between the bearing slides has been reduced, so as to reduce the size of the tailstock.

An entry has been provided at the rear of the machine for work loading to the chuck, and swarf disposal will be via a chute also at the rear of the machine.

Summarising, the machine frame and slideways forms a closed loop structure which results in an extremely stiff and robust frame, and at the same time in a compact machine occupying a small floor space.

Slideway Protection

Various methods of slideway protection are currently in use, these are:- corrugated covers and bellows of either rubber, leather or terylene, telescopic steel covers and wipers.

The first are particularly suitable for the protection of ram shafts and leadscrews, and it is intended to use these in the form of neoprene bellows for the protection of the ram shafts of the hydraulic actuators. Corrugated covers providing full protection for the headstock and tool-post slideways will be used. These will be of

a material fabricated from a woven terylene cloth impregnated with polyurethane rubber, with two layers of terylene film bonded together by a heat setting adhesive to form a laminate.

Appraisal of Design - Reference to fig. 7 shows the final design configuration in which the machine bed is inclined at an angle to floor. This is unconventional but practical for a numerically controlled machine and is also considered to be pleasing to the eye. The machining area and tool loading positions are within easy reach of the operator and the angle slideway enables swarf to fall clear of moving parts.

The final configuration has the advantage that it occupies the minimum floor space and has good accessibility.

6.0. CONTROL SYSTEMS

The terms of reference for the control systems committee were to investigate suitable control and actuation systems, to decide on the best control and actuation system for the machine being designed and to prepare a design of the final system adopted.

To achieve this objective an investigation into the type of control system was first carried out and at this stage the committee was then divided into two sections, control logic and control actuation, to investigate in detail the system selected and produce a final design.

It was considered that, at the present time, a linear path system was the most complicated numerical control system to which a feasible fluidic control could be applied. Although costing at the decision stage was difficult, it was thought a fluidic system would be cheaper than its electrical or electronic counterpart, especially in the long term.

The use of fluidics as the control medium posed certain difficulties, as the number of fluidic interface devices available is limited, and many aspects of the technology are improven. However, wherever possible, currently available commercial units are specified and all components are viable propositions.

Type of Control System

The control system to be used on this machine is to be of the linear path type, that is - to be able to move to a position without overshoot and at a controlled feedrate.

The systems considered were analogue - absolute and digital - incremental. It is considered that an absolute reference system is best suited to a turning machine, because turned parts already have a natural reference axis in the form of the centre line;

diameters are invariably represented as absolute dimensions, and length dimensions are conveniently referred to a face.

The original specification of a linear path control was considered a suitable one for application to a lathe as the majority of movements on a lathe are either longitudinal or transverse. This is supported by an investigation at Messrs. Gebr. Boehringer in Germany, which showed that 80% of their turned parts could be produced with a linear path, or straight-cut machine.

Investigation of Control Systems

This was divided into two sections: electrical, electronic and hydraulic, and fluidic. In the first section - enquiries were made to the five major control system suppliers in this country, I.G.E., Ferranti, Airmec-AEI, Plessey, E.M.I. with a view to buying out a standard or custom built system, or building a system using bought out measuring elements and other suitable components.

A custom built control system could thus be readily obtained with a large number of features and optional extras available. The manufacture of a control system from bought out parts was a less attractive idea. It was therefore considered that in terms of taking full advantage of the relative simplicity and low cost that a two axis straight cut system should be purchased from Airmec-AEI Ltd., that a shaft encoder be included in the headstock assembly and with this system electrical actuation should be used.

In the second section it was considered that a fluidic system was a feasible proposition and that it should comply with the following recommendations.

- 1) the system should be of the "absolute" type
- 2) the two linear axes should be supplied with similar linear fluidic encoders
- 3) a rotary fluidic encoder should be incorporated in the headstock
- 4) the measuring system should be a comparator type circuit with either a Gray code read out from the encoder or some type of scanning system, both systems to incorporate some form of lead/lag signal to prevent overshoot.

When comparing the two systems it was concluded that there was little to choose between them in terms of cost at present although the price of the electrical system was fixed, whereas the development costs of the fluidic system could escalate. Despite this it was decided to recommend that a fluidic control system be developed for incorporation in this machine.

The reasons for this were that although a fluidic system presented immediate development costs, it promised to provide a cheaper system in the future, when the manufacturing concern provided its own elements and encoders, also the Company would have an original and patentable control system, and the control system appeared to be a viable proposition in its own right.

6.1 Actuation

The actuation sub-committee was responsible for defining the way in which various machine elements were to be actuated and the drive systems selected.

Spindle Drive - A hydrostatic drive motor was chosen for the headstock, and this resulted in a compact spindle drive assembly. It was considered that it would have been very difficult to incorporate a conventional electric motor and gear box into the headstock assembly. The hydrostatic motor results in a unit with a high power/weight ratio and also power/volume ratio. It will also have high drive stiffness, continuously variable speed and ease of control on open or closed loop.

The system adopted for controlling the spindle drive was to use a variable displacement pump with variable displacement motor (VP/VM) in which the swashplates are indexed through discrete positions and so provide series of speeds. This system has two limitations, first, it was an open loop system, since each speed represented a fixed pump/fixed motor configuration, however, it would provide a speed regulation within 5% which was adequate. Secondly, the feature of a continuously variable speed range would be lost although the use of an infinite number of spindle speeds would present programming difficulties.

However, it was thought that this VP/VM system could be included in the machine at a reasonable cost to give the required speed range, and an adequate power envelope and also the speeds would be reasonably easy to programme.

Other considerations included noise, usually hydraulic units tend to be more noisy than the equivalent electrical unit, but by suitable mounting and isolating the noise could be reduced to an acceptable level. Hydraulic units tend to run at high temperature unless special precautions are taken; in this unit oil coolers will be used to reduce the temperature and if a large enough cooler were selected the temperature could be reduced to near ambient.

The method of inching the spindle is achieved by fitting an encoder at the rear of the headstock and rotating the spindle at 1.5 rev/min. To achieve this when the tape calls for a creep mode the pump displacement is set at minimum, the motor displacement at maximum and slow pressure relief valve is connected from the pressure line

by opening an on/off fluidic/hydraulic valve. The relief value can be adjusted to give the required creep speed, and when the spindle is locked there will be no build up of pressure. This arrangement is shown on the diagram of the hydraulic circuit fig. 8.

Slideway Actuation - Two forms of axis actuation were considered viz. a leadscrew driven by an electric or hydraulic motor, and hydraulic rams.

Hydraulic rams were chosen for the following reasons - the strokes of the two axes are of the order of 10 in (250 mm), linear encoders have already been chosen to give an absolute system, high pressure oil supply is available on the machine, and a fluidic/hydraulic interface in the form of a Moog two stage valve makes the use of hydraulic rams a feasible proposition.

Hydraulic actuators are most successfully applied to short stroke units, up to about two feet in length, with greater lengths the compliance of the hydraulic column presents difficulties when precision control is required.

Velocity Control of the Axes - To satisfy feedrate requirements the feedrate of the axes had to be controlled to within 5%. It was decided that a sufficiently accurate feedrate could be obtained by an open loop system depending upon the flow of oil through the valve associated with each axis. The valve would be temperature and load sensitive, but load forces would be small compared with actuation forces, and by dumping oil through a by-pass valve on starting up the machine, the running temperature could be reached quickly.

The Indexing Ram - This is required to move the headstock and encoder assembly through a distance of about 14 in (350 mm). It was decided to do this using a conventional ram holding the headstock against set stops. Low compliance of the ram would minimise any movement as the results of cutting forces. A five port fluidic/hydraulic valve would be used so that indexing can be programmed from the tape.

Tailstock Actuation - While the tailstock is in operation it is maintained in contact with the workpiece by the oil pressure in the hydraulic ram. This pressure is limited by a relief valve, the setting of which can be varied for different components. Thus the tailstock will follow the component, and be pushed backwards and forwards by it as the headstock slides past the cutting tools.

Tool-post Motor - The size of the motor was an important consideration and it was therefore decided to use a high speed fixed displacement motor and to control its speed by regulating the oil flow. This results in a constant torque output so that the motor is rated in terms of torque at the low speed requirement. This in turn leads

to excess power when running at high speeds, and hence inefficiency. However, in low power applications of this type, this is relatively unimportant.

Hydraulic Power Pack - This comprises two main power sources: (1) the headstock drive system (2) a constant pressure supply to the rams and auxiliary equipment. The headstock drive has been previously described and is in effect a separate system, although the output from the motor is fed to a common reservoir so as to simplify cooling arrangements. The boost pump and restrictor in this circuit are to maintain positive pressures of approximately 50 lbf/in² (350 KN/m²) at pump inlet and motor outlet and hence prevent cavitation. The pump for the axes and auxiliaries is identical to that specified for section (1) with the addition of a constant pressure servo. Further details of any of the equipment referred to in this section may be seen in the main report.

6.2 Control System Logic

The Linear Encoder - Current fluidic analogue devices are not sufficiently accurate to enable an analogue encoder of the required accuracy to be designed with confidence, and as a result it was decided to use a digital system. It was possible for the encoder to be either rotary or linear. If rotary, it would be mounted on the machine leadscrew or driven via a rack and pinion from the slide, whereas a linear encoder would be incorporated in the slide, or rigidly attached to it and so eliminate backlash errors; in addition it would be more compatible with the ram actuation already selected.

However, the smallest digit used is limited by the sensitivity of the encoder sensing system, and also it must be noted that the smallest digit is not necessarily the smallest discrete position change that can be sensed.

The encoder comprised two parts - the coded strip and the sensing head - since the sensor requires input and output connections it was more convenient to fix the sensor to the frame and the coded strip to the moving element.

Choice of Code - A basic requirement is that the code selected should give an unambiguous signal at any position. In the binary code, for example, more than one digit changes at a time; which could result in an ambiguous reading. This could be overcome by using a dual nozzle sensing system such as U-scan or V-scan, or by using a cyclic code in which only one digit changes at a time eg. Grey, Petherick or creeping code.

It was shown that if each decimal change is 0.001 in (25 μ m) the smallest digit sizes required are:- binary 0.001 in (25 μ m), Grey 0.001 in (25 μ m), Petherick 0.002 in (50 μ m) and creeping

code 0.005 in (125 μ m) and that the creeping code could be represented by an inclined bar. The creeping code was therefore chosen because it should be cheap to manufacture and also it results in the largest digit size for 0.001 in (25 μ m) increments.

Sensing Head - The sensing head translates the data contained on the coded strip into a form which can be used in the control logic circuit. For each decade the sensor contains five readout units. The signal from the sensing jet is low pressure and requires shaping and amplification.

The use of two control jets 180° out of phase can give a "push-pull" control signal to the element which enables a digit on the code of smaller physical size to be sensed.

Coded Strip - The linear coded strip carries a pattern which can be sensed to provide positional information in a manner acceptable to the logic circuit.

The code pattern was arranged so that exhausted air from one track did not affect adjacent tracks. Also the shim was adequately supported, both were achieved by mounting the strip on a base plate which had ridges under the junction of the tracks. The cheapest satisfactory method of producing the strip is etching in shim from a master produced on a numerically controlled machine.

Control Nozzles - The control nozzles used are of the back pressure type integral with an amplifying element. Little detailed work has been published on the use of such jets, but from previous experience it was considered that for satisfactory jet pressure rise time and definition the jet should be rectangular in shape, at least 10 to 20% narrower than the digit to be sensed, and have an aspect ratio of 3 to 6. The sensing gap is critical particularly as the jet size decreases. This meant that the encoder was designed to maintain this gap between 0.0005 and 0.001 in; since the smallest digit was 0.005 in (125 μ m) a jet of 0.004 in (100 μ m) width was used.

Integration of Control System

The final configuration adopted for the linear encoder is shown in fig. 9 together with the velocity selection circuit fig. 10 which is representative of the circuit designs developed in the control report.

The various elements of the control system outlined above, together with the code converters, comparator and velocity control, which it was felt were too detailed to be relevant to this report are fully described in the main report (ref. 5).

Conclusions

The design project was interesting and challenging and provided the team of post-graduate students with the opportunity to exploit their uninhibited ideas in the design of a machine tool.

In the bid for innovation as well as economy practicability was not thrown out of the window; at all times the requirements of the shop floor such as part programming, ease of machine setting and maintenance were carefully considered.

Following such a detailed design study the team engaged on the project would like to see an industrial organisation take advantage of this work and develop a machine for sale as a piece of commercial equipment. In view of the many new and unusual features within the machine and control system, the amount of development work required could be considerable and it is suggested that a possible solution would be for a joint project involving the College, and the organisation.

It was clear from the replies to the technical survey that there is a need for a machine with this specification, so that, following development and manufacture, a machine of this type could have a very promising commercial future. The benefits to industry of such a versatile machine could be considerable.

References

1. Moll H. H. A Users Viewpoint of the Machine Tool of the Future
2. - Report of the Technical Survey Committee, College of Aeronautics Memo 155, Cranfield 1968.
3. - Report of Concept & Configuration Committees, College of Aeronautics, Cranfield 1968.
4. - Report of Design Committee, College of Aeronautics Memo 176, Cranfield 1968.
5. - Report of Control Systems Committee, College of Aeronautics Memo 167, Cranfield 1968.

APPENDIX I

MASTER PROGRAMME

Policy decisions concerning the design project and the formation of committees were made at the meetings of the Project Board, and it was the function of the Master Programme committee to implement these decisions and to co-ordinate the activities of all students engaged on the design project.

It was also the role of this committee to advise the Board on the various committees that would be required in order to achieve the aims of the project and further to define the terms of reference for these committees.

The number of committees formed during this project and the distribution of students among these committees is shown on the Committee Allocation Chart fig. A-1. A P.E.R.T. chart fig. A-2 was compiled at the outset of the project and it was interesting to note that a reasonably close correlation of the running of the project was achieved to that outlined.

Project Survey

The terms of reference for the design project was "the design of a linear path system", and although initially five machines were considered it was decided to form three Concept Committees to prepare machine concepts of three of these. The concept submitted by one of these committees, which was for a turning machine with a limited milling facility, was adopted. To assist in designing a machine which would meet the requirements of a large section of the market it was decided to conduct a survey and to cover a wide as cross-section of the industry as possible.

To do this effectively a Technical Survey Committee was formed whose function was to compile the questionnaire, conduct the survey and analyse the replies. A questionnaire was compiled which requested information on such things as the percentage of turned components which required milling operations, the diameter to length ratios of components, the number of tools, both turning and milling, required per set up and so on. From the replies a statistical analysis was applied and the findings enabled the parameters of the machine specification to be formulated.

It was at this stage that a Configuration Committee was formed to prepare a machine design which would meet the requirements put forward by the Technical Survey Committee. Following the adoption of this design two main committees were formed whose role was to take the design project to a final solution. These committees

were the Design Committee and Control Systems Committee and between them they absorbed every student on the project. The Design Committee was sub-divided into five sub-committees and the Control Systems Committee into two, as shown on Committee Allocation Chart.

PROJECT BOARD 1967/8

Student Members

H. Bera,
Lecturer (Production Engineering),
University of Bogota,
Columbia,
South America.

R. A. Crooks, B.Sc.,
Development Engineer,
Dowty Technical Developments Ltd., (Sponsor)
Cheltenham.

R. V. Jones,
Manufacturing Processes Engineer,
English Electric Company Ltd.,
Rugby.

A. Melsom, B.Sc.(Hons.),
Production Control Engineer,
English Electric Company Ltd., (Sponsor)
Rugby.

M. L. Norton,
Production Engineer,
Marconi Company Ltd., (Sponsor)
Chelmsford.

N. M. Powell, C.Eng., A.M.I.Mech.E., A.M.I.Prod.E.,
Senior Lecturer,
Hatfield College of Technology, (Sponsor)
Hatfield.

M. Rajkumar, B.E.
Executive Engineer,
Ministry of Works,
N. Nigeria.

M. F. Scarffe,
Engineer,
L. Newmark (Sponsor)
Croyden.

B. S. Sodhi,
Research Assistant,
College of Aeronautics,
Cranfield.

A. V. Terry,
Research & Development Engineer,
International Computers Ltd. (Sponsor),
Stevenage.

V. A. M. White,
Research Engineer,
Marconi Company Ltd., (Sponsor)
Chelmsford.

Staff Members

R. E. Bidgood, D.A.E., C.Eng., M.I.Mech.E., M.Inst.M.C.,
Lecturer, (Fluid & Fluidic Systems).

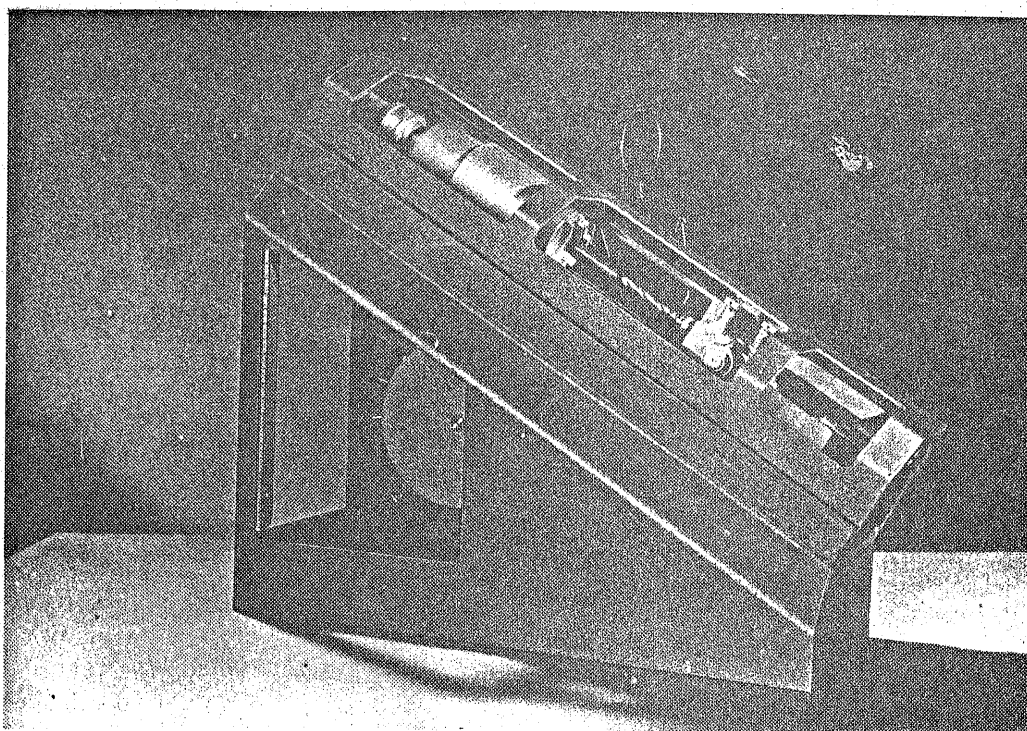
C. J. Charnley, B.Sc.(Eng), C.Eng., M.I.Prod.E., M.Inst.M.C.,
Senior Lecturer (Machines & Automation).

P. Cooke, D.A.E., A.M.C.S.T., C.Eng., M.I.Prod.E., M.I.Mech.E.,
Senior Research Engineer.

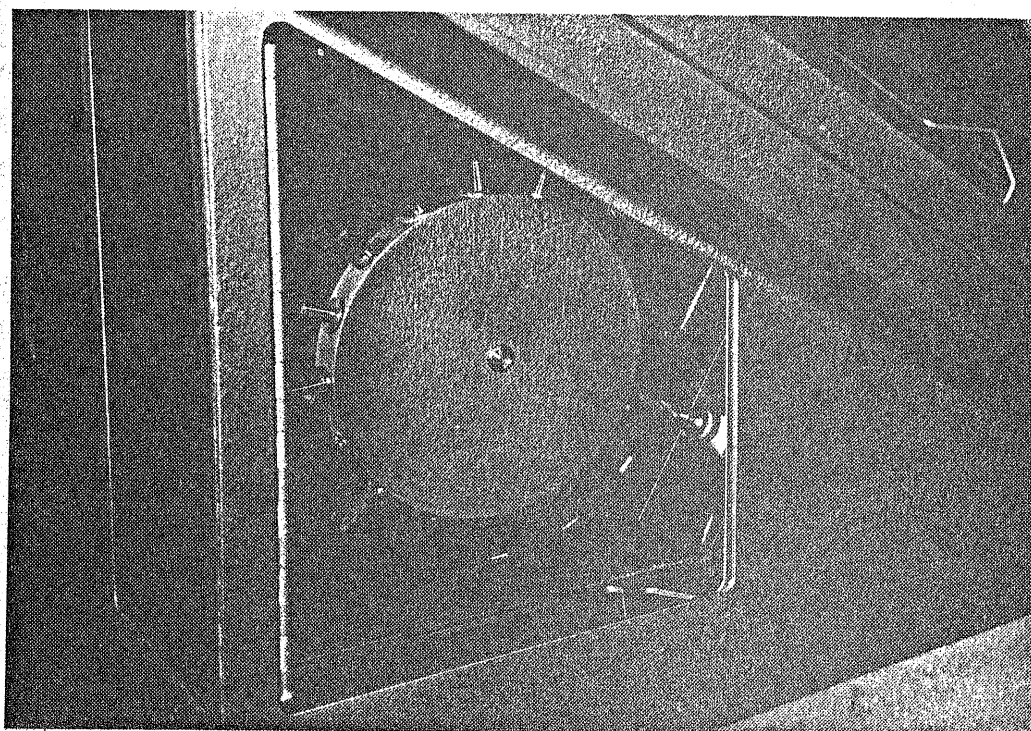
E. A. Powell, D.A.E.,
Research Fellow.

S. Ramanathan, B.E., D.A.E.,
Research Fellow.

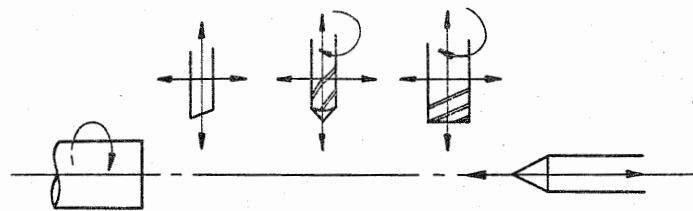
A. J. Scarr, D.C.Ae., Dip.Aero., C.Eng., F.I.Mech.E., F.I.Prod.E.,
Senior Lecturer, (Precision Engineering). A.F.R.Ae.S.,



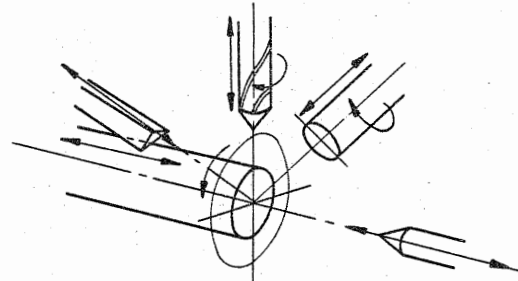
a) General view with top cover cut-away to show moving headstock with integral hydrostatic drive motor



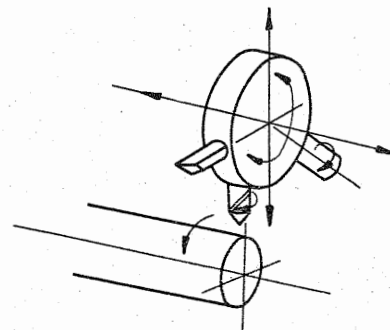
b) Close up of tool changing magazine



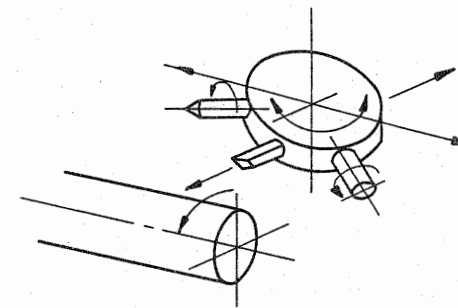
a) Basic relationships.



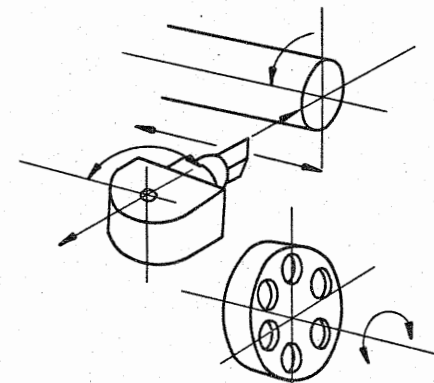
b) Radial displacement of tools.



c) Drum displacement of tools.



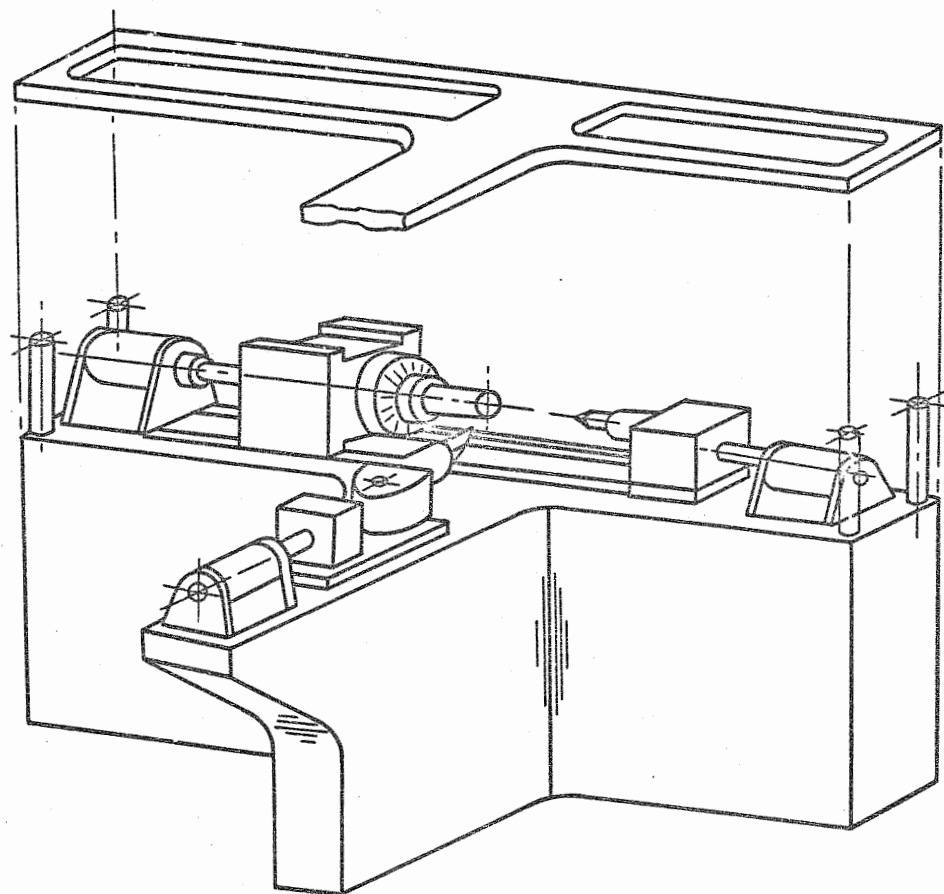
d) Turret displacement of tools.



e) Magazine displacement of tools.

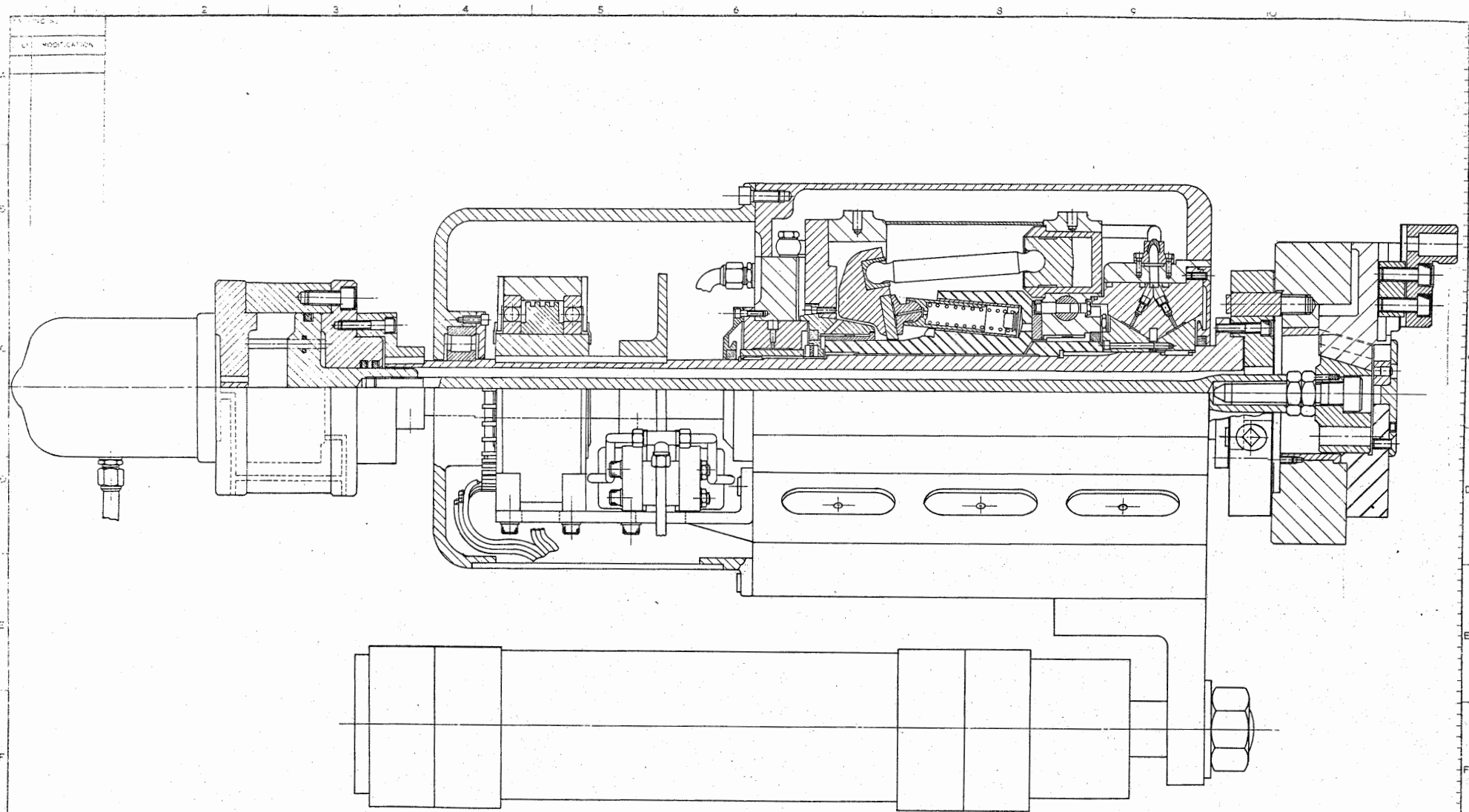
WORK PIECE — CUTTING TOOL REQUIREMENTS

Fig. 2.



PROPOSED MACHINE CONFIGURATION.

Fig. 3.

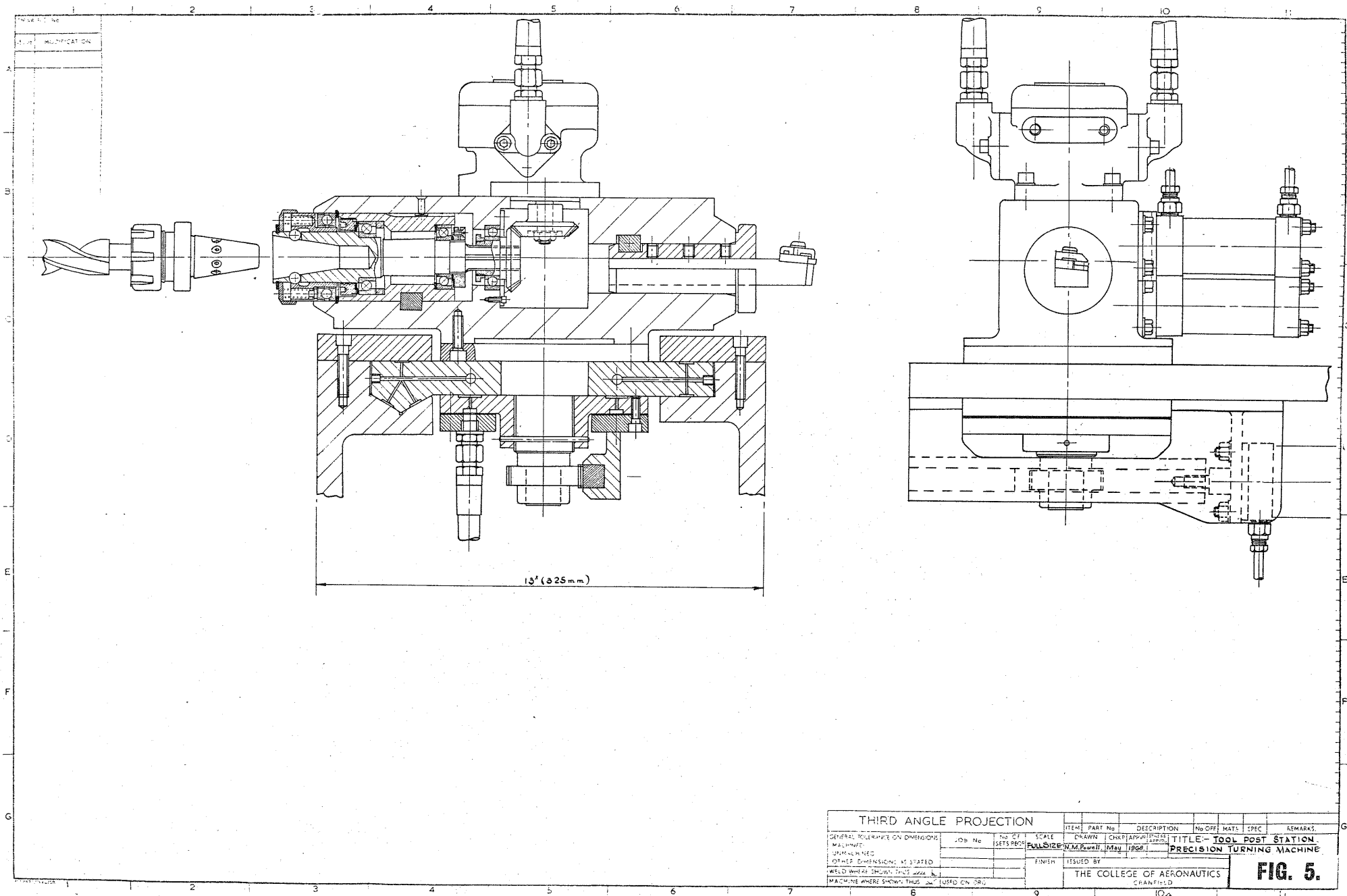


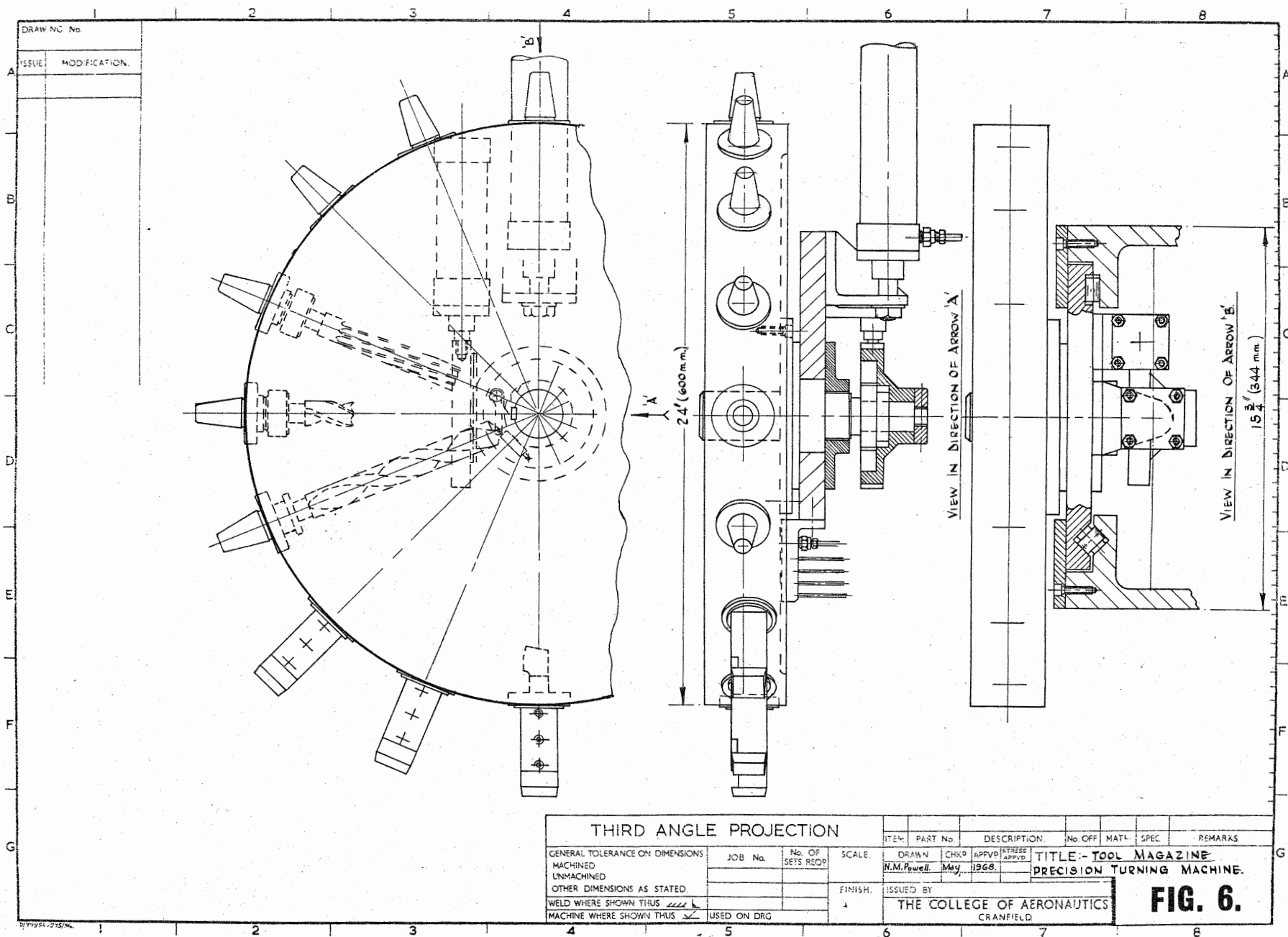
6 in.
150 mm.

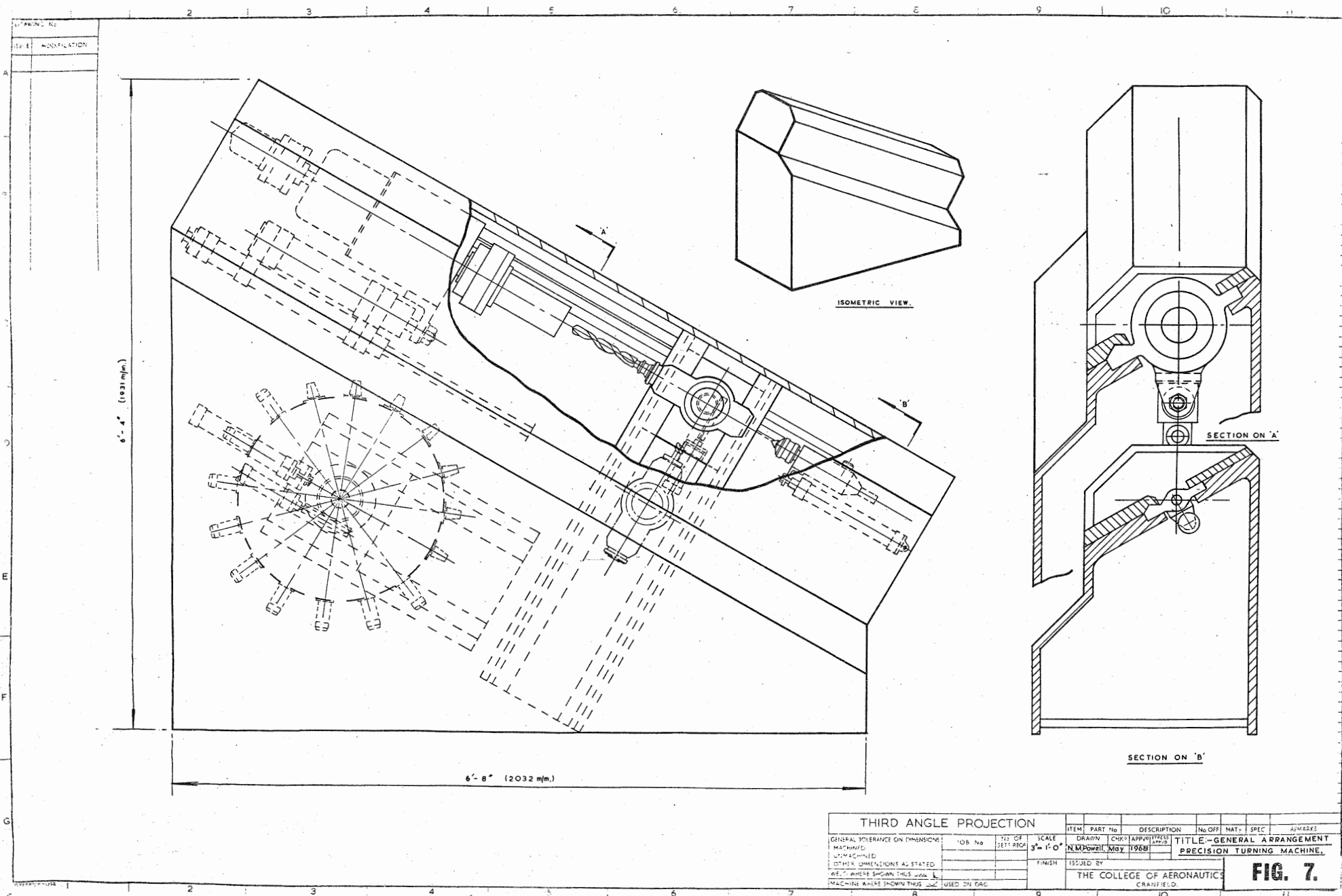
THIRD ANGLE PROJECTION				ITEM	PART NO.	DESCRIPTION	FIG. OFF.	MATERIAL	DATE	REVISION
GENERAL TOLERANCE UNLESS OTHERWISE SPECIFIED	1/32 IN.	NO. OF	SCALE	DATE	BY	APPROVED	TITLE -- HEADSTOCK ASSEMBLY			
MACHINED		SETS	FULL		A.V. Jerry	May 1968				
UNMACHINED										
WELDED										
ASSEMBLED										
PAINTED										
FINISHED										
TESTED										
INSPECTED										
APPROVED										

THE COLLEGE OF AERONAUTICS

FIG. 4.

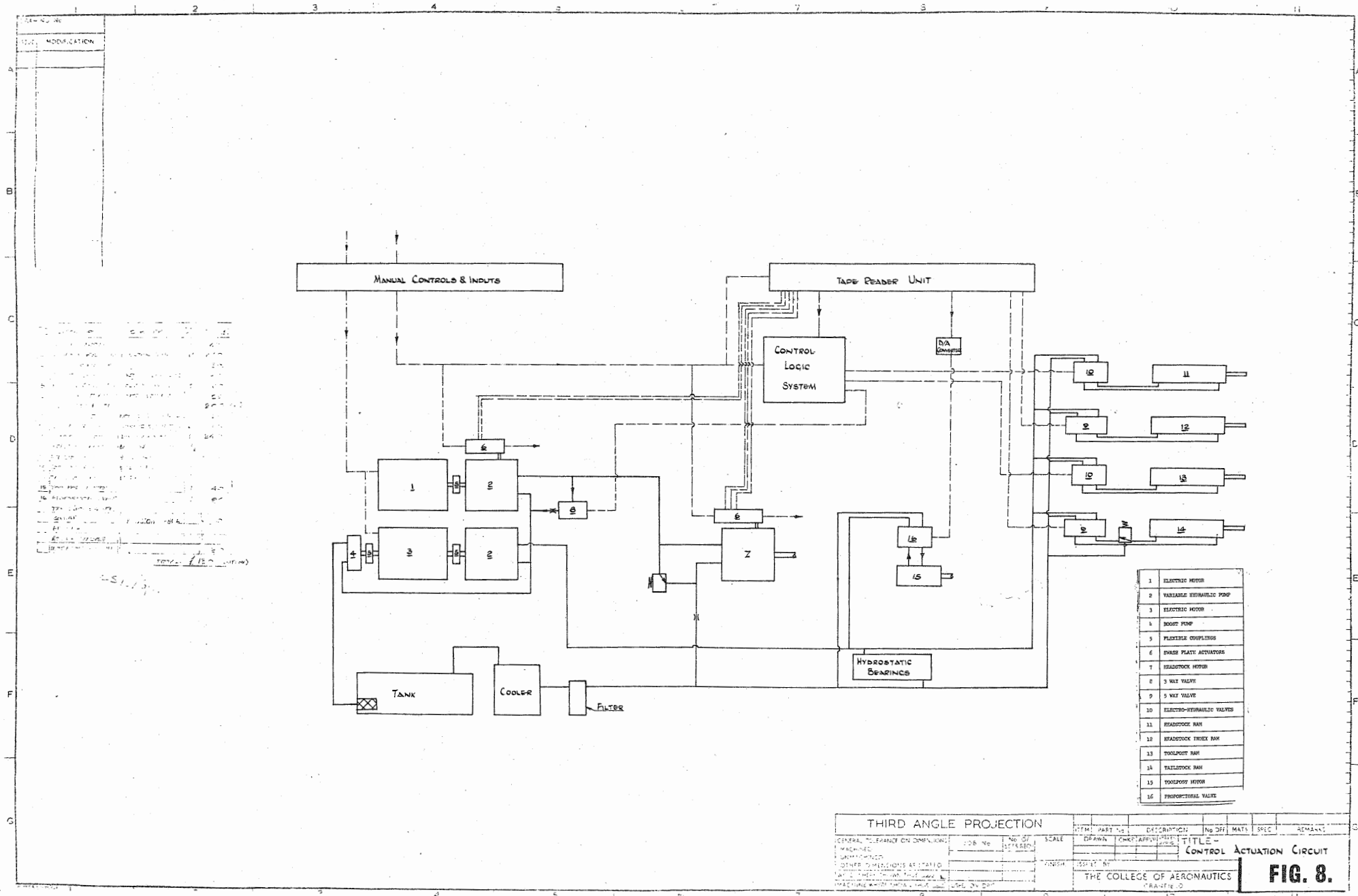


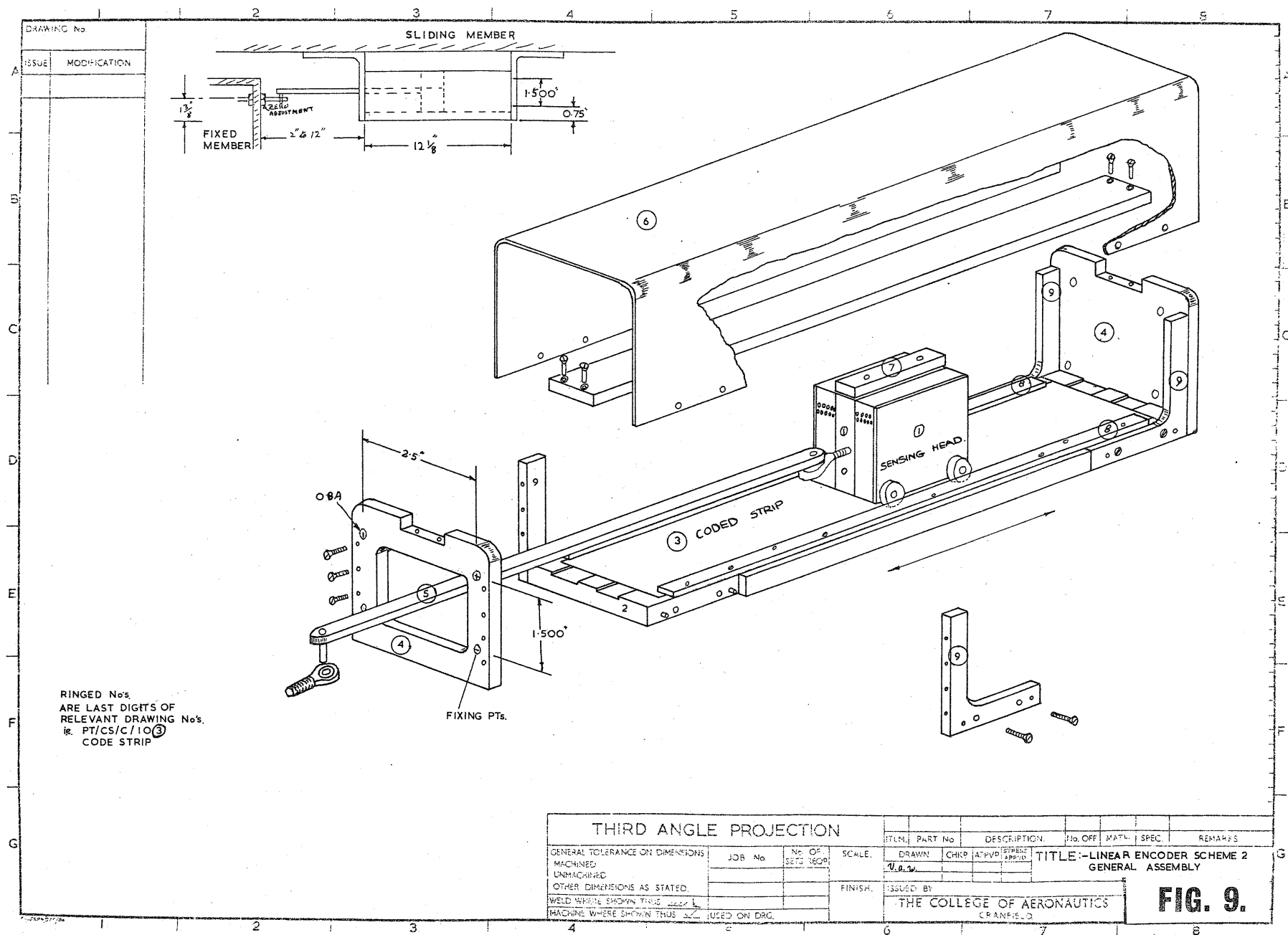


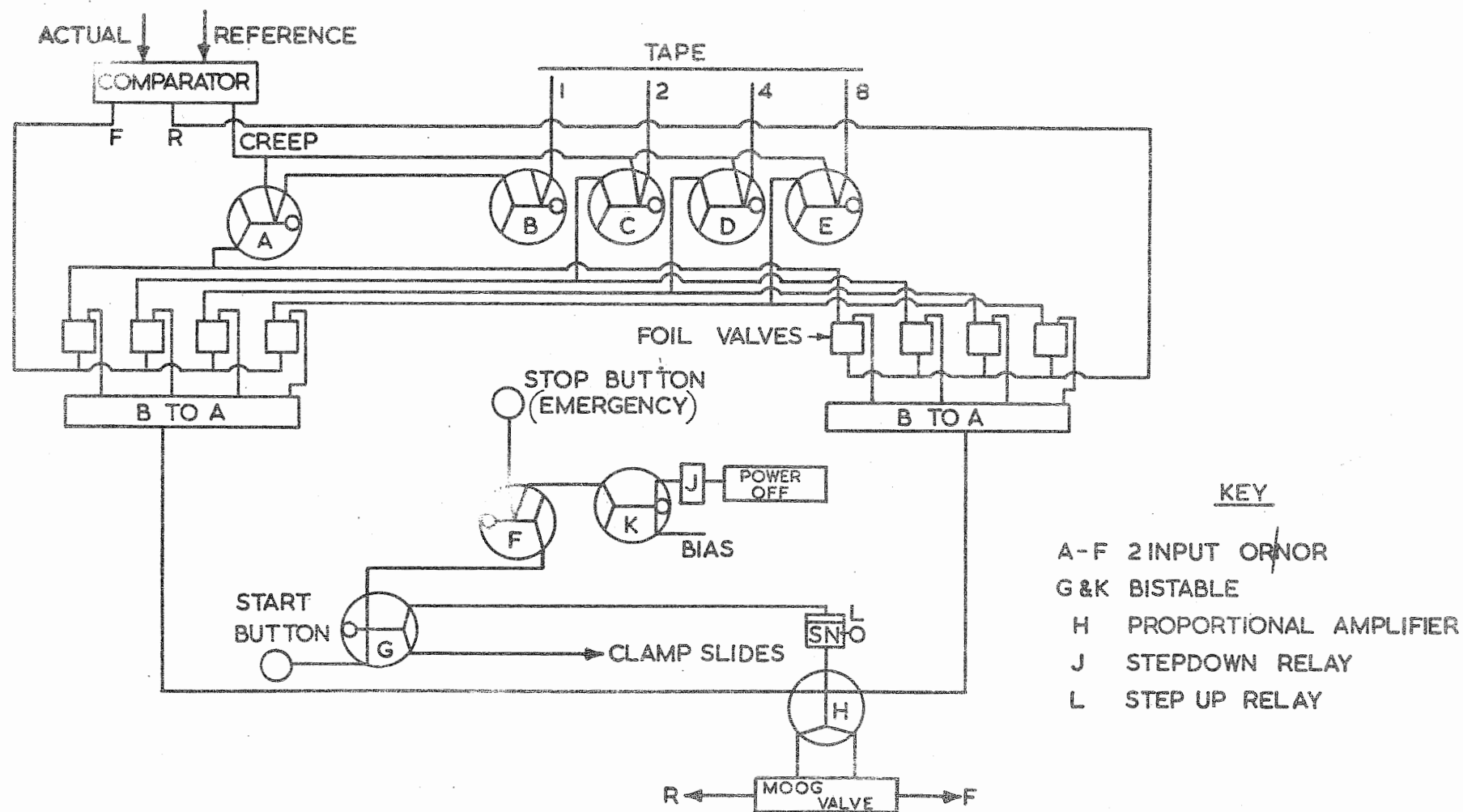


THIRD ANGLE PROJECTION				ITEM	PART No	DESCRIPTION	No OFF	MAT	SPEC	AMARKS	
GENERAL TOLERANCE ON DIMENSIONS:				DRAWN	CHKD	APPROV	DATE	TITLE - GENERAL ARRANGEMENT			
MACHINE				N.M.P.	W.	M.	1968	PRECISION TURNING MACHINE.			
OTHER DIMENSIONS AS STATED				FINISH		ISSUED BY		<div>FIG. 7.</div> <div>THE COLLEGE OF AERONAUTICS CRANFIELD</div>			
SECTION WHERE SHOWN THIS J224				USED ON DAG							
MACHINE WHERE SHOWN THIS J224											

FIG. 7.







VELOCITY SELECTION CIRCUIT

FIG. 10

ROOM No.		L.O	L.O	122	188	L.O	14	94	220	93	L.O	L.O	BUILDING 30					TERMS OF REFERENCE	
COMMITTEES	NAMES OF BOARD MEMBERS	H. BERA	R. CROOKS	R. JONES	A. MELSOM	M. NORTON	N. POWELL	M. RAJKUMAR	M. SCARFFE	B. SODHI	A. TERRY	V. WHITE	R.E.BIDGOOD	C.J.CHARNLEY	P. COOKE	E. POWELL	S. RAMANATHAN		A. SCARR
MASTER PROGRAMME COMMITTEE		C				M				M				A					TO PREPARE MASTER PROGRAMME AND TO SUBMIT FINAL REPORT.
TECHNICAL SURVEY COMMITTEE				M	M				C	M	M					A			TO ASSESS MARKET REQUIREMENTS AND TO PREPARE FINAL MACHINE SPECIFICATION
SUB COMMITTEES	AIRCRAFT AND ACCESSORIES		M	S					M										
	MOTOR AND ACCESSORIES							M	S										
	ELECTRONICS AND COMPUTING					M					S	M							
	MACHINE TOOL AND ACCESSORIES	M								S									
	PRECISION EQUIP. & INSTRUMENTS				S		M												
CONFIGURATION COMMITTEE							M		M				C			A			TO SUBMIT A FINAL MACHINE CONFIGURATION
CONCEPT COMMITTEE	COMMITTEE A	M			M		S			M									
	COMMITTEE B					M					M	S							
	COMMITTEE C		M	M				M	S										
CONTROL SYSTEM COMMITTEE		M			C	M			M			M	A			A	A		TO DESIGN A FINAL ADOPTED CONTROL SYSTEM
	CONTROL ACTUATION		M		C														
	CONTROL LOGIC	M				M			M			C							
DESIGN COMMITTEE				C			M	M		M	S				A			A	TO UNDERTAKE DETAIL DESIGN OF MACHINE
SUB COMMITTEES	HEADSTOCK AND WORK LOADING		M	M							C								
	TAIL STOCK, CUT, LUB, SWARF	M		M				M		C									
	TOOL POST AND TOOL LOADING				M		M	C											
	FRAME AND SLIDEWAYS					M	C		M										
	AESTHETIC, ERGO. AND MODEL	M								C		M							

PT/MPC/6/16

COMMITTEE ALLOCATION CHART.

M - MEMBER
C - CHAIRMAN
A - ADVISOR
S - SECRETARY

FIG. I-1.

