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ORR Rof :

The Nottingham Trent University

Department of Electrical
and
Electronic Engineering

System Design of a Three Dimensional Co-ordinate Measuring Machine

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ABSTRACT

The aim of the project was to produce a new motor control system for the range of Three Dimensional Co-ordinate Measuring Machines (CMM) manufactured at W.A.Metrology, Forbes Close, Long Eaton. The design and implementation of this new generation of Measuring Machines which has created a product to enter an expanding export trade especially in the European single market. The thesis explains about the Measuring Machine industry showing how and why components are measured on Co-ordinate Measuring Machines and indicating how the procurement of a CMM can be justified.

The thesis will show how the existing controller used at W.A.Metrology needed to be improved to enable the company to compete in this high technology industry. An embedded processor was chosen from bench mark tests made on different processors. It was shown from these tests that the Transputer was five times faster in executing the same code as its main competitors. The Transputer was shown to lend itself very easily to the design of the controller, using 16 bit transputers to control the readout, drive and handbox, and a 32 bit transputer with a co-processor to control the move algorithm and the mathematical calculations. The electronic configuration of the control system is explained, showing how the system interconnects and communicates using the Inmos links. The modular design of the electronics is shown indicating how each of the components of the system are independent of each other. The parallel processes on each of the transputers are indicated showing how the system interconnects in software.

The performance of the new controller is shown to accelerate and decelerate over ten times faster than the previous system. The loop time of the new controller has decreased from 64 milliseconds to a possible one millisecond allowing greater control over the movement of the Measuring Machine. The results of the move algorithm enables a move tunnel of less than 100 microns enabling the measuring probe to move very accurately round the work piece. The adaptive design of the controller is shown with the addition of the non-contact probing system which was added to the control system by using an Inmos link and simple protocol. The overall improved performance of the new controller has enable parts to be measured up to four times faster than the previous controller without changing the mechanical construction of the Measuring Machine.

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1.0 INTRODUCTION

1.1 The Metrology Industry

A standard Co-ordinate Measuring Machine (CMM) consists of a very flat granite base, a moving bridge and a probe, which together can measure an object in three dimensional space. The purpose of these machines is to measure manufactured parts to verify that they are machined to the correct specification. For many parts particularly in the aircraft industry the tolerance of components is usually +/-20 microns and therefore the measuring machine must perform to an accuracy of greater than +/-2 microns. The accuracy is such that conformance to the specifications will virtually guarantee that the parts will interlock. The most significant users of CMM machines are the motor industry and the aircraft industry and their suppliers where increasing accuracy levels are demanded.[19]

Recently "just-in-time" programmes have increased the pressure on suppliers of these parts to adhere rigorously to specification. Increasingly suppliers are being subjected to batch rejection of highly valuable parts if accuracy's are not maintained on individual units. This has promoted the use of CMM machines to measure all such units and often to have this measuring process as part of the line production operation; often the equipment is actually sited alongside a major production line. It can be integrated into the line by moving parts by robots into position.

An important element of the CMM machine is its computer controller which can rapidly measure quantities of individual units, presented to it. This measuring time is an important element of the efficiency of the metrology equipment.[21]

In order for a supplier to prove that his parts conform to specification, printouts are available of each item measured. This is clearly leading to a "zero defect" mentality within the suppliers normal production operations which is the hallmark of a just-in-time operation as far as the customer is concerned.

The 1980's thus saw an enormous expansion in the production and sales of CMM equipment. Installation occurred in almost all advanced engineering environments where accuracy was an essential ingredient of the part produced. Another major reason for the introduction of this equipment has been the improved efficiency of the metrology equipment when compared to conventional manual inspection times; an individual components might take 4.5 man hours against a CMM inspection time of as little as 12 minutes. Increasing labour costs have therefore added to the advantages of inspection equipment.

Within the UK there is a potential market of £20M p.a. with a world potential of over £400M. In the last two years the recession has lead to a fall in demand for capital goods in the market, demand is now increasing again, sales in the Pacific area will be particularly significant in the next year as America. Aerospace joint ventures begin there. In addition, there will be a competitive advantage for companies operating within the E.E.C. as a result of the single market.

1.2 Outline of Project

There is a much greater emphasis on Co-ordinate Measuring Machines to measure components both faster and with a greater accuracy. This is because customers requirements are changing due to increased competition in the market place. A larger number of companies are turning to 100% inspection of their manufactured parts and placing a CMM on the end of the production line. The time taken to measure the component will directly effect the output of the production line and hence customers are asking for shorter times to measure their parts.

The increase in speed is also required by customers who measure batch samples of manufactured components and want to increase the batch size in order to produce a greater statistical reliability from the CMM results. The greater emphasis applied to the reliability of products is being forced on the measuring machine industry by customers requesting much higher tolerances. Hence, the need for measuring machines to be a lot more accurate to achieve the required specifications.

The overall project specification was to produce a embedded control system for a 3-dimensional co-ordinate measuring machine which would reduce the time to measure components by up to 50% and do so more accurately.

The hardware system should incorporate the design of a motor control system, using digital techniques, to improve the ability to control the movement in the x y and z directions and also reduce the steady state drift caused by the present servo's. The motor must be able to accelerate uniformly to a maximum rate and then decelerate to stop at the correct position to a high degree of accuracy. Also, it is necessary to be able to turn the motors slowly so that the measuring probe can be placed in any position to an accuracy of ten microns.

1.3 Thesis outline

This thesis demonstrates the need for an improved control system and the method used to achieve this. The existing system is outlined showing its components and how it operates. The thesis outlines the design criteria used to arrive at the transputer based control system and all the advantages of this parallel system over a two processor serial control system. It will also show how the hardware and software of the system lend to parallelism to produce a modular design which can be used for the different products produced by W A Metrology. The main advantages of a multi processor transputer system are discussed showing how the increased loop time of the system is achieved.

The actual hardware design and the method of operations of the various PCB's is discussed. Indicating the main problems arising during the design process and showing how these problems were overcome.

2.0 Co-ordinate Measuring Machines

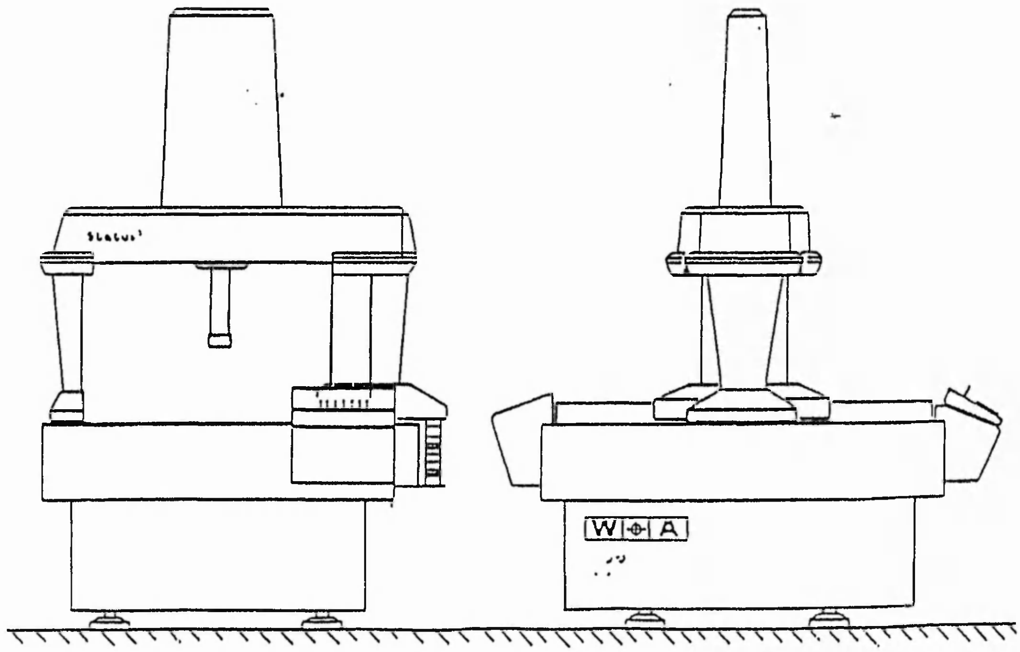


Figure 1 A Co-ordinate Measuring Machine.

A three-dimensional Co-ordinate Measuring Machine (CMM) is an inspection tool which determines the physical size of objects by measuring them using a touch probe or an optical probe either manually or computer numerical controlled (CNC).[18]

Co-ordinate measuring machines offer large savings in inspection time when measuring manufactured parts. The conventional method of inspection of machine parts was done with micrometers and height gauges. This was both time consuming and labour intensive and had the drawback that no two inspectors would obtain the same results and so repeatability is difficult to obtain. The introduction of CMM's using CNC programs produced an inspection technique that reduced inspection time by up to 90 percent without the need for an inspector to be present throughout the measuring process, with the advantage of repeatability (The part being measured more than once and the same results being obtained each time) of the measured part.

The CMM introduced batch processing, a technique of measuring more than one machine part without the need for human intervention by placing a number of components on the machine bed and measuring all the components using a part program. The introduction of batch processing direct from the production line enables a larger number of complex manufactured parts to be measured and statistical process control (SPC) software can be applied to the results. This information can then be used to adjust the cutting tools or lathe to correct the manufacturing process.[20]

The greater emphasis now placed on quality control within the Aerospace, Motor vehicle, Defence and Manufacturing industries ensures a greater demand for CMM's which can measure manufactured parts with greater accuracy and also much faster than before. The main purpose for a faster CMM is to enable one hundred percent inspection of components directly from the production line.

The main material used in the construction of the CMM's produced at W.A.Metrology is granite. This is an ideal material for the construction of CMM's having a significantly lower coefficient of expansion than steel, cast iron or aluminium(see table 1), but with similar density to aluminium (see table 2).[2]

Table 1

Linear expansion per unit lengt per degree centigrade	
Cast Iron	11.7×10^{-6}
Steel	11.3×10^{-6}
Aluminium	22.0×10^{-6}
Granite	7.92×10^{-6}

Table 2

	Weight per cubic foot (Kg)
Cast Iron	198.99
Steel	221.81
Aluminium	76.43
Granite	76.20

The granite slabs are of a very high surface grade (Grade-0 surface plate finish conforming to BS817 1983) and only available from France, Italy, USA and South Africa.

2.1 The Construction of a CMM

The construction of a CMM consists of a large granite bed which can vary in size from approx. 0.3m by 0.3m to approx. 5m by 3m.

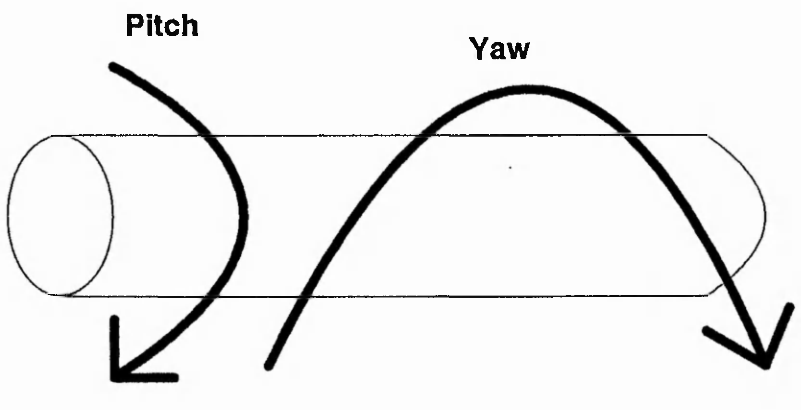


Figure 2 Pitch and Yaw of a CMM

A bridge is constructed out of granite (This is designed on the kinematic principle of triangulation to reduce the pitch and yaw of the bridge see fig 2) and is placed on top of the granite bed. Both ends of the bridge are floated on air bearings (air bearings are phosphor bronze blocks, connected in series, with a hole through the middle to allow pressurised air to pass through the bearing block and on to the next block; a small pin hole, 0.4 mm, is then drilled from the top surface which allows the pressurised air to escape). Only a few air bearings are needed to lift several tonnes of granite bridge allowing the bridge to be almost frictionless as it moves up and down the granite bed. A granite dovetail is fixed along one side of the bed which holds the bridge in place, the bridge is held to the granite dovetail with air bearings which prevents the movement of the bridge to the left or right whilst it moves down the table. This provides a linear accuracy of 2 microns/meter along the whole length of the table. The direction of motion of the moving bridge is always referred to as its x-axis.

A spindle (a square column with a linear accuracy of 2 microns/meter) provides the Z-axis (vertical) measuring range. The spindle is counterbalanced by means of lead weights, the guidance is again obtained by the means of air bearings enclosed within a carriage. The horizontal movement of the spindle is the Y-axis. The movement of the bridge and the spindle on the granite plate provides three degrees of freedom; a fourth is sometimes added in the form of a rotary table known as the R-axis.

2.2 Touch Probes and Stylus

A probe and stylus is placed at the end of the spindle which is used to determine the position within the three-dimensional envelope of the measuring machine. The various probes available are fixed, motorised or optical probes; the styli mounted on the probes can also vary on the part being measured.

A stylus is mounted directly into the probe, the stylus is that part of the measuring system which makes contact with the component causing the probe to produce a trigger signal. The type and size of stylus used is dictated by the feature to be inspected. In all cases, however, maximum rigidity and sphericity of the stylus are vital. There are three main types of styli.[1]

◆ Ruby Ball Styli

This incorporates a highly spherical industrial ruby ball. Ruby is an extremely hard crystalline material and hence wear of stylus balls is minimised. It is also of low density keeping tip mass to a minimum which avoids unwanted probe triggers caused by machine motion or vibration.[1]

◆ Star Styli

Star styli offer multiple tip probing of complex features and bores. Four or five ruby ball stems are mounted rigidly on a stainless steel centre, with several sizes available.[1]

♦ Disc Styli

These styli are used to probe undercuts and grooves within bores which are inaccessible by star styli. They are "sections" of highly spherical balls and are available in various diameters and thickness.[1]

♦ The Fixed Probe

The fixed probe is mounted directly into the spindle. It is the device which signals to the CMM that a contact has been made between the stylus ruby ball and the work piece surface. The precise co-ordinates at the point of contact can then be read and stored by the CMM. The probe is designed around the kinematic principle, figure 3 illustrates the principle of triangulation by ensuring that the probe comes to rest in same position after each probe hit and that only a small deflection of the probe is needed to trigger the probe.

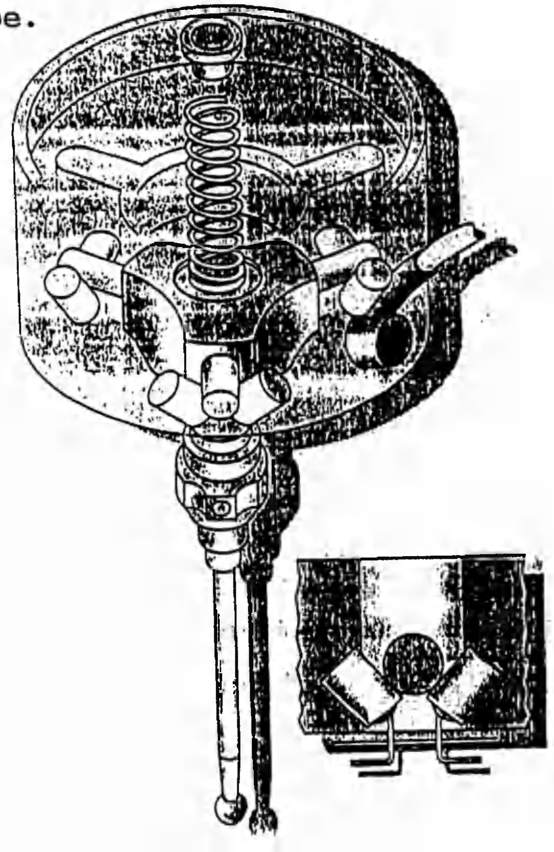


Figure 3 The Touch Probe

◆ The 3-Dimensional Probe

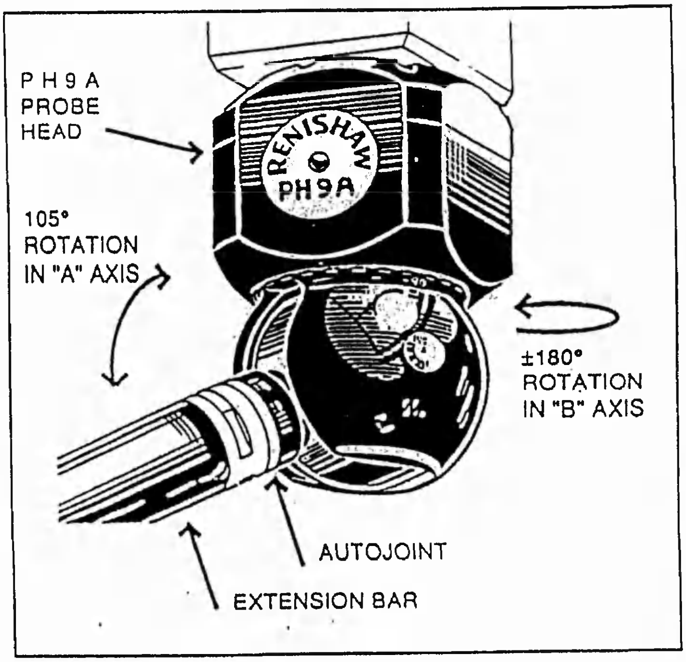


Figure 4 Renishaw PH9

The probe produced by Renishaw Metrology rotates by 105 degree up and down and by 360 degrees left to right. The movement of the probe enables very complex areas on machine parts to be measured. The probe has been designed to position in any one of 720 positions in steps of 7.5 degrees. There are 15 discrete positions through 105 degrees in the "A" axis and 48 positions through the +/- 180 degrees in the "B" axis (see diagram). The vast number of alternative positions means that probing can be carried out from many different angles. The fixed probe head is attached to the motorised probe directly or with special extension pieces, this effectively produces an extra three degrees of freedom to the measuring machine.[1][22]

2.3 Justification For The Procurement Of A Co-ordinate Measuring Machine (CMM)

The inspection operation within the manufacturing industry is an important part of Total Product Quality Assurance. The true purpose of inspection is not to segregate good components from rejects after manufacture, but to prevent non-conformance occurring in the first place. The segregation operation is expensive in terms of time; manpower; scrap and rectification.[18]

The act of inspection involves the following:

Measurement
Recording
Analysis
Decision
Action

Independent of whatever inspection method is adopted, the parameters of analysis; decision and action are similar, except for developments in recording which will make analysis and decision easier. The two parameters which have the influence on cost of inspection are:

Measurement
Recording

It is in the above two processes that the Co-ordinate Measuring Machine has the most to offer in terms of savings. Many industrial assessments have shown that when Co-ordinate Measuring Machines are introduced into the manufacturing process they can reduce inspection times by up to 90% when compared with conventional inspection techniques. Furthermore the automatic recording of results ensures a true representation of the component quality independent of Inspector/Operator.

♦ Benefits Associated with Co-ordinate Measuring Machines

Increasingly, drawings, especially from the aerospace and automotive industry, are CAD (Computer Aided Design) generated. This means datum reference points and other measured-elements are often not conventionally placed, i.e. theoretical planes and points in space. This leads to subtle changes in shape and form, often very complicated which can no longer be measured by first principles. Therefore, it would also be very difficult to produce by the manufacturer.

Both Rolls Royce and BNFL are committed to SQVP (Supplier Quality Verification Procedure). By adopting SQVP, the onus of total quality is placed with the supplier. Parts go directly into the customers' stores and if incorrect are only found when withdrawn for build. The manufacturer must be in a position to guarantee the accuracy of the product.

♦ Disadvantages

- Conventional equipment is able to measure only one dimension at a time, which is slow and therefore costly.

- Without manual calculation one dimension cannot be related to another.

- The need to borrow Tool Room capacity by using the jig borer for inspection purposes.

- Inability of special purpose inspection fixtures to cope with changes or modifications to a component. Fixtures become inoperative for the period of change to accommodate modification whilst production continues.

- Dedicated special purpose gauges are expensive and when associated with a market-led product have to be written off over the life of a product. (Product lives are reducing due to increased market competition).

- The high labour content associated with conventional productivity increases.

- Little or no ability of Statistical Process Control (SPC).

♦ Advantages

- Elimination of requirement for component alignment tooling. Components need only to be roughly aligned on the machine table. Datum's are established and features are inspected with respect to the component reference system created.

- No requirement to reset component through 90 degrees to enable Bore Centre Lines to be established.

- Provision of a measuring system which is indisputable on complex components when existing inspection techniques are found wanting.

- Greater assurance of measurement and to an accuracy machine tools.

- Microprocessor Control enables all calculations to be made with regard to any of the following Geometric Elements/Features: POINT; LINE; PLANE; CIRCLE; SPHERE; CYLINDER; CONE; Thus eliminating lengthy manual calculations and the possibility of errors.

- Advanced electronics and measuring capability leading to reduced inspection times and a quicker assessment of component conformance. The average time to check a "point" is 1.2 seconds, therefore, the time to check a bore by 4 points would be 4.8 seconds. The information obtained in this time and printed out is as follows:

  Circle Diameter.
  Centroid Co-ordinates with respect to present datum (Rectangular & Polar Co-ordinates).
  Comparison with drawing information, including:
  Actual Size.
  Theoretical Size.
  Upper Tolerance.
  Lower Tolerance.
  Deviation (if any).

- The saving in inspection time must also be related to the hourly cost of Machine Tools whilst they are idle hours to check a component by conventional techniques, the true cost of the inspection operation is as follows:

  Down time of machine tool at hourly rate.
  Inspection cost.
  Value of lost production.

  As an identical cost relationship has to be made when using Co-ordinate Measuring Machines:

- More reliable information, quickly and accurately computed.

- Greater quality control as more components can be checked at any given time.

- Statistical Process Control (SPC) identifying trends.

- Reduction in scrap and rectification by actually measuring, (not to pass and fail).

- Better control of the machining process, tool wear, cutter offsets, etc.

◆ **Advantages Of Part-Program Inspection And Printout.**

- To ensure that inspection of parts takes place fully and to a planned sequence in the shortest time.

- Reduction in need to consult digital displays and relate these to drawing requirements by completing the mental or written calculations.

- Production of Inspection Reports automatically and free from human error. On complex components clerical work can occupy 25% of inspection time using conventional techniques.

- Continuity of inspection from day to day, shift to shift.

- Reduction in inspection planning time.

◆ **Areas Of Potential Savings.**

Co-ordinate Measuring Machines offer a host of potential savings in the every workshop. Most CMM applications have produced tremendous savings in time and labour and at the same time actually raised the level of RELIABILITY and QUALITY in the inspection process. In some applications the savings are obvious, in others, such as prototype layout/inspection, the potentials are unique to each company. The following represents the nine most widely used applications for Co-ordinate Measuring Machines.[23]

The actual value in savings depends upon the individual company's application and cost analysis methods:

- First Article Inspection - N/C Machines

  Conventional methods require many hours for first article inspection of N/C machined parts, CMM reduces this time dramatically. Machine down time while inspecting first article is substantially reduced; expensive rework is virtually eliminated if the process requires the machine to run during inspection. CMM is more accurate and reliable than complicated conventional methods using surface plates and height checking tools, etc.

- Special Gauging

  The CMM reduces the need for costly special gauging by its three axis versatility. The costly design, modifications and obsolescence of special gauging is avoided (the CMM is simply re-programmed to suit Modification or New component). The CMM reduces set-up and measuring time of the actual part and the required inspector skill level and human error are reduced. This gives savings in investment, inspectors skill requirements, and inspection time, for most companies. This cost analysis is easy to estimate and actual savings may be substantial.

- Receiving Inspection (Goods Inwards)

A reduction in inspection time - especially when 100% inspection is achieved. As is an increase in inspection accuracy, the opportunity to increase sample sizes and thereby increasing inspection reliability. Direct savings in inspection time, indirect savings in waste from out-of-tolerance parts in assembly and other areas of manufacturing occur. Most savings are in time "ploughed back" into larger sample sizes, etc.

- In-Process Inspection

Parts can be measured faster and more accurately, the increased frequency of sampling can create inspection reliability and scrap reduction. There is reduced time wasted by the inspector in shop and there is less skill required by inspector, with reduced human error.

- One-time Inspections

Set-up time and labour are saved for one-unit inspections requiring complicated fixtures / set-ups and skilled inspectors. Also engineering prototypes can be easily checked on all three axis, making valuable information immediately available.

- Batch Loading

  Once programmed, the CMM will operate totally unattended. This offers considerable savings in time and money, especially on overnight runs when the machine table can be loaded with components not necessarily the same.

- Trend Analysis

  Inspection of various machining method, feeds and speeds, and set-ups can be used to determine optimum machining. Sample inspection of finished product inventory can verify your final inspection methods.

- Training

  The CMM eliminates the need for skilled inspectors, experienced hands are not necessary - measuring "feel" is no longer a requirement for quality inspections, accurate and complicated measurements are easily made.

2.4 How components are measured

A CMM is an Inspection tool which determines the physical size of a machine part. This is achieved by first taking three or more points on a surface and producing a plane within the envelope of the CMM. This is called a 3D alignment, two or more points are taken on another surface to give a 2D alignment to the original plane. A datum and point is then taken which will reference the part to the 3D and 2D alignments made.

Once this process is followed the orientation of a part within the envelope will not matter provided the part does not move during the measuring process. All points taken with the probe will be reference to the datum.

The software can calculate seven Geometric Elements from points taken on the part using mathematical best fit methods:-

A point (1 point taken)
A line (two points taken)
A plane (3 points taken)
A circle (3 or more points)
A sphere (4 or more points)
A cylinder (two planes and 4 points)
A Cone (1 plane and 3 points)

The software can produce reports giving geometric form and orientation tolerances such as Cylindricity, Squareness, flatness, roundness, straightness, sphericity, conicity and concentricity. A batch of results can be put through on an SPC software program (statistical process control) to determine if a batch of parts are manufactured differently.

2.5 The Control and Operating System

The CMM control system currently used by W.A.Metrology relied upon a IBM PC computer for all of its processing power. The first systems released used an apricot Zen to control the machine and then progressed to use an IBM PC (XT or AT bus) or clone and also the IBM PS/2 range with the micro channel architecture. The processor used the I/O bus to control the various functions of the measuring machine. The machine readout, micro console 2000 and the motor speed control are memory mapped to the PC bus at the I/O addresses. There were increasing problems with the speed of IBM PC's and clones external bus, this was because of the dramatic increase in speed over the past years from 5Mhz to over 30Mhz. The logic which interfaced to the PC had to be continually updated to cope with this increase in speed. The control loop time of the controller is the major factor which determines the ability to control the machine accurately, this is the time taken to monitor the readout from the scale, calculate and output the appropriate speeds to the motors. The maximum loop time available on this system using a standard AT bus interface was 0.064 seconds (see abstract).

Block Diagram of the W.A.Metrology Control System

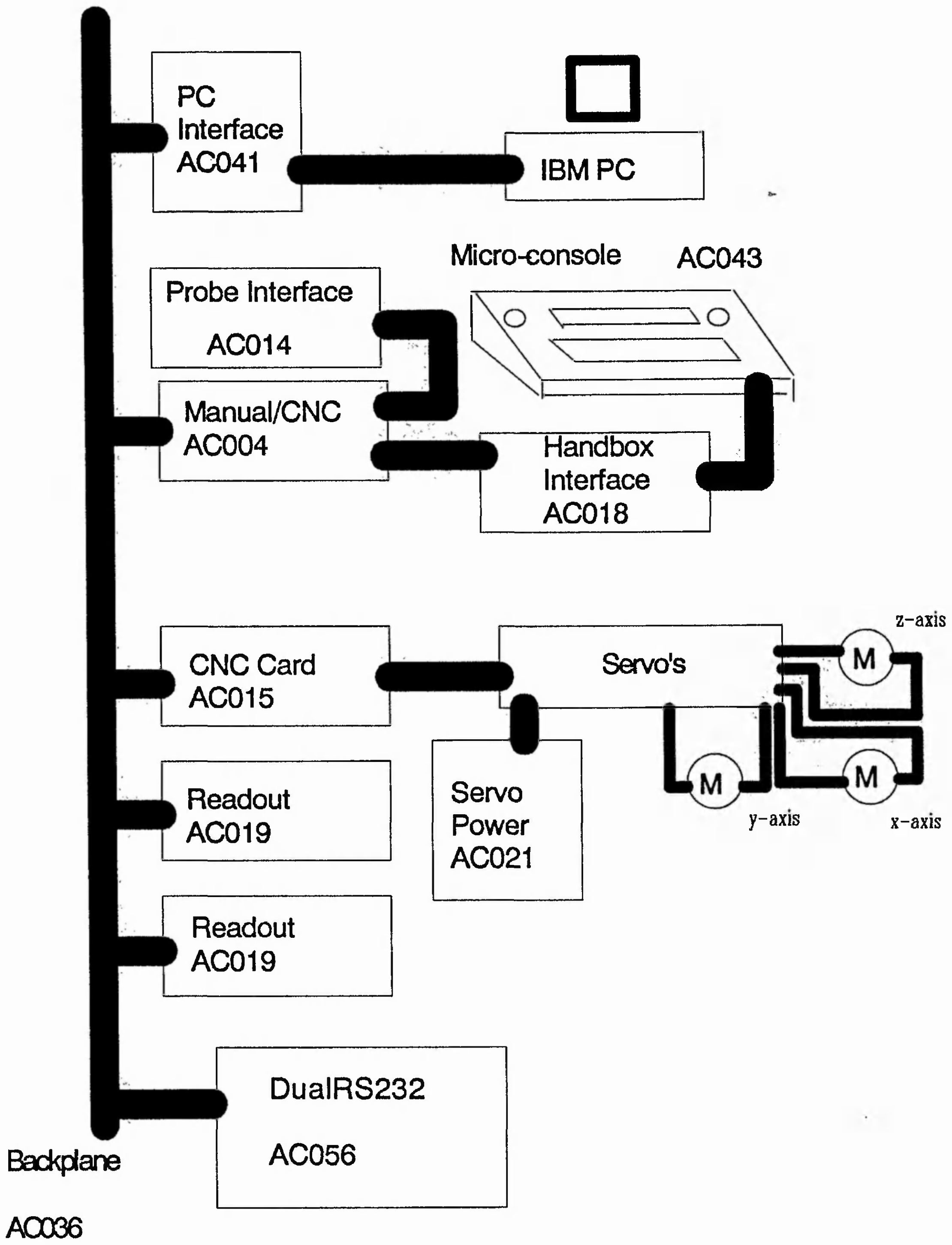


Figure 5 Block Diagram of W.A.Metrology Control System

2.6 Hardware

The existing system as shown in the schematic diagram is controlled mainly by hardware switches. The disadvantages of this type of system is that there is very little scope to alter the performance of the machine in software and a lot of importance is placed on the hardware set up of the machine. The control over the probe backoff is set in hardware which will not allow the user to vary this distance for different components, the scale zero is a hardware switch which will not allow automatic set up of the measuring machine. The acceleration and deceleration are pre-set maximums which will not allow much flexibility with the control algorithm. The various PCB's in the system are described briefly indicating the functionality of the cards.[3]

♦ AC004 MAN\CNC SWITCH

This is the manual/CNC card and is used to switch the machine operation from being controlled by the computer to being controlled by user in manual mode with the use of joysticks. It incorporates 10 diagnostic LED's on the front edge to indicate the present state of the lock and enable signals for each axis (max. 4 axis). There is an LED which indicates if the measuring machine is in CNC or manual operation and the final LED indicates if the probe is armed or unarmed. The card is fitted with two 10K pots which determine the length and volume of the probe bleep.

♦ AC014 Probe interface

This PCB is attached to the AC004 and is used to signal condition the triggered pulses from the touch probe which are passed to the PC through the MAN/CNC card.

◆ AC015 4 axis CNC interface

The main purpose of this card is to convert the digital signal from the pc bus into an analogue signal to drive the dc servos. The DC servos are intelligent motor controllers which automatically accelerate and decelerate the motors smoothly when an analogue voltage is applied to them. The probe backoff is controlled and set up by this card, it operates automatically by firstly ramping the three servos down to stop the machine when a probe detection occurs. The motor directions are reversed and the speeds reapplied to the motors for a specified time. This has the effect of moving the probe away from the surface in the same vector from which it made contact.

◆ AC018 Handbox interface

This card is electrically connected between the handbox joystick buffer amplifiers and the MAN/CNC switch card. The card detects any joystick deflection and switches on the appropriate axis servo in the appropriate direction if the machine is in manual operation, it also detects if the machine is operating in fast or slow speed by being hard wired to fast/slow switch on the handbox. This card also has the electronics to control the manual backoff of the probe when a touch occurs.

◆ AC019 Dual axis 24 bit readout card.

This card contains two complete 24 bit counters which determine the position of the measuring machine. The scales used on the measuring machine have a resolution of 20 microns and so an interpolator is (EXE) used to provide a 1 micron count in to the 24 bit counters. These counters are read directly by the PC I/O address bus to provide the computer with the positional information required to operate the machine. Each machine has two of these cards fitted to provide up to four axis of readout information.

◆ AC021 Servo power control bistable

The power supplied to the electronics rack is divided into two separate parts that need to be switched on in the correct order to ensure safety requirements are met. This card disables the 24v to the servo's if the rack power is not available. A relay attached to the power transformer is operated from this card to enable power to the motors.

◆ AC0036 Control rack back plane

Most of the low power signals to and from the individual cards in the main electronics rack including the power rails are feed by the back plane. There is a none-standard bus which interconnects the whole system together.

◆ AC037 AC038 AC043 Micro console 2000

The micro console controls an LCD of 40 characters with four lines, a customised qwerty keyboard and 8 switches. The handbox communicates using a 6402 uart which converts all the parallel data to RS232 serial data and all the RS232 serial data to parallel data. The keyboard is memory mapped to the PC bus and allows the operator to input commands from either the computer handbox or the remote handbox to operate the machine. The LCD is continually updated with the current readout information and much more information which is useful to the operator. The switches on the handbox are hard wired to the back plane and provide the operations to disabling motors and unlocking the motors from the drive rack.

◆ AC041 IBM PS2 Computer interface

The computer interface cards sit in the back of the computer and talk to the computer via the I/O bus. Initially this card sent the signal to the controller by using differential drivers but with advent of faster computers the card now uses 74F chips and a ribbon cable 500mm long with alternate earth returns.

◆ AC050 Limit switch logic

The optical limit switch sensor PCB is a very small circuit board that is situated at the ends of the travel of the machine axis. They are operated by a small vein of metal fixed to the moving axis which enters a slot just as the machine touches the end stop shock absorbers. The machine uses the shock absorbers to stop the momentum only, the optical switch is used to ramp down the drive for that axis.

◆ AC054 4 axis profiling CNC interface

The card replaces the CNC interface card when the customer requires profiling. The main difference is that the backoff is more controllable and allows the probe to effectively peck a surface very quickly, the points collected are used to create a profile of the object being measured using special graphics software.

◆ AC056 Rack interface Dual RS232 ports

This card acts as the decoder for the other cards. It decodes the 16 I/O addresses from the PC which are used by the system rack. The card is also used to talk to the Renishaw PH10 motorised probe via the RS232 port.

2.7 Machine Operation

The movement of the machine in manual mode is totally hardware controlled i.e. the joysticks control the motor speeds directly and the computer is only used to store the touch positions of the probe.

The CNC operations which are of vital importance can vary from canned cycles such as a move to a new position or measuring a hole, to measuring the whole component, all these operation are performed by the PC. To activate a CNC operation there is a menu system on the PC which is used to select the appropriate operation. To operate a CNC move command the PC will ask for the final position. The PC will take control of measuring machine and move the probe to the required position by using the target position to calculate a move vector and apply appropriate speeds to the servos for the move. The PC will calculate the vector which it has to move down and output the speeds to the motors each loop time and adjust the speeds accordingly.

♦ The IBM PC Loop Time.

The various tasks the PC has to perform during the loop time of the CMM are the major reasons why this controller can not be updated to produce speeds which would be acceptable in the 1990's. The tasks performed by the PC during the loop time are outlined below:-

- Reading the three/four 24 bit counters which determine 3D position of the probe when the machine is moving and when a probe hit occurs. This information has to be displayed on the PC screen and on the LCD on the handbox.
- The vector speeds for the move is calculated by the PC and motor output speeds are sent to the three

analogue servo cards.

- The many latches on the remote handbox are monitored and acted upon.
- The touches recorded by the CMM have to be applied to mathematics functions to obtain the roundness of circles, the flatness of planes etc.
- The results of the calculations have to be stored in a data base and printed or plotted in a specified format.
- The IBM PC keyboard and remote handbox keyboard have to be continually monitored for key depressions.
- The VGA monitor and the handbox LCD has to be continually updated with readout and other relevant information.

2.8 The Control Of The Existing Measuring Machine.

The method of control employed by existing control system is a basic method of recalculation. The disadvantages of controlling the system this way are visible to the eye. When the probe is moved from position A to position B the stylus of the probe can be seen to bend in an arc off the straight line path and towards the end of the move the machine can even move backwards in order to achieve the required position. The control of the machine is achieved by using the IBM PC to read the position of the three axes from the 24-bit counters on the readout cards each loop time. The PC then recalculates the motor speeds required to achieve the final position each loop time and the speeds are applied to the analogue servos. This method of control is not very effective in producing accurate control of the machine because the positional information of the machine lags the loop time (0.064 seconds) and so that when the recalculated vector speed is applied to the motors it is already out of position by 7mm.

A maximum speed of the machine = 110 mm/sec

loop time = 0.064 seconds

110 * 0.064 = 7.04mm

The positional error could be up to 7mm when the new speeds were applied to the motors. This can be compared with the new control system with a loop time of 0.001 second using the same top speed.

110 * 0.001 = 0.11mm

The increase in loop time shows how the inaccuracy of position can be improved. A much better method of positional accuracy could be obtained if the loop time could be decreased.

One of the inherent problems of using a PC to control a measuring machine is the DOS operating system. This can cause problems because it spends a variable amount of time to monitor the various ports and peripherals. This effects the controlling of the machine by changing the loop time by as much as 0.04 seconds i.e. the best loop time is 0.065 seconds. The worst case is 0.105 seconds, this variation is not known and can not be accounted for. These variations cause the positional errors to be exaggerated making the controlling of the machine accurately very difficult. This is the main reason for including an embedded controller to drive the machine. The best positional accuracy of this system was approximately 100 microns. The variation from the straight line path is in the order of millimetres.

The overall performance of the controller is effected by the machine stopping between moves whilst in CNC operation to perform specialist calculations on the touch points received. The worst case is when the PC is calculating the profile of a component, the algorithm used is an iterative method which takes up to 20 seconds, depending on the number of points used in the process. An embedded controller would be able to carry on moving the machine and taking more points during this time and greatly increase the efficiency of the measuring machine.

2.9 Systems Design Improvements Required.

W A Metrology during 1989 concluded that the present controller needed to be updated because the competitors had gained a significant advantage in component measurement times. The main areas of improvement were identified as:-

- A constant loop time was needed to enable greater control of the measuring machine.

- Customers were purchasing a second PC to analyse the data compiled from the measuring machine to perform Statistical Process Control and Attributes analysis and to utilise the profiling graphics software. This added a significant cost to the machine and a method of multi tasking with one PC was needed.

- A significant increase in acceleration and deceleration was needed in order to reduce the time taken between measured points. When the measuring machine is utilised correctly most of the points taken on a component are very close together and it is not often that the present controller reaches full speed between moves. If the acceleration was increase by ten times then the top speed would be achieved in a tenth of the time and distance. This area was identified as the best way to reduce the overall time to measure a component.

- An increase in the top speed would save a significant amount of time over long moves.

2.10 The Specification

- A reduction in loop time to 10 milliseconds or less.
- An intelligent controller which could be used without the PC monitoring the results.
- A microprocessor based handbox capable of controlling the measuring machine.
- Software control of the backoff distance to produce better profiling techniques.
- An automated set-up routine for the machine by reading the scale reference marks and calibrating the probes.
- The ability to interface the laser directly to produce an error map more accurately than the manual method.
- A digital drive system to reduce analogue drift of the motors due to temperature change or thermal vibration (agitation noise).
- The ability to update existing systems in the field without changing the mechanics of the measuring machine.

3.0 Transputer Control System

3.1 Choosing A Processor

The design of the controller was based on a multi processor system. The PC's processing power had to be released to enable the results to analysed using SPC or Attributes software. All design paths incorporated an extra processor to supervise the micro console 2000 which is used to continually update the LCD and monitor the keyboard. Once a multi processor system was identified, different microprocessors were tested to find the most suitable to this application. [14][15][16][17] An embedded transputer system was demonstrated at Nottingham Polytechnic which showed the advantages of control in real time applications.[12]

3.2 Bench Mark Tests

The first step in choosing which microprocessor to use in the system was to bench mark various processors. A method of bench marking was devised using the main control algorithm code from the existing controller. The main control software was compiled on the various processors, estimates of the various possible loop times of each processor using the existing method of control were obtained.[16]

Intel 80286	loop time = 40 milliseconds
Intel 80286/287	loop time = 20 milliseconds
Motorola 68000	loop time = 20 milliseconds
Inmos T414	loop time = 4 millisecond
Inmos T800	loop time = 0.4 millisecond

These results were obtained by using C source code and a serial program.

The results of the bench mark test showed that the transputer lent its self better to the type of control algorithm used on the measuring machine. The results showed that the Inmos T414 was ten faster than its Intel equivalent, on this basis alone it would justifiable to choose the transputer as the new embedded processor. The Transputer was designed as a parallel processor, the utilisation of this parallelism in the design of the system hardware and the placement of the software would produce an even greater saving in the loop time.

3.3 Parallelism

The concept of parallelism in software creates a new dimension to computer programming. The basic principle is that a serial program will perform all its tasks one after another until all tasks are performed, the length of the program is calculated by adding the time taken to perform each task together to give an overall program time.[6]

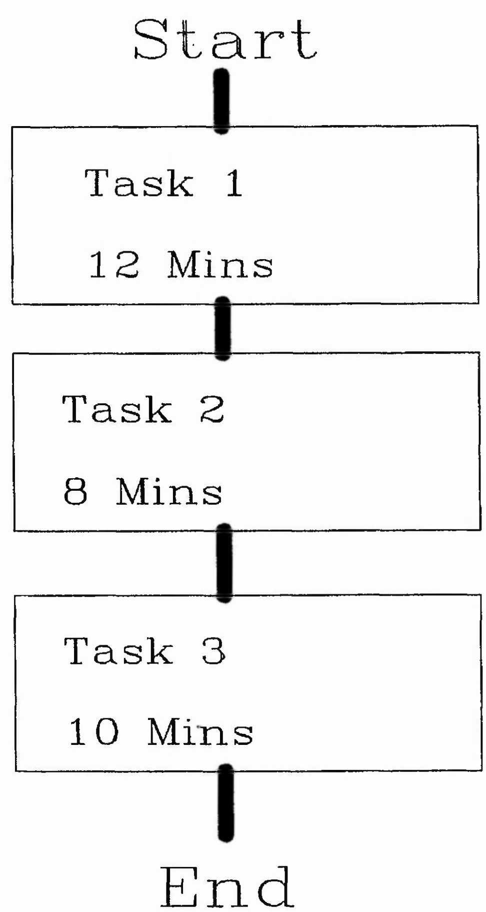


Figure 6 Serial Flow Diagram

The total serial time = 30 minutes

The parallel program will perform all its tasks at the same time and the length of the program is equal to the time taken to perform the longest task.[6]

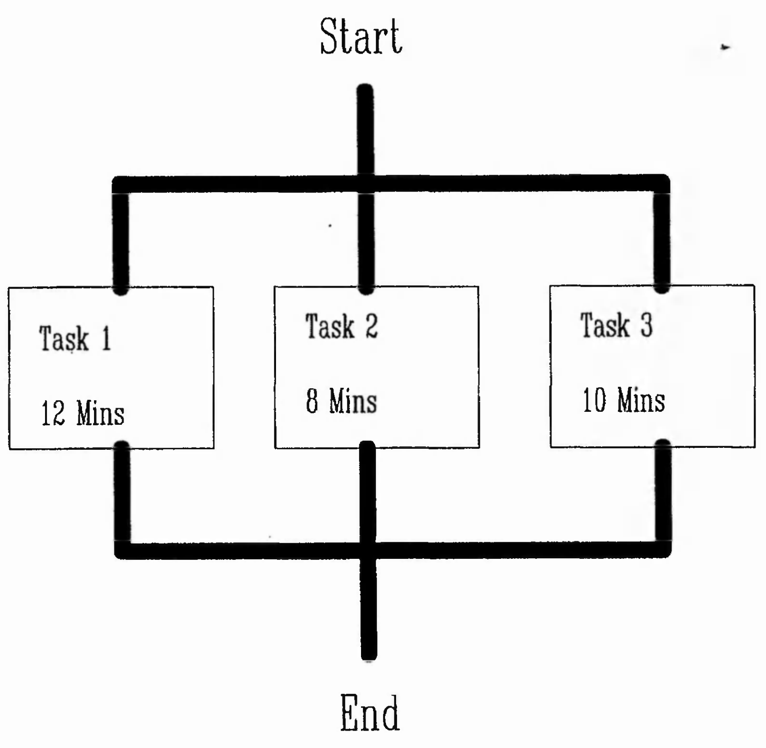


Figure 7 **Parallel flow Diagram**

Total parallel time = 12mins

3.4 The Transputer

The two types of transputer used in the controller are shown below:-

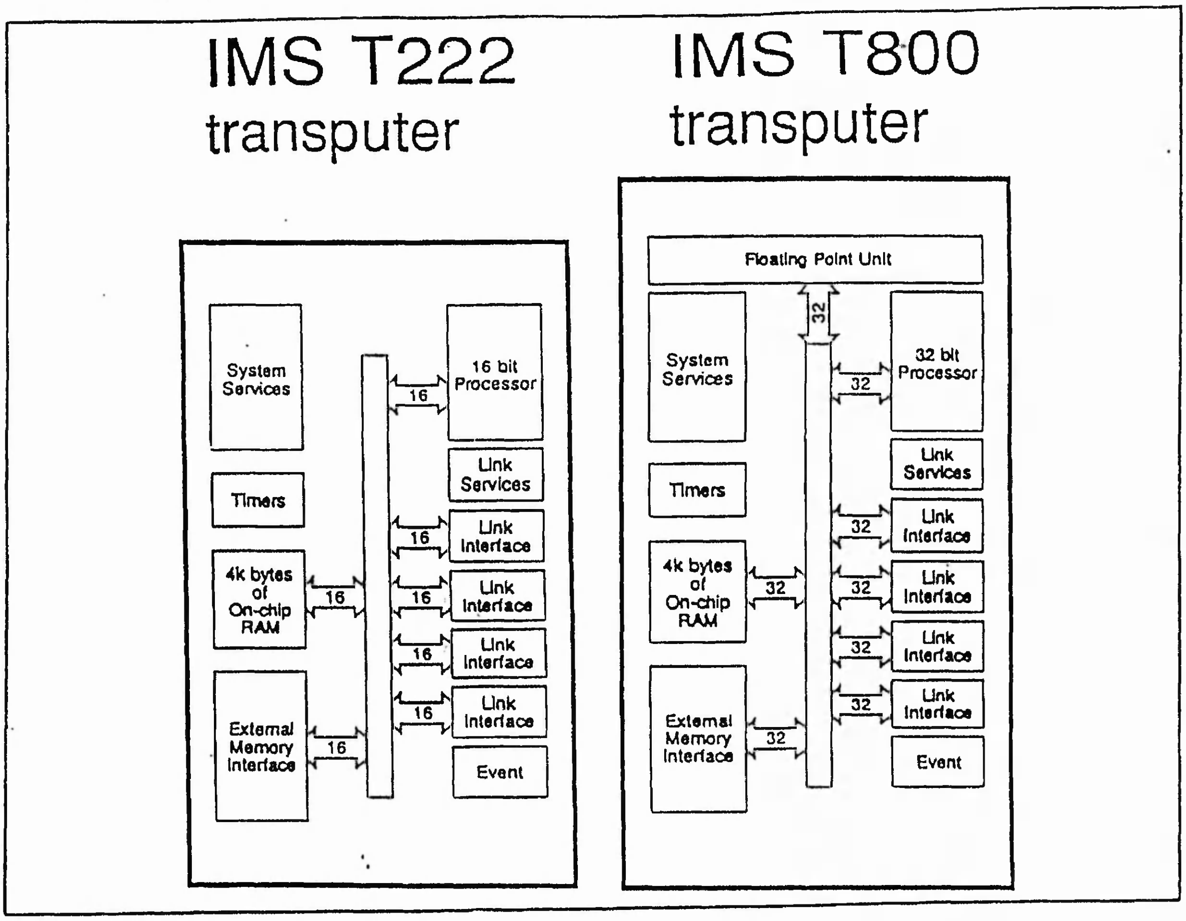


Figure 8 Block diagram of the Transputer

The transputer is a microprocessor with its own local memory and with links for connecting one transputer to another transputer. The single chip transputer contains a processor, memory and communication links which provide point to point connection between transputers. A transputer can be used in a single processor system or in networks to build high performance concurrent systems. A network of transputers is easily constructed using the communications links, these links allow serial data to be transmitted at speeds of up 20 MHz. To gain most benefit from the transputer architecture, the whole system can be programmed in occam. In order to optimise the system for real time parallel control it is best to use the parallel language of occam which was designed by Inmos for the transputer. This provides all the advantages of a high level language, the maximum program efficiency and the ability to use the special features of the transputer.

The transputer architecture simplifies system design by using the point to point communications links, this allows transputer networks of arbitrary size and topology to be constructed easily and quickly.[5]

3.5 The Transputer System

Prior to building the system a study of various tasks to be carried was made. This showed that the operation could be subdivided into five major tasks as follows:-

Readout system
Handbox
Motor drive
Controller
Host operations

Having allocated these tasks as above, the first design strategy was to allocate each task to a separate transputer. It was then found that the construction of each unit was virtually independent of each other. This contrasted with a previous outline design using an Intel 80188 controller where the integration of each part must be thought out prior to the implementation of the design. When transputers are used the design is naturally modular and consequently a very attractive design.

The system hardware was designed to utilise the parallelism of the transputer. It also allowed the readout system to operate independently to produce a manual measuring machine. The basic configuration is shown in the block diagram.

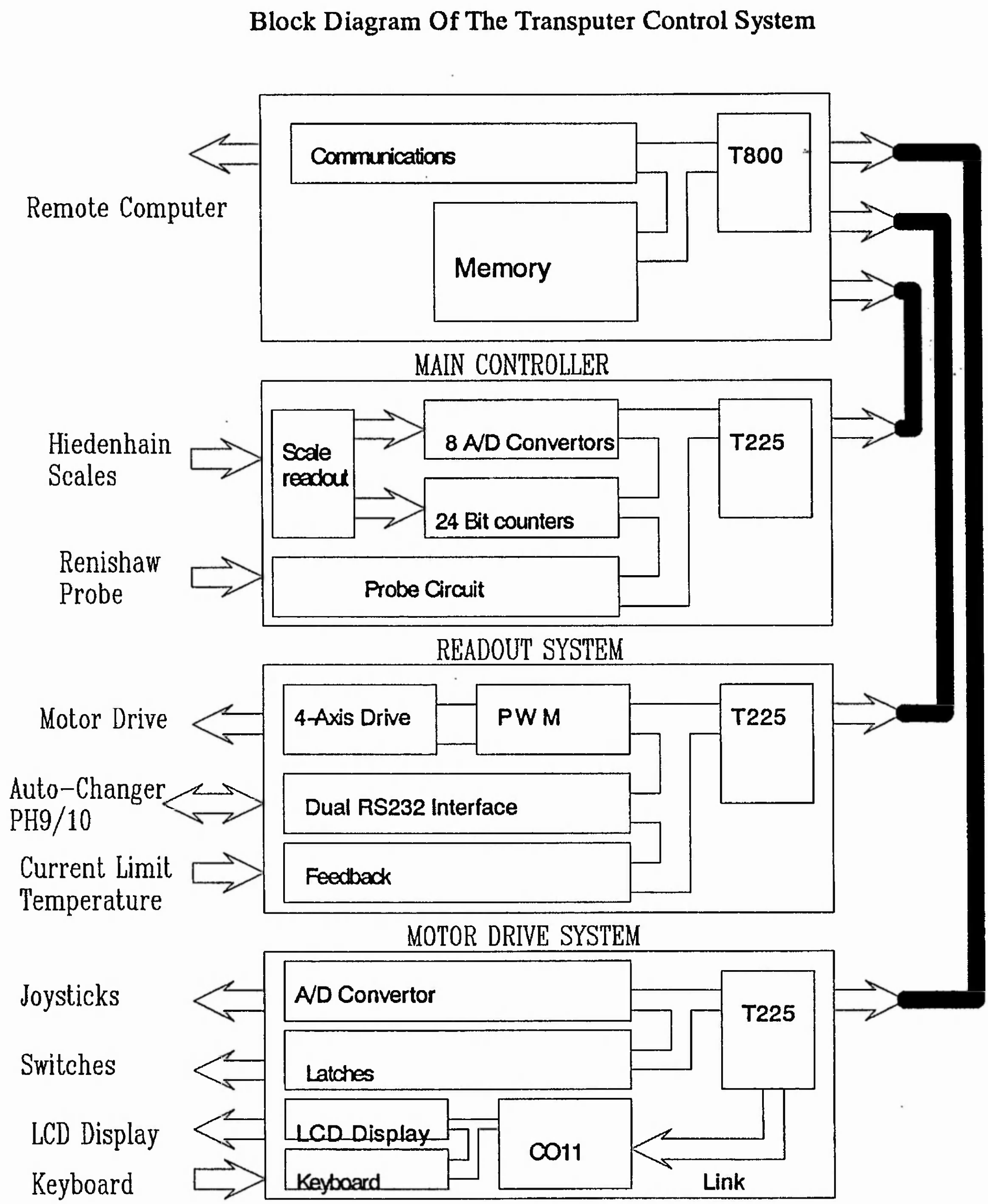


Figure 9 Block Diagram of the Transputer controller

The present controller operated out of a single extended euro card rack using a customised back plane to distribute the signals. This type of system was chosen again so that the new system could be used as a direct replacement for the existing controller. Each customer would be provided with a set of service spares so each of the cards could be replaced if a fault occurred. A new customised back plane is used with two link wires connecting the cards together. Each of the identified areas were allocated their own transputer and placed on separate PCB's (extended single Euro card). This enabled each system to control its own functions and then provide and receive information from the other systems. Relaying the information between the systems was achieved using the Inmos transputer links at a speed of 10 MHz.

3.6 The Readout System.

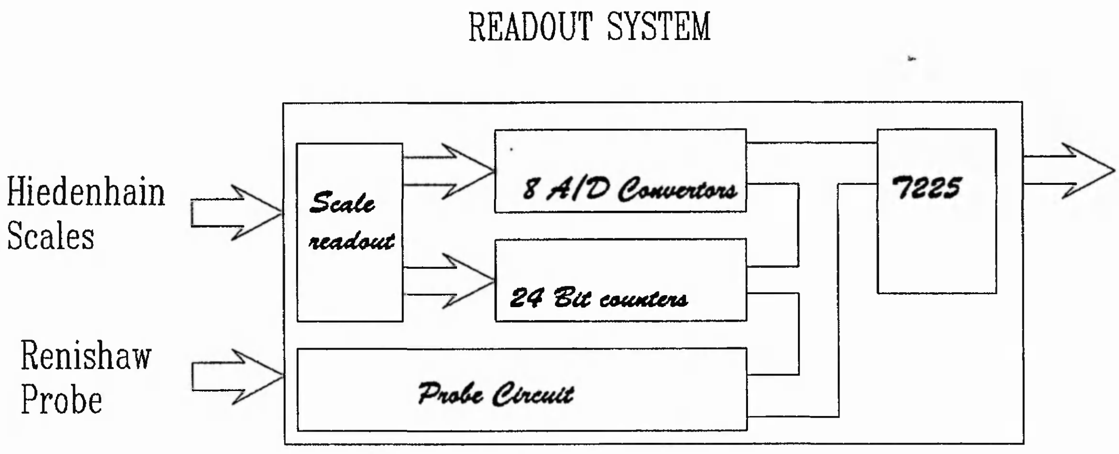
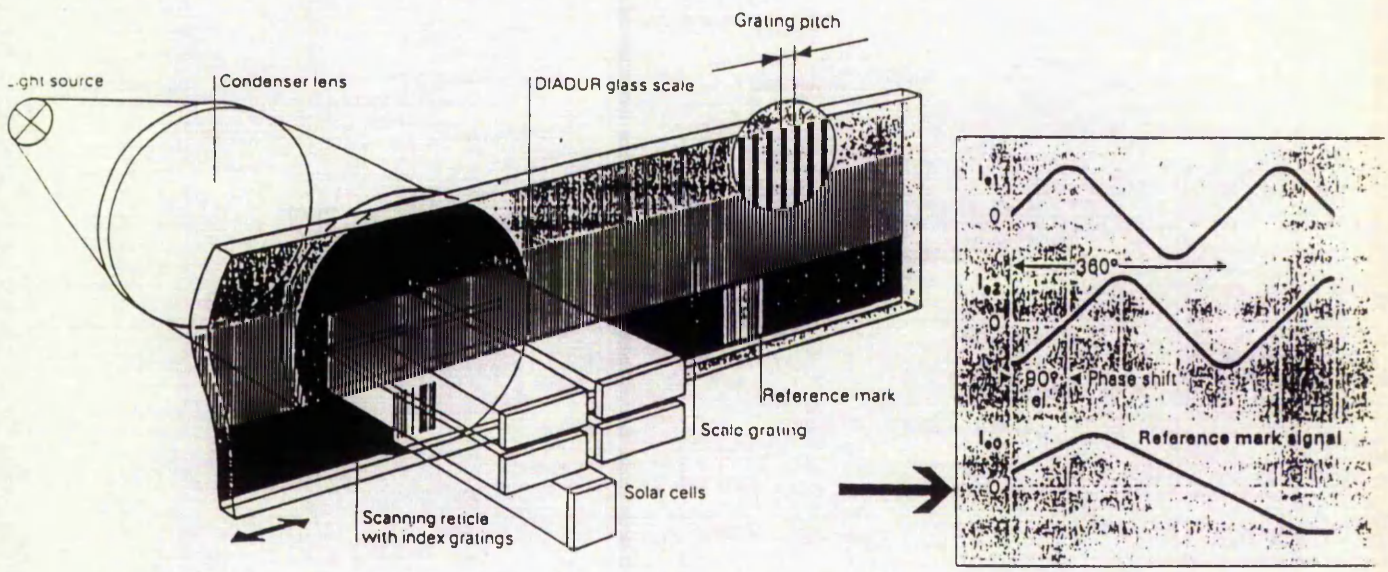


Figure 10 Readout System

The function of the readout card is to continually read the scales from four ax'es, monitor the probe and detect if a probe touch occurs. The card contains a T225 transputer operating at 20 MHz which has 4k of on board memory. The internal memory of the T225 is sufficient to control the functionality of this system, so extra memory is not used on this card. The various devices such the A/D converter and the Quadrature encoders are memory mapped to high memory.

◆ The Hiedenhain Scales

The Hiedenhain scales are glass with a grating pitch of 20 micrometers. The glass scale produced by the DIADUR-process consists of opaque lines and transparent spaces of equal width. One or more reference marks constitute a second track. The scanning unit comprised of a light source, a condenser lens for culminating the light beam, the scanning reticule with the index grating and silicon solar cells. when the scale is moved relative to the scanning unit, the lines and spaces of the scale alternately coincide with those of the index grating. The corresponding fluctuations of the light are sensed by solar cells, which generate two sinusoidal output signals le1 and le2 and a reference mark signal le0. Signals le1 and le2 of approximately 10 micro amps are phase-shifted by 90 degrees Hiedenhain NC-linear encoders contain no electronics other than the solar cells.[7]



Scanning signals of encoder

Figure 11 Diagram of the Hiedenhain scale

The output current from the scale is received as a differential sinusoidal voltage in the order of a few milli-volts. This signal is amplified and signal conditioned at the input to produce a sinusoidal voltage between 0v and 5v. These sine waves represent 20 micro meters for each cycle. The sine waves are converted in to square waves using a 2.5v reference which squares the sine wave on crossing the reference level using comparators. Each edge of the square wave represents a 5 microns count. The square wave output is applied to an incremental encoder, this encoder can independently determine the direction of the input signals from transducers in quadrature and count up or down accordingly. The distance travelled is stored in a 24 bit counter which can be read by the transputer bus. The principle of converting the differential current signals to a quadrature voltage output is used by Hiedenhain in black boxes called EXE's these are used by the existing controller. The removal of the EXE's from the controller produced a cost saving of over 500.00 pounds.

The fine position of the readout down to 0.1 microns is achieved with aid of a sample and hold circuit and an analogue to digital converter as shown in the block diagram.

READOUT SYSTEM

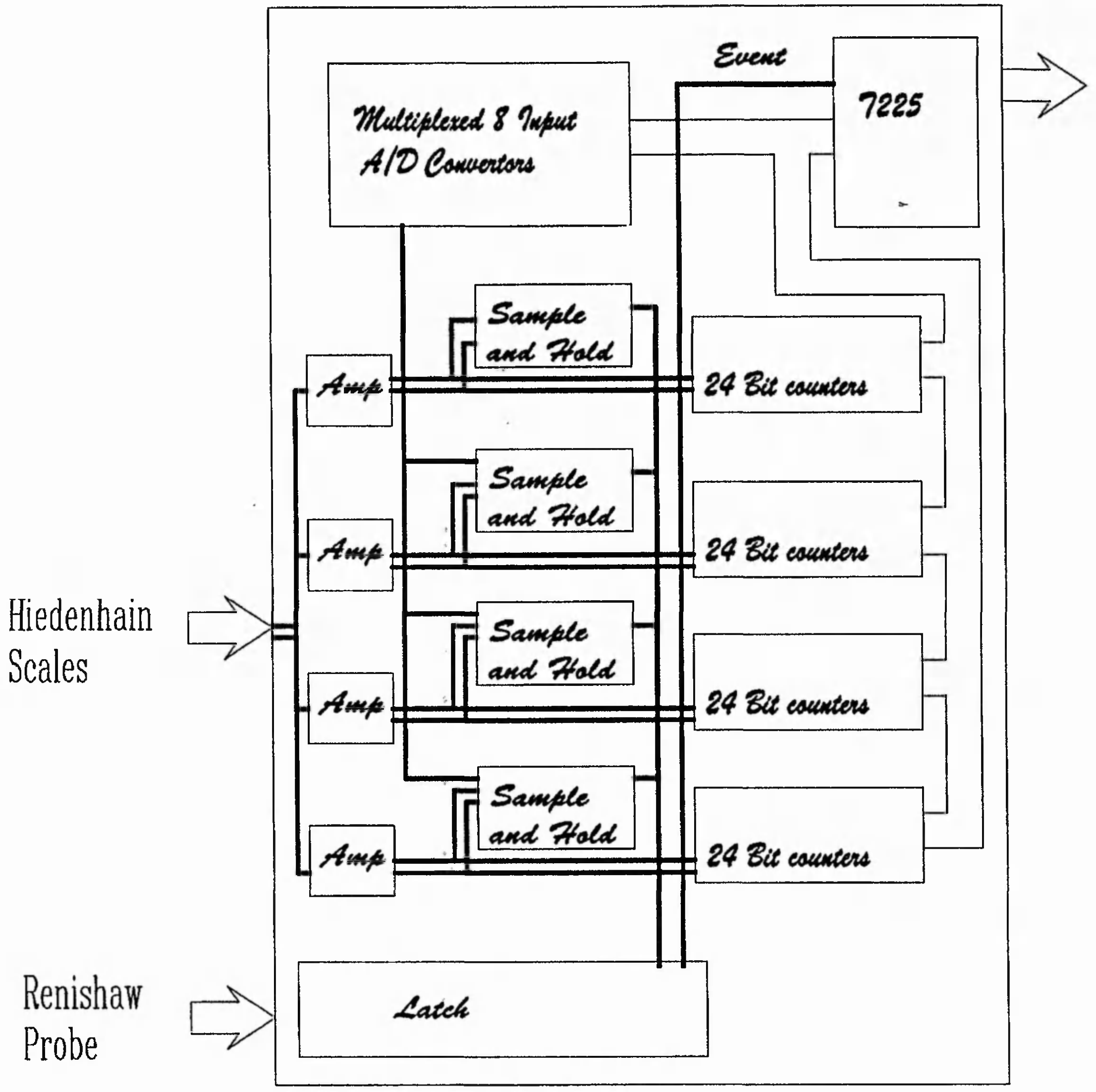


Figure 12 Block diagram of readout system with A/D converter.

The readout fine position is a very important part of the controller, in a high accuracy measuring machine the position of the probe has to be accurately known. The fine position is needed when a probe touch occurs, when the readout information is sent to the controller to indicate the three dimensional position of the probe at the time of the touch.

◆ The Sample and Hold Circuit.

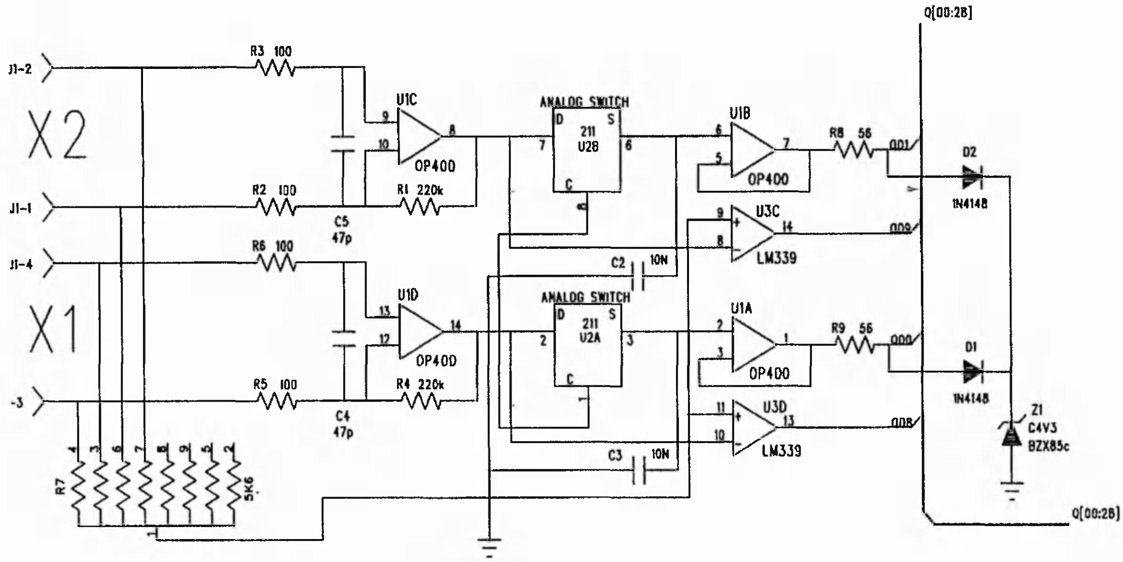


Figure 13 The sample and hold schematic

The operation of the sample and hold circuit starts with a probe touch signal. There are a series of eight analogue switches which are activated by a probe touch. These switches normally allow the amplified 0v to 5v sine waves signals to pass on to the analogue to digital converter. During normal movement of the machine the a/d will read the sine wave signals on the fly as the positional information does not have to be very accurate until probe positions are taken. The probe touch circuit is connected to the analogue switches so that when a probe touch occurs the analogue switch is broken leaving the sampled sine wave signals in the sample and hold circuit. This signal is then read by the analogue to digital converter as quickly as possible.

The technique of reading the readout information is important so that the correct information is received with the highest accuracy possible. The probe touch signal is also used to trigger the event pin on the transputer (the event pin is similar to an interrupt request on most microprocessors). The transputer then reads the quadrature information from the encoders, this gives a three dimensional position to an accuracy of 5 microns. The analogue to digital converter is used to produce an interpolated position between the 5 microns. The input signals from the sample and hold circuit are the sine and cosine signals from the scales which produce a count of resolution 0.1 microns which can be added or subtracted to the quadrature counter.

◆ The Readout Interpolation

The sine and cosine input signals are generated from the same light source. The intensity of the light source can change with time as the light intensity reduces. The peak to peak voltage is dependant on the distance the scale reader head is placed away from the scale. As each of the sine and cosine signals are obtained from the same light source this ensures that variation of the signals is same for both signals. The interpolation method has to take account of the following signal variations.

- The peak to peak voltage can vary considerably between two different scales.
- The 2.5v reference signal will not indicate the half wave point of the signals
- The maximum and minimum input voltages will change with time.

The interpolated signals need to be added or subtracted from the quadrature count. This quadrature count relies on the 2.5v reference signal to determine its count. A method had to devised that only used the quadrature counter as indication of the distance travelled.

The following method was employed to analyse the signals so that the variation in peak to peak voltage didn't effect the accuracy of the interpolation.

- A reference signal is obtained from each of the scales by moving the measuring machine over a short distance and taking many A/D readings. This will establish the maximum and minimum voltages produced by the scale. The reference signal is the difference between maximum and minimum readings.

- The cosine and sine A/D reading are compared to the reference signal, the sine and cosine signals are given a digital number between +/- 127, where the reference signal is equal to zero.

- The small position is then calculated by changing the sin and cosine in to a tangent and applying it to an arc tan look up table.

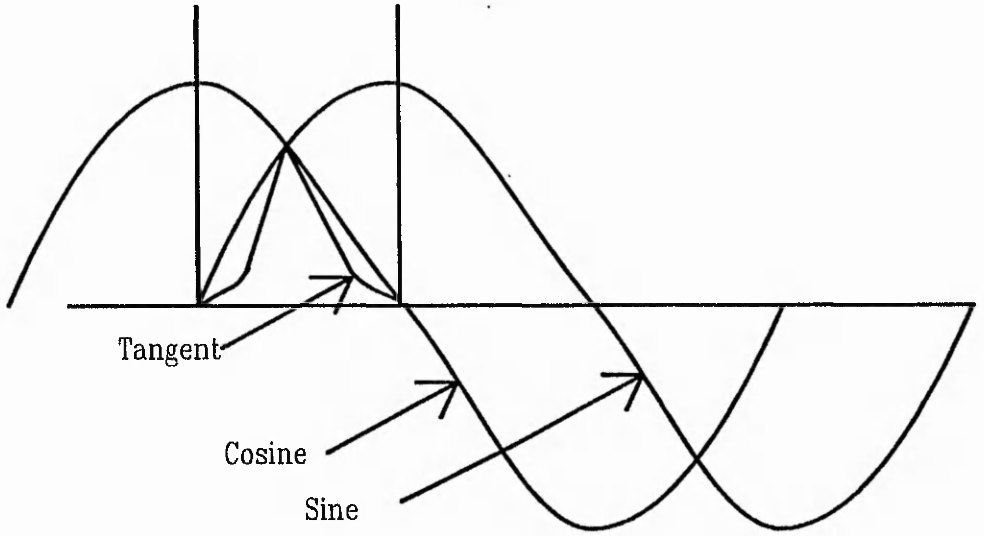


Figure 14 Diagram showing the tangent from sin and cosine

Where sin>cos

small.position = 256 - arctan[{cos/sin}*n]

cos>sin

small.position = {arctan[{cos/sin}*n]

n = number of elements in arctan look up table

arctan = a number between 0 and 127

cos and sin = number between -127 and +127

- The small position is a distance which has to be added or subtracted from the 5 micron count. A set-up routine is used to relate the quadrature count with the A/D system. An Adder is obtain in this set-up

◆ **Set-up routine**

- Ensure both the sin and cosine are not near the zero crossing point.

- Mask off all but the first two digits of the quadrature count giving a number between 0 and 3. This number represents the quadrant number for the quadrature counter.

- The sine and cosine signal are assigned arbitrary quadrants.

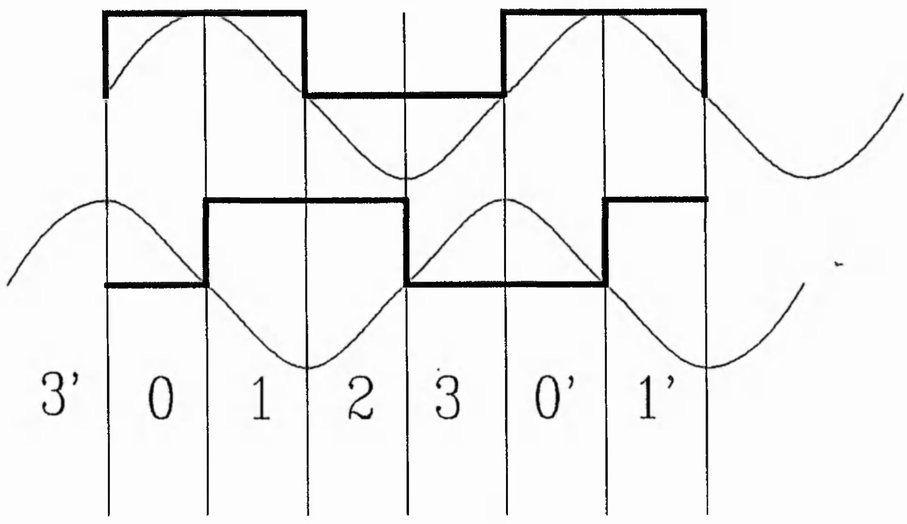


Figure 15 Diagram showing the quadrant allocation

- The two readout system have been allocated quadrants which can produce a multiplier by comparing the two actual quadrants from the set-up routine.

ADDER = A/D QUAD - QUADRATURE QUAD

The A/D quadrant can not be more than one quadrant difference from the quadrature quadrant even when the machine is moving at the full speed. To ensure that this always true the maximum delay time between a quadrature count and an A/D reading is calculated below.

One quadrature count = 5 microns = 0.000005 meters
Maximum velocity of an axis = 120 mm/sec
= 0.12 Meters/sec

velocity = distance / time
time = 0.000005/0.12 = 41 micro seconds

This time has to be greater than the time taken from a probe touch (this triggers the sample and hold circuit) to the time taken to read the quadrature counters.

The possible allocated quadrants

Quad difference	0 quad	1 quad	2 quad	3 qua
A/D Quad	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2
5 micron Quad	0 1 2 3	1 2 3 0	2 3 0 1	3 0 1
A/D - 5um Quad (adder)	0 0 0 0	-1-1-1 3	-2-2 2 2	-3 1 1
ideal adder	0 0 0 0	1 1 1 1	2 2 2 2	3 3 3

- Convert actual adder to the ideal adder so adder value is between 0 and +3.

Three Axis

```
SEQ i=0 FOR 3
  IF
    ADDER[i] = 3 (INT16)
      ADDER[i] := 1 (INT16)
    ADDER[i] = 1 (INT16)
      ADDER[i] := 3 (INT16)
    ADDER[i] > 0 (INT16)
      ADDER[i] = -ADDER
    TRUE SKIP
```

- Quadrant checking

A quadrant check is needed to see if the A/D Quad is different to the quadrature counter. The 5 um quadrant is converted to the equivalent A/D quadrant by firstly masking the first two digits of the count.

```
Quad.check[i] := (position[i] /\ #00000003 (INT32))
```

The ADDER is added to the masked count and masked again giving the counter quadrant.

```
CASE (INT quad.check[i])
  0
    counter.quad[i] := 0 (INT16) - ADDER[i]
  1
    counter.quad[i] := 1 (INT16) - ADDER[i]
  2
    counter.quad[i] := 2 (INT16) - ADDER[i]
  3
    counter.quad[i] := 3 (INT16) - ADDER[i]
counter.quad[i] := (counter.quad[i] /\ #0003 (INT16))
```

- Quadrant slippage

It has been shown in the set-up routine that the Quadrant slippage can not be more than one quadrant. It is possible to slip one quadrant because there is a finite time between reading the A/D count and the Quadrature count. The zero crossing (reference signal) used for each count is obtained from two different methods i.e. the 2.5v reference for the quadrature counter and the difference signal on the A/D count.

The effect of a quadrant slip can cause an inaccuracy of up to 5 microns. When a quadrant slip is detected the A/D count will take preference as this is a more accurate method of producing zero crossing.

The possible quadrants are:-

2' | 3' | 0 | 1 | 2 | 3 | 0' | 1'

A/D count	5 um count	5 um count - A/D count	
0	0	0	-
3'	0	-3	*(+1)
1	0	-1	
1	1	0	
0	1	1	
2	1	-1	
2	2	0	
1	2	1	
3	2	-1	
3	3	0	
2	3	1	
0'	3	3	*(-1)

* theses two cases are changed from +3 to -1 and -3 to +1

The table shows that if the 5 um count is greater than the A/D count then the result is +1 and if it is less than the A/D count the result is -1. If the slip check result is +1 then 5 microns are subtracted from the small.position and if the result is -1 then 5 microns are added to the small.position.

The accurate position of the readout is :-

Readout position = Quadrature count + Small.position

◆ Zero Markers

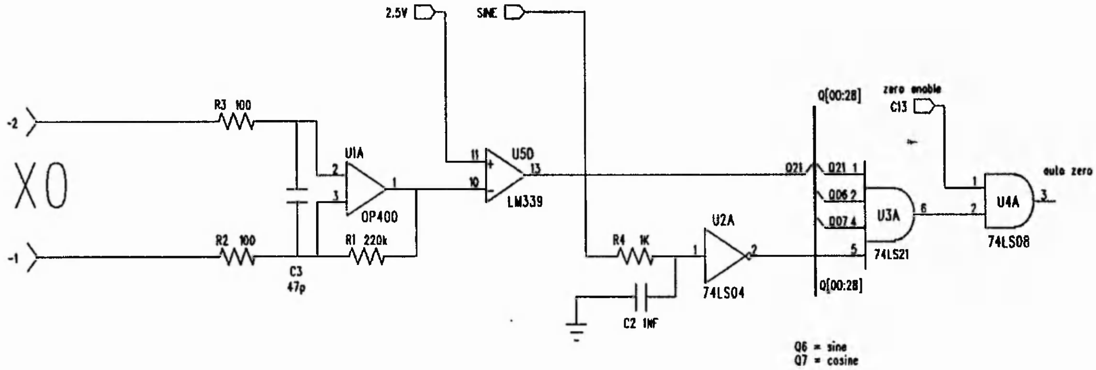


Figure 16 Zero Markers

All Hiedenhain scales are fitted with zero reference marks, these can be set at either one end of the scale or at the centre of the scale. The zero reference mark signals are used to reset the counters at a predetermined position to produce a datum for all the measurements taken. This signal is a sine wave approximately 5 um long which is signal conditioned using the same circuit as the scale counters producing a square pulse of 5 um. If the 5 um pulse is used to zero the scales a difference in 5 um would occur if the scale was moved in the opposite direction.

To ensure that a zero pulse occurs in one direction and for a much sorter period the following four signal are passed through a four input nand gate.[7]

The zero pulse.
The squared sine wave.
The squared cosine wave.
The sine wave signal delayed.

This modified zero pulse is allowed to pass directly to the zero on the counter if enabled by a further two input nand gate.

◆ **Distance Coded Reference Marks.**

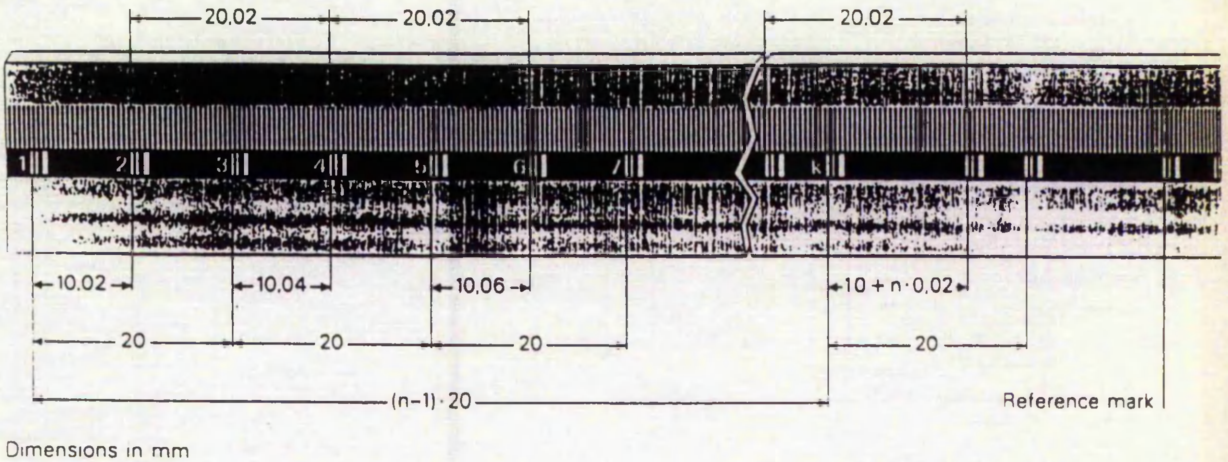


Figure 17 Diagram of distance coded reference marks.

The Hiedenhain scales can be purchased with distance coded reference marks, the scale comprises of a line grating and an adjacent track for reference marks. The spacing between the reference marks vary by a defined rule. By counting the measuring steps between two consecutive reference marks, the absolute position can be established. The purpose of distance coded reference marks is to allow the controller to determine the position of reader head by only passing through just two of these markers. Each of the reference marks pulses can be monitored by the transputer when two have been passed, the distance difference between the two pulses will established the true count. The counters can then be loaded with the correct distance.[7]

♦ Probe Circuit.

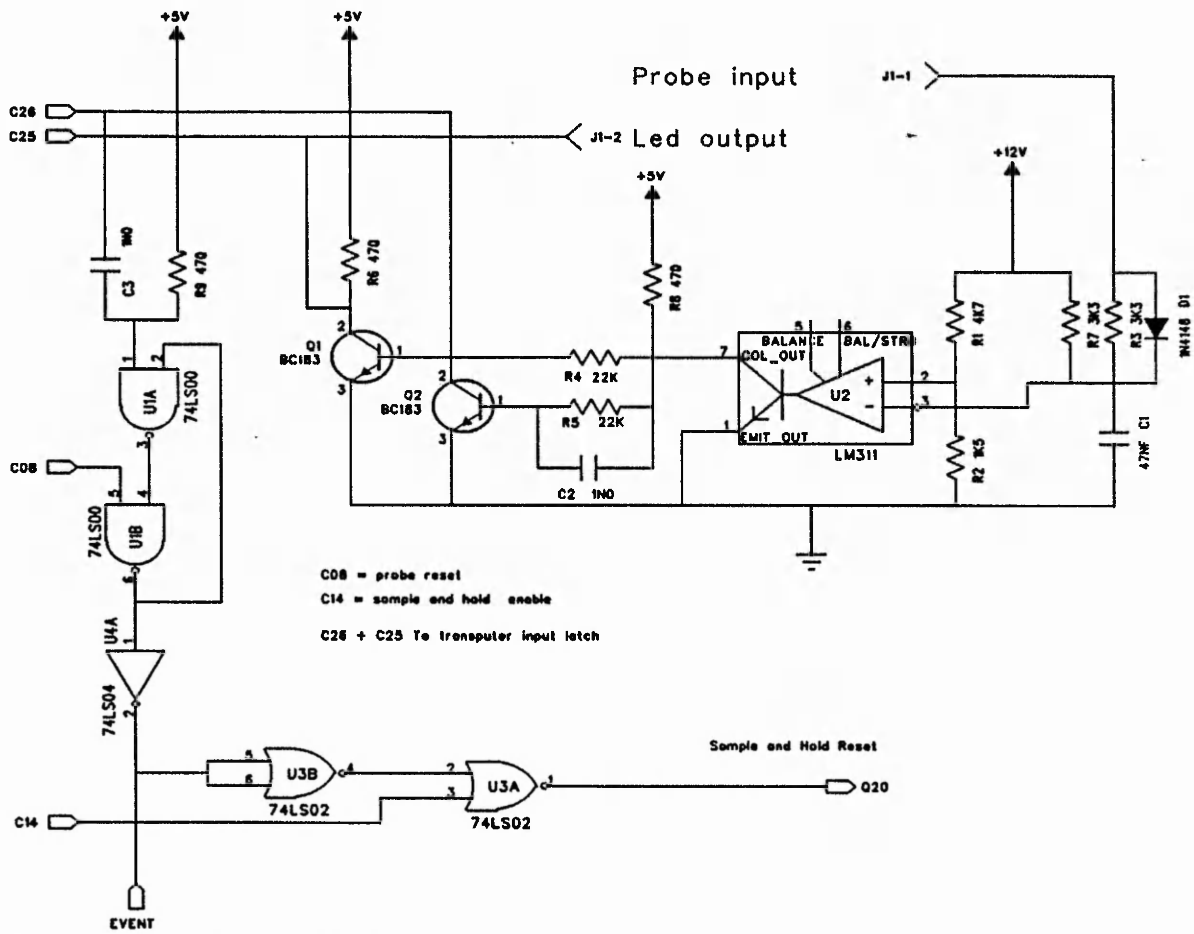


Figure 18 Probe Circuit

The touch probes supplied by Renishaw indicate when the probe is deflected by sending a short pulse to the readout card. The probe circuit on the readout card latches this pulse and triggers the event pin on the transputer. The latch also switches the analogue switches on the sample and hold circuit to enable an accurate readout at the time of the touch.[1]

There is an output latch which controls the probe enable/disable, the sample and hold circuit enable/disable and the probe reset, which resets the probe latch and will allow another probe trigger to occur. The probe LED is also controlled from this card and simply switches off the LED when a trigger is detected.

♦ Testing Of The Readout Card

The readout system of the co-ordinate measuring machine produces the positional accuracy of measurements taken by the measuring machine. These measurements determine an important criteria from which the performance of the machine is measured against the competition.

The methods used to test the accuracy of the readout system were firstly by designing a variable frequency test rig and then to use a helium neon laser to compare the readout of the machine.

The test rig used look up tables to produce the sine and cosine outputs. These outputs could vary in frequency to simulate the machine movement at different speeds and could also be single stepped through a cycle to test the analogue to digital measurements. The software described in 3.6.3 was thoroughly tested using this method. The results obtained are shown below.

The input from a 20 micron scale produces a quadrature input of 5 microns. The A/D converter divided this input by 256 (8-bit resolution)

5 microns / 256 = 0.0195 microns

The quality of operational amplifiers and the analogue to digital converter produced a maximum drift of +/- 2 least significant bit. This enabled a resolution of 0.1 microns to be used successfully.

0.0195 * 4 = 0.078 microns

This was an improvement of a factor of ten from the previous controller.

The laser is used as a final tool to test the accuracy of the readout system and to produce a three-dimensional error map which is applied to the readout results of the machine. The error map produced by the laser is used to correct the mechanical errors of the machine as well as the readout errors. Mechanical errors are always present in a measuring machine because it is impossible to produce a machine with three ax'es which are perfectly square to each other. These Squareness errors produce other errors such as pitch and yaw errors which are turning forces of the machine. A Status 3 measuring machine was error mapped using the transputer controller the results were put into a look up table which was used to produce an accurate measurement system.

The accuracy of the readout system was verified by doing repeatability tests on length bars calibrated by the National Physics Laboratory (NPL). The results can be seen in appendix 1.

3.7 The Motor Drive Amplifier

The motor drive card is used to control the brushed DC motors placed one each axis. The T225 transputer is used to produce a digital PWM (pulse width modulated) which is applied to the motors, temperature and the current feedback from the output amplifiers is used for fault diagnostics. The control of the Renishaw PH9/10 controller and probe autochanger are operated using a duart on this card. The machine end stop or limit switches are monitored to prevent the machine from driving off the surface plate.

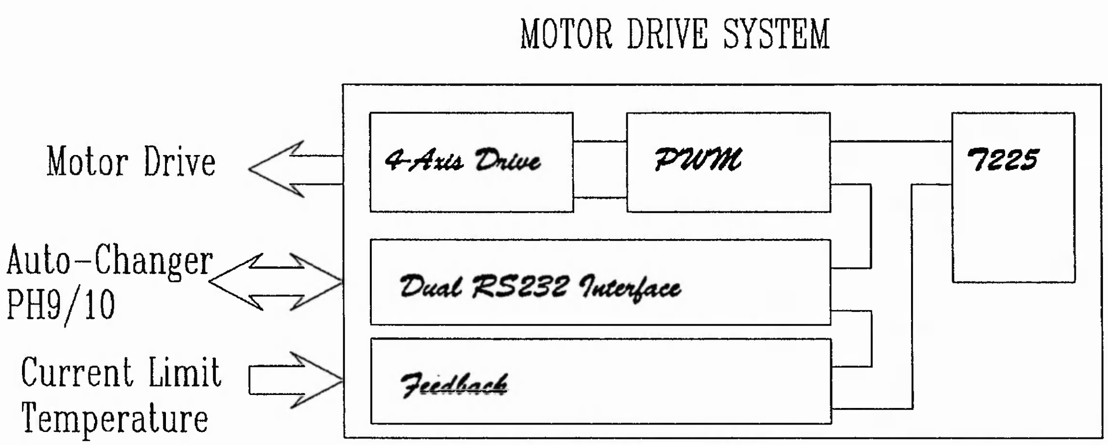


Figure 19 **Block diagram of the motor drive system.**

The motors used on the measuring machines manufactured at W A Metrology are Harmonic Drive servo actuator HDSH14 with a 50:1 gearbox ratio. The unit is also supplied with an integral 24v DC motor, 3v per 1000 rpm tacho generator (HDSH 14-S-R50-T3-U24). These motors are designed with zero backlash. Backlash is the angular displacement deviation between input and output, measured at the output with the input fixed. The reduction of backlash in the motor drive system enables very small moves to take place, without the sudden surge at the start of a move which would occur if backlash is taken up at the start of the move. The 50:1 gearboxes limit the top speed to 120 mm/sec and introduce a stiffness to the drive which enables the measuring machine to stay in position when stationary.[8][24][25][26]

The present control system uses a DC Servo amplifier supplied by Digiplan. This type of servo is analogue controlled and is prone to drift off position due to the temperature variations and thermal agitation of the semiconductor devices used. The transputer drive card implements a digital drive system to control the motors in the form of a PWM signal applied to the motors. The control system makes use of the IXDP610 bus compatible digital PWM controller IC from IXYS. The IXDP610 Digital Pulse Width Modulator (DPWM) is a programmable CMOS LSI device which accepts digital pulse width data from a microprocessor and generates two complimentary non-overlapping pulse width modulated signals for direct digital control of a switching power bridge. This IC incorporates output disable logic which can be activated either by software or hardware. This facilitates cycle by cycle current limit, short circuit, over-temperature and desaturation protection schemes.[27][28]

The PWM signals are amplified by MOSFETs in a full bridge configuration. The PCB's have been designed with options on the amplifiers used. the following table indicates the variation of drives systems required for the different models of measuring machine.

Machine type	x axis	y axis	z axis	r axis
STATUS 1	2 amps	2 amps	2 amps	not used
STATUS 2	2-4 amps	2 amps	2 amps	up to 4 amps
STATUS 3	2-10 amps	2-4 amps	2-4amps	up to 10 amps
STATUS 4	2 amps	2 amps	2 amps	not used
STATUS 5	10 amps	2 amps	2 amps	up to 10 amps
STATUS 6	10 amps	10 amps	10 amps	up to 10 amps
UPDATES	10 amps	10 amps	10 amps	up to 10 amps

The main processor board AC211 which has the T225 transputer and provides the PWM signal via the IXDP610 has 3 axis of amplification suitable to drive a STATUS 1, STATUS 2 and STATUS 4 without the need for a external amplifier board. Two of the amplifiers are rated at 3 amps continuous and 6 amps peak, with the third axis rated at 6 amps continuous and 12 amps peak. When a STATUS 3 or a machine update is required a separate amplifier is used. An amplifier card was designed to control the larger machines, these cards contain two axis of 12 amps continuous and 24 amps peak current. The back plane is devised to hold two extra amplifier cards which will enable four axis of 12 amp drive, suitable for the old heavy machines which need updating.

♦ H-Bridge Control

Many applications of semiconductor switching devices use the basic H-Bridge configuration shown below:-

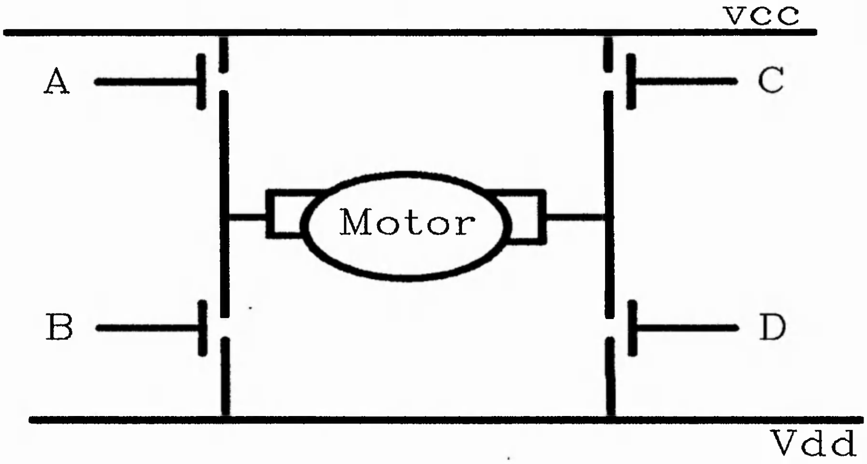


Figure 20 H-Bridge

The H-Bridge operates from a dc input voltage and provides 4-quadrant control of the load (i.e. either polarity of output voltage with either polarity of output current). This system of dc control was chosen from the many configurations of dc control because it provides a greater stiffness in the drive at slow speed enabling a much greater accuracy of position which is needed with a co-ordinate measuring machine.

The design of the motor drive system was adapted from many experiments of controlling the Harmonic motors using different configurations Half bridge and Full bridge control. The two main methods of control used were sign and magnitude and locked anti phase. A test rig was initially designed which could be adapted to find the best method of control of the Harmonic motors on a co-ordinate measuring machine.

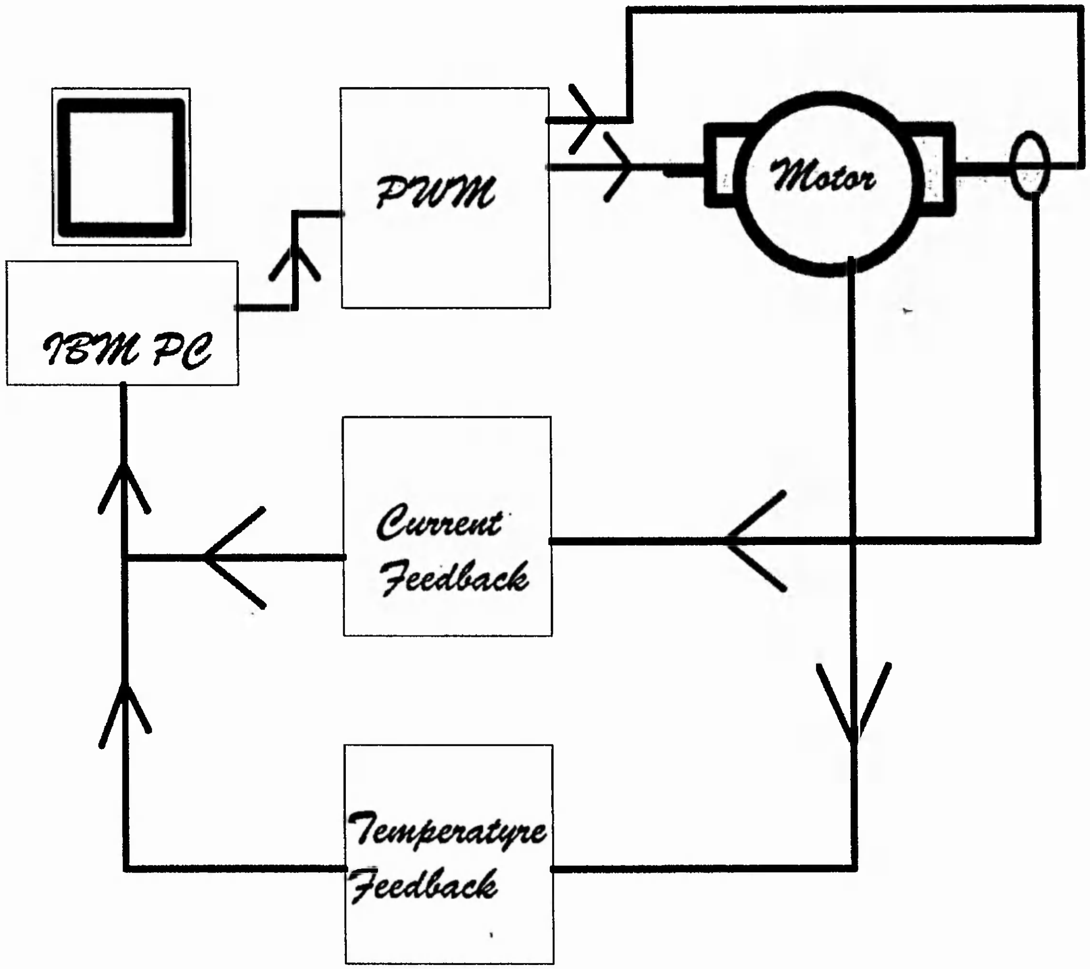


Figure 21 **Block diagram of the test rig**

- **Sign and magnitude**

The voltage of the output terminal of one leg is held 'stationary' (either at the positive rail or ground rail) and the average value of voltage at the other output terminal is regulated between the rails by pulse width modulation. This control method is so called because the sign of the average output voltage is dictated by the transistor that is permanently switched ON, and the magnitude of the average output voltage is determined by the switching duty cycle applied to the other leg.

- **Locked Anti-phase**

The conduction periods of diametrically opposite top and bottom switches are locked together (hence lock anti-phase). At zero average output voltage at each output terminal is midway between the dc voltage rails (hence there is no average voltage difference between outputs), and the conduction duty cycles of all switches are 50%, this method of control is often referred to as '50% equals zero'.

- **Choice of drive**

The experiments on the test rig showed that the best method of control was obtained using the sign and magnitude with a full bridge configuration. The locked anti-phase needed a large current flowing at zero speed to ensure that the machine did not drift off position. It also had the disadvantage that it had only half the possible digital control of the sign and magnitude method. The full bridge configuration provided a greater stiffness over the half bridge (the machine was prone to drifting), when using both methods of control.

◆ Renishaw PH10 and Autochanger

The two devices operate using simple ASCII commands sent down an RS232 link. The PH10 is a motorised probe which enables the operator to probe in difficult positions without changing the probe stylus and the autochanger is a device similar to a pen plotter. It has eight bays which hold different types of styli, these styli can be interchanged with the PH10 styli to enable even greater flexibility of probes. The drive card can control these two devices using a Duart which is addressed by the T225 transputer. The chip enable pulses from the transputer have to be delayed by four clock periods using an 74ls175 (quad D-type flip flop) attached to the memory wait input of the transputer, to suit the timing requirements of the SCN2681 Duart.

◆ Limit Switches

The limit switches which are situated at the end stops of the measuring machine are monitored on this card using 74F240 octal line driver/receiver chip. The limit switches are used to detect if the machine is at the end of the table. The limit switches are a safety feature of the measuring machine which prevent each of the axis from crashing in to the end of travel. The machine will ramp down to stop when a limit is detected and will slowly backoff out of the limit.

3.8 The Handbox

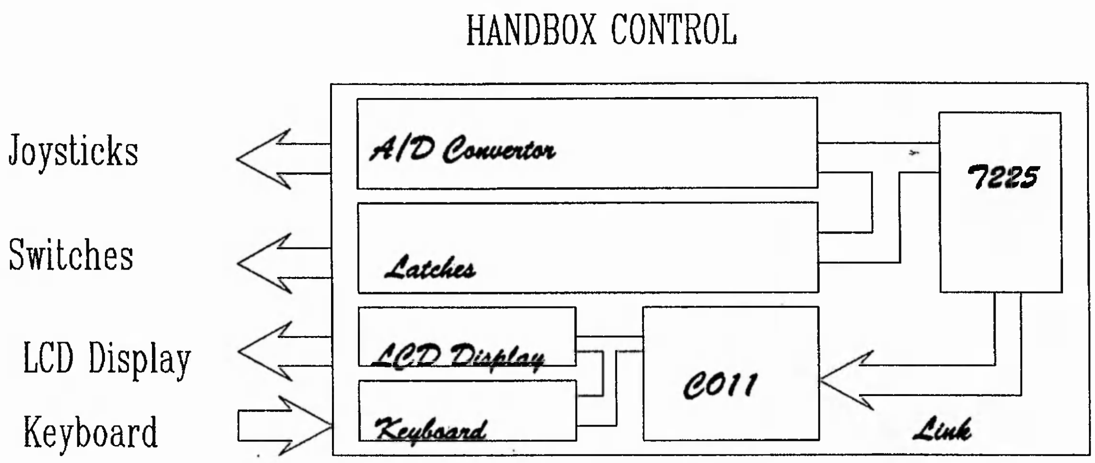


Figure 22 **Block Diagram of the Handbox**

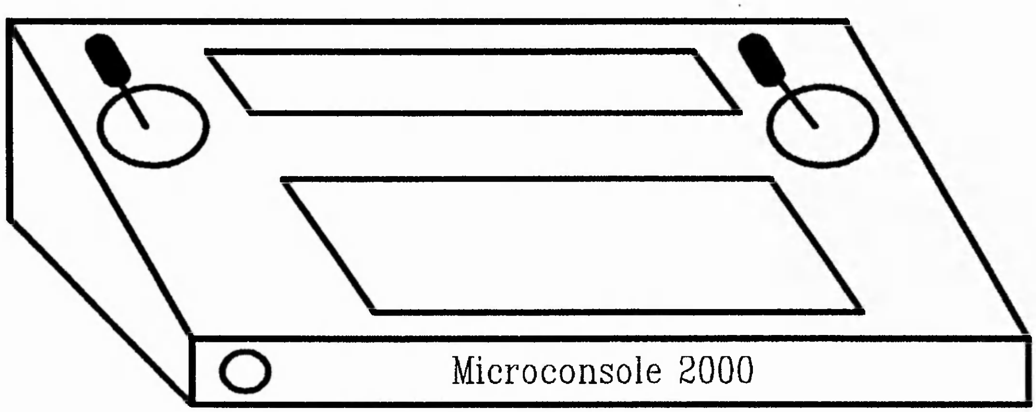


Figure 23 **The Microconsole 2000**

An important selling point of the present W A Metrology's control system is the remote handbox (micro console 2000). The advantage of the micro console over the competitors style handbox is the ability to control and program the whole machine from the handbox without having to use the PC to input commands. The PC can sited up 30 feet from the measuring machine which would take the operator a lot more time to operate the machine. The new handbox is designed to emulate the old system with the added benefit that it is microprocessor controlled.

The new handbox consists of a customised qwerty keyboard, 4x40 LCD display, two joysticks and a speed switch. The previous system had seven switches which controlled various functions of the machine in hardware.

- X lock off / X lock on / X axis enable
- Y lock off / Y lock on / Y axis enable
- Z lock off / Z lock on / Z axis enable
- Change end   Front / Rear
- Probe   Electronic / Manual / Print result
- Speed   Fast / Slow
- Learn   Learn / Rotary

These functions are now software controlled using a menu system this allows the options to be chosen in CNC operation as well as in manual. A large saving is made because the seven switches are no longer needed.

The handbox PCB communicates with the main controller board down a transputer link. This link is line driven using a 75179 RS422 driver/receiver at each end of the link, this allows up to 20 MHz of serial communication (10 MHz used)and a cable length of up to 10 meters. The reduction in hardwired functions has reduced the handbox cable from sixteen wires to seven.

The two joysticks are two axis 10k pots which are signal conditioned by operational amplifiers and passed to an eight channel A/D converter. The transputer reads these signals and passes the move vector to controller for manual speed operation.

The LCD and keyboard are controlled by an Inmos C011 which converts transputer link information to an eight bit bus to control the LCD. The serial keyboard data is translated to link information by the C011 allowing simple operation of both these devices. The handbox card is also

fitted with the logic to interface to a standard AT serial keyboard and a larger 8x80
LCD (graphics display) for a later update on the handbox to allow half the PC screen to be displayed. The T225 transputer uses an extra 32k of memory on this PCB because of the extra processing needed to update the LCD menu system.

A buzzer is fitted to the handbox which signals when a probe touch occurs. This buzzer is programmable to allow different tones and volume control.

3.9 The Main Controller

The main controller is a T800 transputer tram with 2 mega bytes of memory which is situated on a single Euro card in the rack. This euro card is called the tram board and is capable of holding a size 4 tram, two size two trams or four single trams. The transputer mother board is used to talk to the pc interface card by a transputer link and to buffer the reset and analyse signals to other cards in the system. This card has ten standard link input/outputs and three line driven input/outputs which could be utilised if four trams were fitted. The system interconnection is achieved using a T225 tram as a multiplexer which uses its four links to relay information from the readout, drive and the handbox to the controller tram. The controller tram is used to operate the machine in both manual and CNC operation by receiving information from the system and sending out PWM speeds to the drive card.

4.0 Software configuration

4.1 System Interconnection

The transputer system is a network of transputers which are used to control the measuring machine. The network configuration is shown below:-

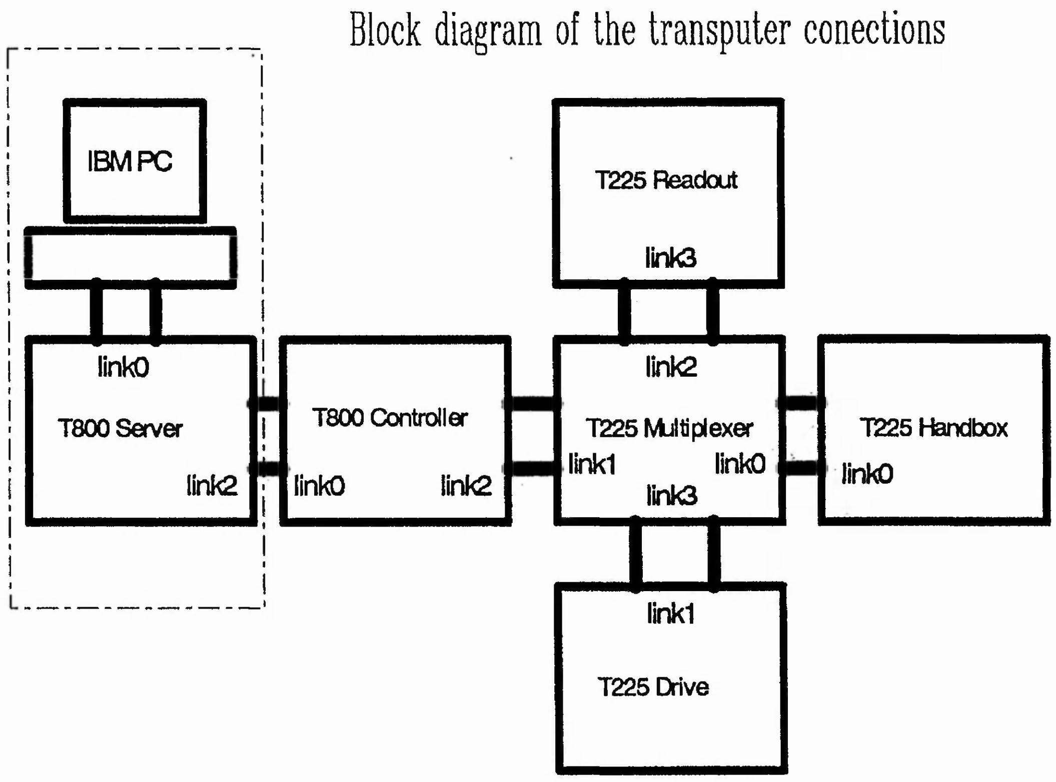


Figure 24 Diagram of Transputer Interconnections

The hardwired connections of the system are indicated by the numbers on each process, this interconnection can be two twisted pairs which sends serial information at a speed of 10 MHz using RS422 line drivers or it can be a link through the back plane of the controller also operating at 10 MHz. The type of transputer used for each process is indicated. A T800 is a 32 bit processor with a built in co-processor and 4K of internal memory and the T225 is a 16 bit processor with 4K of internal memory. There are many parallel processes running on these transputer which together produces the Transputer controlled measuring machine.

The Link connections and memory available

	Part	[Link0	Link1	Link2	Link3]	RAM,cycles
0	T800 Server	[HOST		1:0	...]	4K,1 32K,3 2016K,4
1	T800 Controller	[0:2	...	2:1	...]	4k,1 1024K,3
2	T225 Multiplexer	[3:0	5:1	4:3	5:1]	4K,1
3	T225 Readout	[2:0	...	...	...]	4K,1.
4	T225 Handbox	[...	...	...	2:2]	4K,1 28K,4.
5	T225 Drive	[...	2:3	...	...]	4K,1.

This table shows the system interconnections of the network.

Part - indicates the processor type
RAM - indicates the memory available to each processor
cycle - indicates the memory access speed in clock cycles

4.2 The drive

This transputer has five parallel processes running on it simultaneously. The individual processes perform unrelated tasks which send and receive information from the multiplexer.

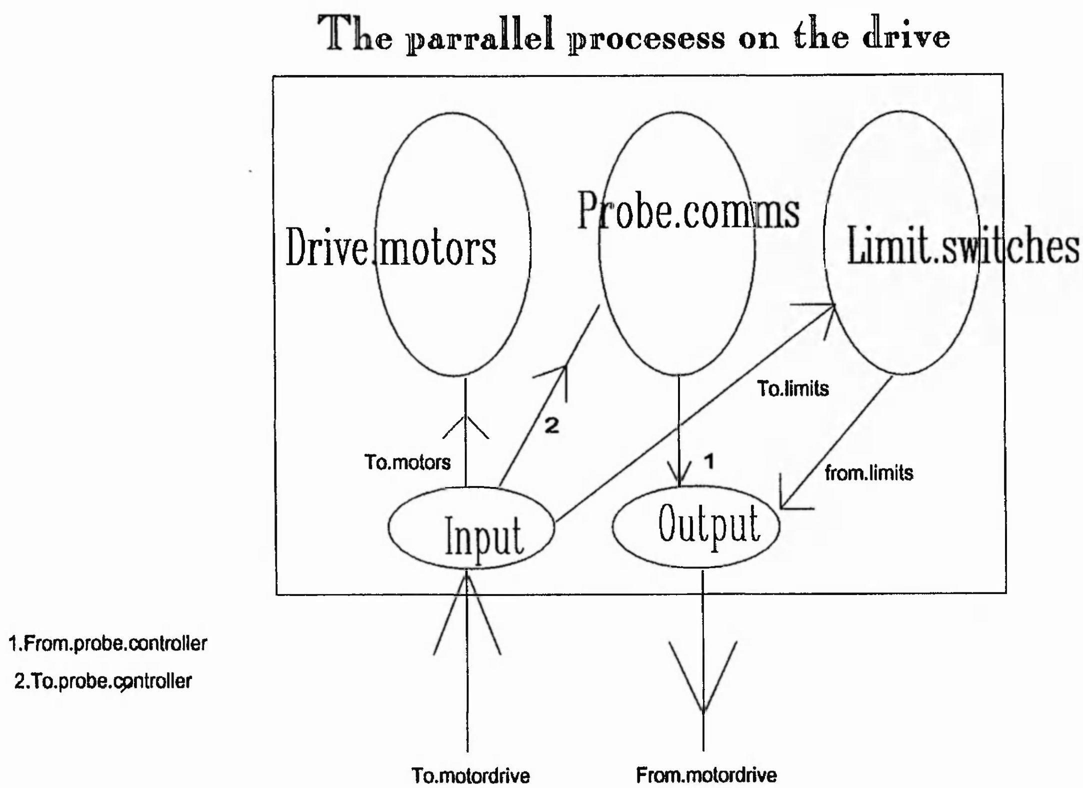


Figure 25 The Parallel Processes on the Drive

◆ **Drive motors**

This process receives the PWM speeds from the multiplexer when the machine is operating in both manual and CNC mode. These speeds are applied to the motors by the memory mapped PWM controller chip (IXDP610).

◆ **Probe comms**

The Renishaw PH9/10 motorised probe and the Renishaw autochanger are operated from this process by relaying information to and from the devices by RS232 communications link. This is achieved by using the memory mapped dual RS232 IC (duart).

◆ **Limit switches**

This process monitors the limit switches at end of travel of each axis. When a limit is reached this program indicates which limit is broken to the controller, the machine then backs off out of the limit whilst the controller is checking to see if the machine has left the end stop.

◆ **Input/Output**

Input and output are two separate processes which control the transfer of information down the hardwired links. A protocol is used to indicate what type of data is being transferred and to which process.

4.3 The readout

This processor provides the positional information for the measuring machine.

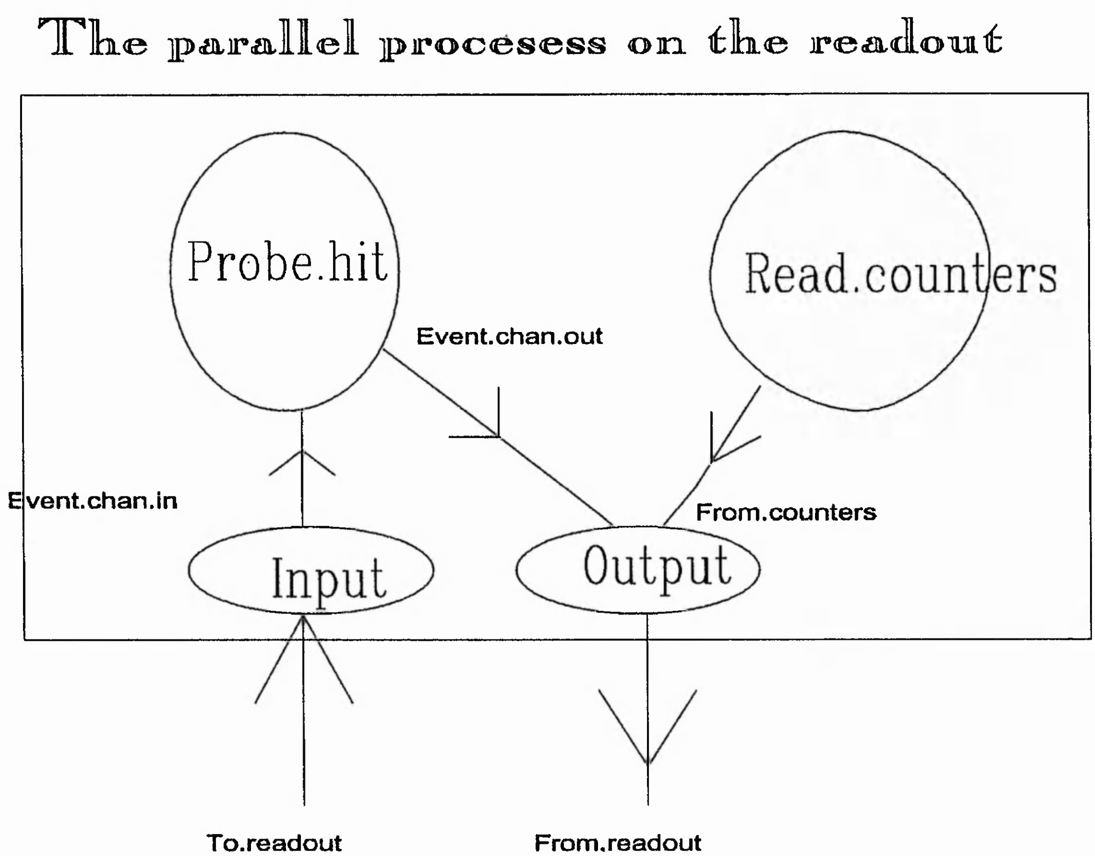


Figure 26 The Parallel Processes on the Readout

♦ Read.counters

This process reads the quadrature counters and the A/D converter to obtain a three axis position. This process uses a clock timer to calculate a new position four times a millisecond, this is used in the control algorithm to move the machine in CNC.

♦ Probe hit

The probe hit operates off the event channel. This channel is an external link which operates from a high to low edge, it operates similar to the interrupt of a standard processor. When the event channel is triggered the readout position is then calculated and sent to the controller as a probe hit position. When the machine has backed off after a probe hit the event.chan.in is used to reset the event channel link and so enable another probe hit to occur.

♦ Input/Output

Input and output are two separate processes which control the transfer of information down the hardwired links. A protocol is used to indicate what type of data is being transferred and to which process.

4.4 The handbox

The link information which travels to and from this processor is sent down a cable up to ten meters long using RS422 line drivers to the multiplexer. This processor has an extra 28K of memory of which most is used in controlling the LCD and keyboard on the handbox.

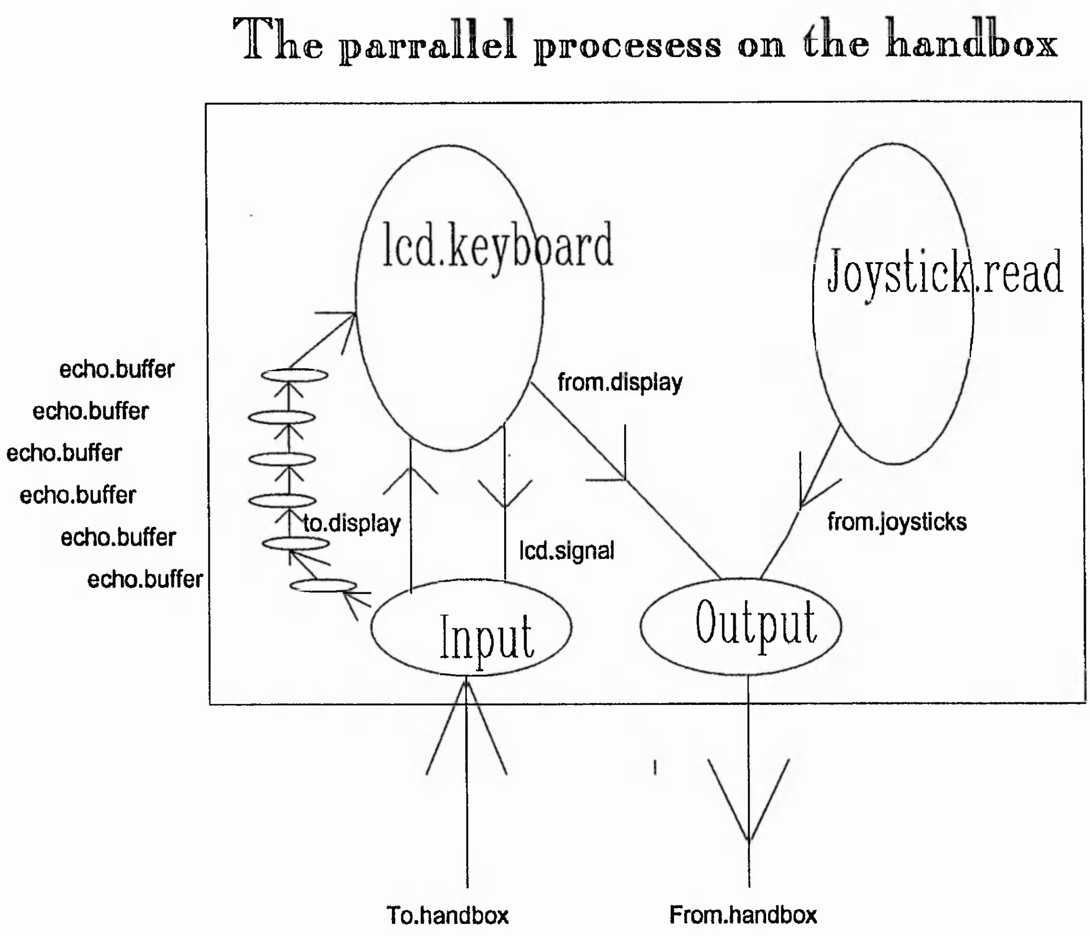


Figure 27 The Parallel Processes on the Handbox

◆ **Joystick.read**

This process continually reads the analogue to digital converter which provides the four axis manual drive speeds from the joysticks. These speeds are output to the controller via the multiplexer.

♦ **LCD.keyboard**

The LCD display information is very complex because it displays a menu system which is up to five operations deep, it mirrors all the commands issued by the stand alone PC., it indicates the number of probe hits that have occurred, whilst continually updating the positional information from the readout on the display. The positional information displayed on the LCD is controlled using a handshaking method with the input buffer, the readout information is sent to the display only when requested. The echo buffers are used to send the menu displays and command information to the LCD, the echo buffers stack up the display information until the appropriate time for display. All the keyboard information is sent to the stand alone PC. through the multiplexer, controller and server path and is sent back to the LCD for display down the same path.

4.5 The multiplexer

This processor controls the flow of information around the system, it is a T225 transputer with no hardware connected. The input and output channels indicated on the diagram have the same names as the input and output channels on the various processors. Each of the processes indicated on the block diagram are effectively buffers which receive and send information without changing it, to and from the processors of the system.

The parrallel processess on the multiplexor

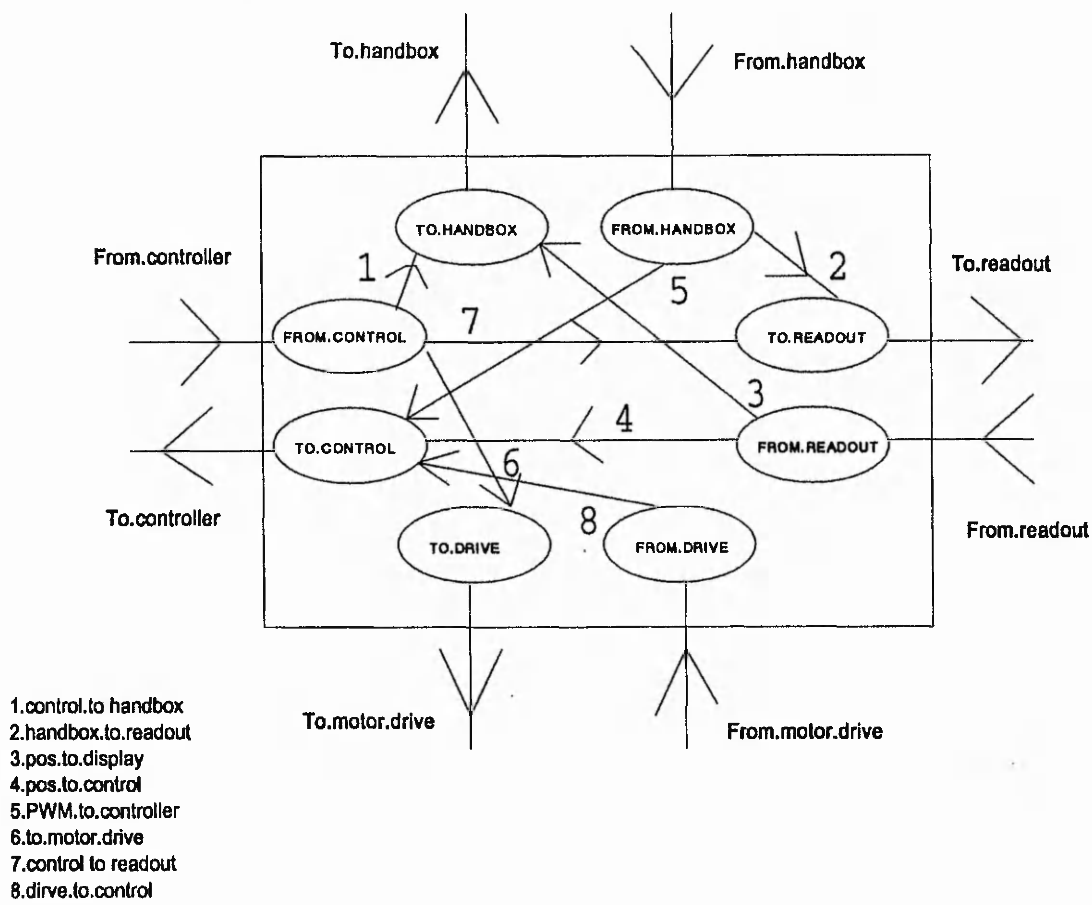


Figure 28 The Parallel Processes on the Multiplexer

◆ **To.drive**

This process receives PWM, PH10 and autochanger, and limit signals from the controller processor and sends it to the drive processor.

◆ **From.drive**

This sends the limit, PH10 and autochanger information from the drive processor to the controller processor.

◆ **From.readout**

The readout information from the readout processor is sent to the handbox processor and the controller processor.

◆ **To.readout**

The probe.hit hit and zero information is sent to the readout processor.

◆ **From.handbox**

This receives joystick and keyboard information and sends it to the controller.

◆ **To.handbox**

The relaying of readout and display information is passed through this process.

◆ **From.control**

This process sends the relevant information from the controller processor to the three processes indicated.

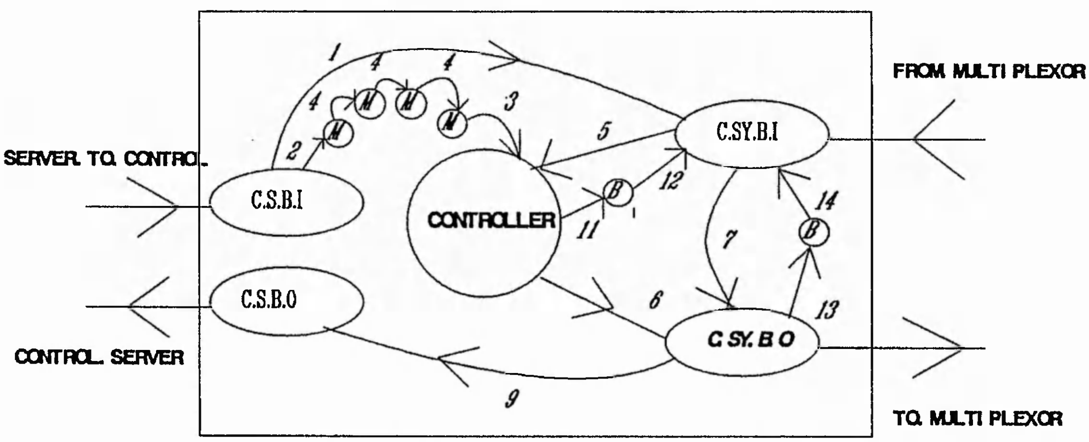
◆ **To.control**

This process receives information from all three processors and sends the data to the controller processor.

4.6 The controller

The main function of this processor is to control the machine both in manual and CNC motion. The information is gathered from the network of transputers and processed to produce the instructions to control the other processors.

The parrallel procesess on the contoller



M = Move.Buffer
C.S.B.I = C.Server.Buffer..Input
C.S.B.O = C.Server.Buffer.Output
C.S.Y.B.I = C.System.Buffer.Input
C.S.Y.B.O = C.System.Buffer.Output
B = Buffer

1.server.buffer.system.buffer
2.server.buffer.to.move.buffer
3.move.buffer.to.controller
4.move.buffer.to.move.buffer
5.system.buffer.to.controller
6.controller.to.sytem.buffer
7.from.input.buffer
8.to.input.buffer
9.system.buffer.to.server.buffer
10.controller.system.buffer
11.controller.to.buffer
12.buffer.to.system.buffer.input
13.system.buffer.output.to.buffer
14.buffer.to.system.buffer.input

Figure 29 The Parallel Processes on the Controller

♦ The controller

The controller receives PWM signal in manual operation and filters this signal before sending out the appropriate drive speeds to the motors. To operate the machine in CNC the move required is collected from the move buffer, the position of the machine is obtained from the readout processor. A move algorithm is used to calculate the motor speeds from the continually updated readout information as the machine is moving.

◆ **Buffer and move buffer**

These processes are used to store information until the next processor is ready to receive it. They are primarily used to stop dead lock on the processor by enabling a process to output at the time required. The addition of these processes actually speeds up the possible loop time of the system.

◆ **C.server.buffer.output**

The information required by the stand alone PC. is transferred through this buffer.

◆ **C.server.buffer.input**

Keyboard and LCD display information to the handbox.

◆ **c.system.buffer.output**

All the information send to the multiplexer is sent through this buffer.

◆ **c.system.buffer.input**

This process receives the information from the multiplexer and sends it to the controller and the stand alone PC.

4.7 The Server

This processor is used to relay information to and from the stand alone PC. to and from the controller processor.

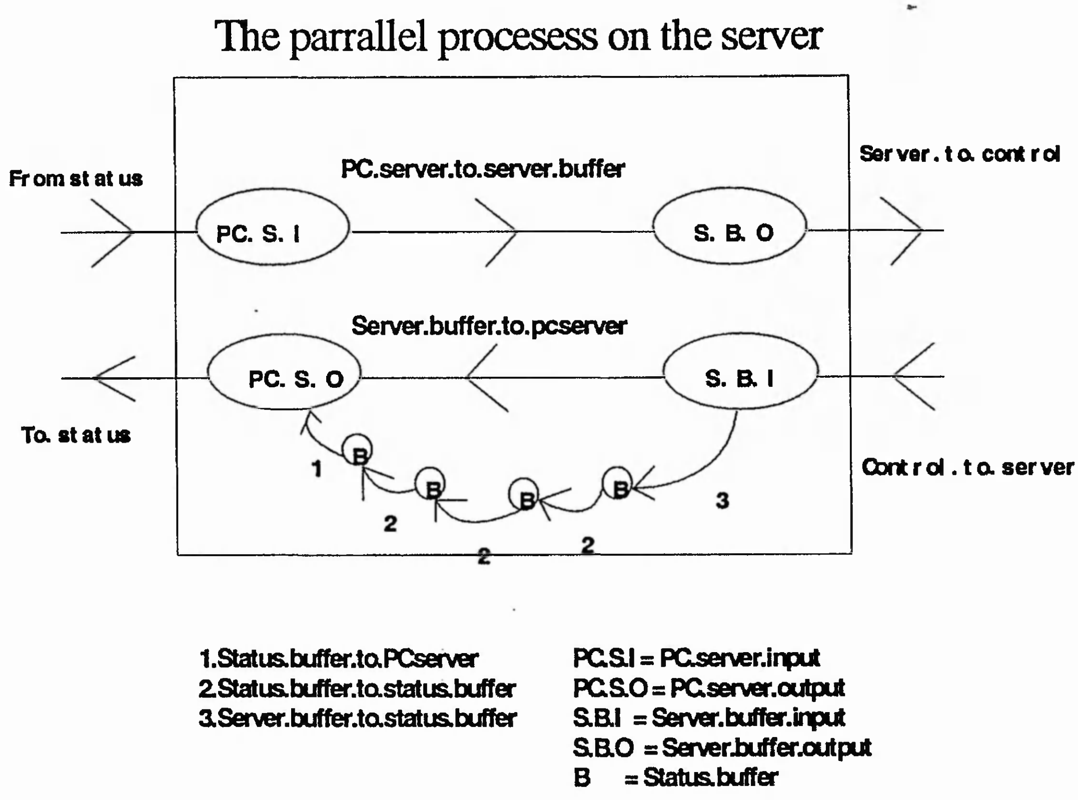


Figure 30 The Parallel Processes on the Server

◆ PC.server.input

The stand alone PC. sends information in the form of eight bit words from the PC interface card. CNC moves and LCD information passes through this process.

◆ **PC.server.output**

This process receives touch positions from the status buffer and Keyboard depressions, PH10, and autochanger information from the server.buffer.input.

◆ **Control.to.server**

The PC.server.output information is received from the controller processor and sent to the PC.server.output and the status buffer.

◆ **Server.to.control**

This process is a buffer to relay information to the controller processor.

5.0 Testing the Controller

5.1 Design problems encountered

♦ Inmos links

The initial development of the controller used the Inmos IMS T222 transputer which was updated to the T225 transputer. The Inmos IMS T225 is a direct replacement to the T222 in hardware so no physical modifications to the circuits were needed. The main enhancement provided by the new T225 was that the links fully support overlapped acknowledge so each IMS T225 link can transfer data bidirectionally at up 2.4 Mbytes/sec and the link speed setting are the same as those on the IMS T800. The T225 also supports break point instructions to enable ease of debugging.

The robustness of the T222 links were not sufficient to run the full system without the link engines locking to the link to re-initialise a link if a link engine failed. This caused many problems due the very large protocols used on the link communications.

A test program was written for the cross shaped network of transputers used in the design, This program sent information from one transputer across the link to another transputer and back again. It was found that using the T222 the system was only robust if the information sent was in bytes, if INT16 or INT32 or arrays of either were sent the link engines of one of the transputers would lock up in less than two or three minutes. This problem was passed to Inmos, the only solution suggested was to use the T225 because of its more robust links. This processor was not available until December 1991, which slowed the design. Software was written to reinitialise the links when they locked up. This software is used on all the hardwired links to prevent communications failure.

The link hard wire connections used on the design were either line driven using the RS422 standard or connected using 74F244 buffers. There were many problems in overcoming transmission line effects, noise and crosstalk, line attenuation, pulse dispersion, skew, and propagation delay. The main solution was to terminate the link by matching the impedance of the transmitter and receiver to the characteristic impedance of the transmission line, this was achieved with the aid of a series termination of 56 ohms on the buffered outputs and two schottky clamping diodes and a 1k pull down resistor on the input. The RS422 drivers used a termination of 1K pull up/down resistors with a terminating resistor of 100 ohms.

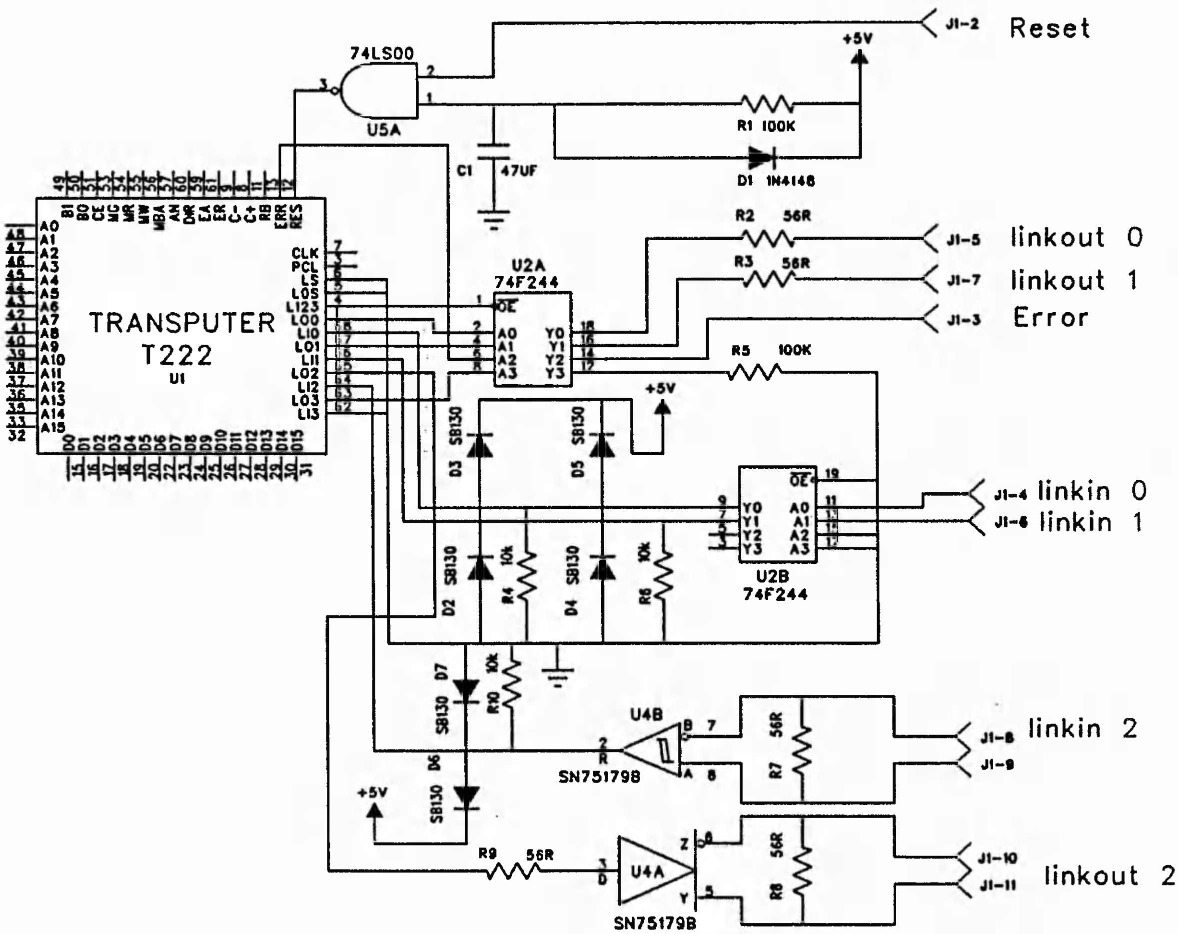


Figure 31 Circuit diagram of the link termination

◆ **Readout circuit**

The Analogue to digital converter used on the readout was a very sensitive device, if the input voltage rose over twice the reference voltage the device would no longer work on that channel. The maximum input voltage from the hiedenhain scales could change with the scale used and the speed of movement of the scale. This variation caused over voltage at the A/D inputs and the destruction of the devices. A protection circuit was added to prevent this reoccurring.

5.2 The Testing of the New Controller

◆ Positional accuracy

The positonal accuracy of the measuring machine is determined by two main criteria.

- The move tunnel tolerance

  This is the Positional variation of the machine from the expected path whilst moving in CNC. The move tunnel of the existing controller is between 1mm and 20mm depending on the size of measuring machine. The new controller provides a move tunnel of 100 microns. The variation of the new controller from its path is due to the acceleration and deceleration of the machine, this could be reduced considerably if the accelerations were reduced.

- The move tolerance

  The Positional variation of the probe from its final expected position. The existing controller can produce a move tolerance of 50 microns on a high accuracy machine compared to 5 microns using the new controller. It is possible to move the machine to the resolution of the scale if required.

◆ Acceleration and deceleration of the machine

The new controller was able to improve the acceleration of the machine from 100 mm/sec/sec to 1000 mm/sec/sec and deceleration from 100 mm/sec/sec 500 mm/sec/sec with having to change the mechanical construction of the machine. This improvement in performance resulted in the reduction of component measuring times by a factor of four. A greater improvement in the accelerations is possible if the mechanical design was made more robust.

5.3 Development Projects

◆ Non-contact probe

A vision system has now been added to the range of probes available to the measuring machines of W.A.Metrology. The vision system used is AVS101 from Azure, this system is also transputer controlled which enables a simple link interface between the two systems. The vision system is attached to a transputer link on the readout card and replaces the event channel in producing the probe hit information for the system. The AVS101 is a transputer based image processing system which uses two T800 transputers to capture an image from a CCD camera and display this image on a Super VGA monitor. The measuring system calibrates the image on the screen by taking measurements of a calibrated gauge of known size, each pixel can then be represented by a number of microns.

There are many new applications for this new non contact probe which has opened new markets for W.A.Metrology. It would not be possible to interface this type of probe to the existing controller because it would not be able to process the results fast enough.

♦ The 1991 M.Eng project

The 1991 M.Eng students at Nottingham polytechnic were given a project on the transputer readout system. The design specification was to improve the incremental encoder so that the quadrature counts of each axis could be latched at the same time when a probe hit occurs and to be able to read the counts with a 32 bit transputer in one read cycle. The finished design was able to fit a two axis incremental encoder on each axis having a 24 bit counter in to a 3 micron gate array.

The gate array was fully tested and simulated, the results indicated satisfactory operation in accordance with the specification, the silicon layout was not completed due to lack of time. The cost of producing the gate array did not make it commercially viable to incorporate the gate array in the readout design at present, it is expected that when the price of the 3 micron gate array reduces this design will be used.

♦ The 1992 B.Eng Project

This project was a feasibility study of the readout input circuit. Five students over twelve weeks looked in to the method used to produce the accurate positional information received from the Hiedenhain scales. The M.Eng gate array was also examined to see if addition logic from the readout card could be incorporated in the design to make commercially viable to use in the design.

A series of recommendations were made by the group on improving the design of the probe input circuit and introducing a new analogue to digital converter (National semiconductor ADC08068) which has an input sample and hold facility and a faster conversion rate.

5.4 Recommendations and Further Work

The control parameters of the machine are at present found by trial and error. When the machine moves it stores various information every loop time which can be displayed in the form of graphical output to the PC screen. This method of setting up the parameters is slow and inaccurate, an automatic set-up routine which is adaptive is needed to get the best performance out of the controller.

An expert system is needed to check the functionality of the control system and report specific faults to the PC so that an engineer can repair the machine quickly and efficiently.

The mechanical design of the co-ordinate measuring machine could be made structurally stronger to enable the acceleration of the machine to be increased and further reduce measuring times.

The present gearboxes used on the machines have a fifty to one gearbox ratio which could now be reduced to increase the top speed of the measuring machine. This would not significantly effect the performance of the new controller but would reduce the time taken on long moves.

An improvement in the quality of the analogue to digital converter as suggested by the B.Eng students could possibly increase the repeatability of the readout system.

The handbox could be improved by using a T800 Transputer instead of the T225 it presently uses. This part of the controller has the processor which has the largest programs to be implemented. A larger LCD 8x80 would enable the stand alone PC screen to mirrored on the handbox making the machine more user friendly. The present keyboards are custom made and could be replaced with a standard keyboard with a significant cost reduction.

The user PC software could run in UNIX or Windows NT which would allow the host computer to multi task its operations and allow Statistical process control and graphics software to be used when the machine is operating.

There are over 150 existing W.A.Metrology measuring machines operating through Britain, all these machines can be easily updated to the new controller without any mechanical changes and using many of the existing peripherals.

5.5 Conclusions

♦ Performance

The performance of the transputer controller has exceeded all the expectations required from the initial specification. A move tolerance of less than 5 microns is possible on moves of more than 1 mm (The specification was a move tolerance of Ten microns). The CMM has a move tunnel of less than 100 microns and this error only occurs during acceleration and deceleration, the steady state error of a move is less than 10 microns. It is expected that as the algorithm is improved these tolerances will be reduced further. The Transputer controller can accelerate and decelerate over ten times faster than it predecessor, at over 1000 mm/sec/sec.

The evaluation of time saved by the Transputer controller is dependant on the component being measured. When a component is measured with a lot of short moves it can then utilise the faster accelerations and declarations of the new controller, components can be measured up to four times faster than the previous controller (Rolls Royce turbine blade 8.6 mins to 1.45 mins). From section 1.2 the specification was to reduce the measuring time by 50%. This has been achieved and improved upon without increasing the top speed of the Co-ordinate Measuring Machine. The steady state drift of the CMM has been eliminated because of the digital drive techniques used.

The performance of the drive is more predictable than the previous controller. This predictability enables the controller to aid the mechanical set-up of the CMM, i.e. Setting the air pressure on the air bearing, adjusting the pressure of the motor against the drive rod. All the initial improved design requirements for the control and drive system have been met and in most cases improved upon.

♦ **Adaptive design**

The new non contact probe used on the measuring machines was not part of the original specification. This probe was easily added on to the transputer controller using a spare link from the readout transputer card. This would not have been possible using the old controller. This non contact measuring probe has the ability to measure components over 50 times faster than the previous method.

♦ **Modular design**

The design of the controller could be easily updated because of the modular design. The main functions of the controller i.e. readout, drive and handbox are connected to the system via two link wires. The drive card and amplifiers can operate any type of measuring machine and can also drive any 24v or 48v DC motors up to currents of 12 amps.

♦ **System costs**

The cost of the controller was not thought to be of major importance as the present controller represented only 10 percent of the cost of the overall machine. The total cost of the new controller is significantly cheaper on the cost of components and has less manufacturing costs because of the reduced number of circuit boards required. The existing controller needed servo's to drive the motors, Hiedenhain EXE's to interpolate the readout signals, neither of these are needed reducing not only costs but the ability for the company to support its own products.

♦ The Market place

The new transputer controlled measuring machine was exhibited at Metcut 92 at the NEC for two weeks ready for sale to the public. The controller has also been exhibited at IP92 and Automan92 at the NEC using the new non contact vision probe. This product enables W.A.Metrology to compete with any of its competitors for speed and accuracy in the Co-ordinate Measuring Machine industry.

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APPENDIX 1

COORDINATE MEASURING MACHINES

1. PURPOSE

1.1 To define the basic mandatory requirements, unless otherwise stated, for the calibration control of Coordinate Measuring Machines.

2. APPLICABILITY

2.1 To all delegated calibration areas.

3. DEFINITION

3.1 Coordinate Measuring Machine (CMM). Machine capable of taking measurements in three axis either manually or CNC controlled.

4. RECOMMENDATIONS

4.1 Ensure that the calibration reference/standard is allowed to 'soak' in the vicinity of the machine for a period of 24 hours prior to test.

Ensure complete cleanliness of Reference Standard and machine table.

Ensure no downward clamping pressures are exerted.

Allow an operator who is familiar within the operation of the machine being calibrated, to perform the test and ensure he fully understands what is required.

5. REQUIREMENTS

5.1 New

5.1.1 To the manufacturers or Rolls-Royce plc specification, as applicable.

5.2 Calibration

5.2.1 Check the volumetric accuracy U_3, using a suitable reference standard comprising a series of length bars. These may be either round or rectangular section, suitably supported on a fixture. See Fig 1. Preferably five bars should be used, covering the measuring range at equally spaced intervals. The minimum number of bars to be used is two.

5.2.2 Take measurements at four cross diagonal positions. See Fig 2. Operational measurements may include in-place diagonals and/or x, y and z axis.

5.2.3 Take total of 50 measurements of reference standard comprising:

10 measurements each on 5 bars
or
25 measurements each on 2 bars

Other length bar combinations - pro rata. Where reference standard is shorter than the measuring line, additional measurements can be taken by moving reference standard along measuring line, overlapping by a minimum of 30%.

5.2.4 Obtain values of ΔL, the difference between measured reading and reference standard, for each measurement. Taking maximum and minimum readings for each bar size, plot results graphically, deviation ΔL against length of bar.

5.2.5 Include the CMM Manufacturers volumetric specification U_3, for the machine being calibrated on the graph.

The performance of the CMM is verified if not more than two ΔL values are greater that the manufacturers U_3 value.

5.2.6 Where no Manufacturers specification exists, it will be necessary to determine the machine accuracy by applying boundary lines to contain the measured deviations, both plus and minus. Up to two readings may be outside the boundary lines. The volumetric accuracy U_3 is the value obtained where the boundary line intersects the Y axis, plus the maximum slope of the line. See example Fig 3.

5.2.7 Record results as per CCP 1.10 and apply appropriate Calibration Control in accordance with CCP 1.11.

5.2.8 Optional

A stepped gauge may be used in place of the length bars if required.

5.3 Alternative method, using the Rolls-Royce plc volumetric calibration frame GTR 2352

5.3.1 Select the frame size to suit the machine capacity.

NB The basic aim is to determine the distance between pin centres from a datum No 1 pin, using the X, Y and Z movements of the machine. The frame is moved to various diagonal positions on the machine table and the results compared. Any differences obtained gives a measure of the volumetric accuracy of the machine. The basic frame concept is shown in Fig 4. A minimum of four positional checks must be carried out at positions shown in Fig 5. Additional checks may be carried out to increase coverage of the machine, in particular, checks at the cardinal points N, S, E and W are the most useful.

5.3.2 Position the frame on machine table at '1st Diagonal' position, Fig 5. This can be assessed visually as accurate positioning is not essential.

5.3.3 Secure the frame to prevent movement using magnetic clamps, if practical, or plasticine positioned as shown in Fig 6.

5.3.4. Establish the vertical datum on the top surface of No 1 pin. Zero the 'Z' axis readout.

5.3.5 By contact with the outer diameter on No 1 pin at position shown in Fig 4, establish the pin centre (ie, X datum). Zero 'X' and 'Y' axis readouts.

5.3.6 Repeat 5.3.4 and 5.3.5 at each subsequent pin positions and record values of the 'X', 'Y' and 'Z' readouts (NB Do not zero readouts after establishing No 1 pin position as datum).

Some machines automatically provide the longitudinal distance 'X' between pins which is the hypotenuse of X and Y.

5.3.7 After measurement of highest pin position, tabulate all results: for positions shown in Fig 7.

Z1 to Z2	Z1 to Z3	Z1 to Z4 etc
X1 to X2	X1 to X3	X1 to X4 etc

5.3.8 Reverse calibrator frame through 180° and repeat step 5.3.3 to 5.3.7.

5.3.9 Position the frame at 2nd diagonal position, Fig 5, and repeat steps 5.3.3. to 5.3.8.

5.3.10 On completion of the reversal check at 2nd diagonal position the basic calibration procedure is complete.

5.3.11 Using the X, Y and Z readings obtained for each diagonal check, calculate the point to point size AC for each position.

Test value AC = $X^2 + Y^2 + Z^2$

5.3.12 Compare the test values of AC with the calibrated values supplied with the frame. Identify the largest $\pm$ and - deviation and add these values together to obtain the volumetric accuracy of the machine under test.

5.3.1.3 Plot the results graphically as shown in Fig 8. This will show if the volumetric variation is disposed equally about a zero datum or has a bias toward + or -.

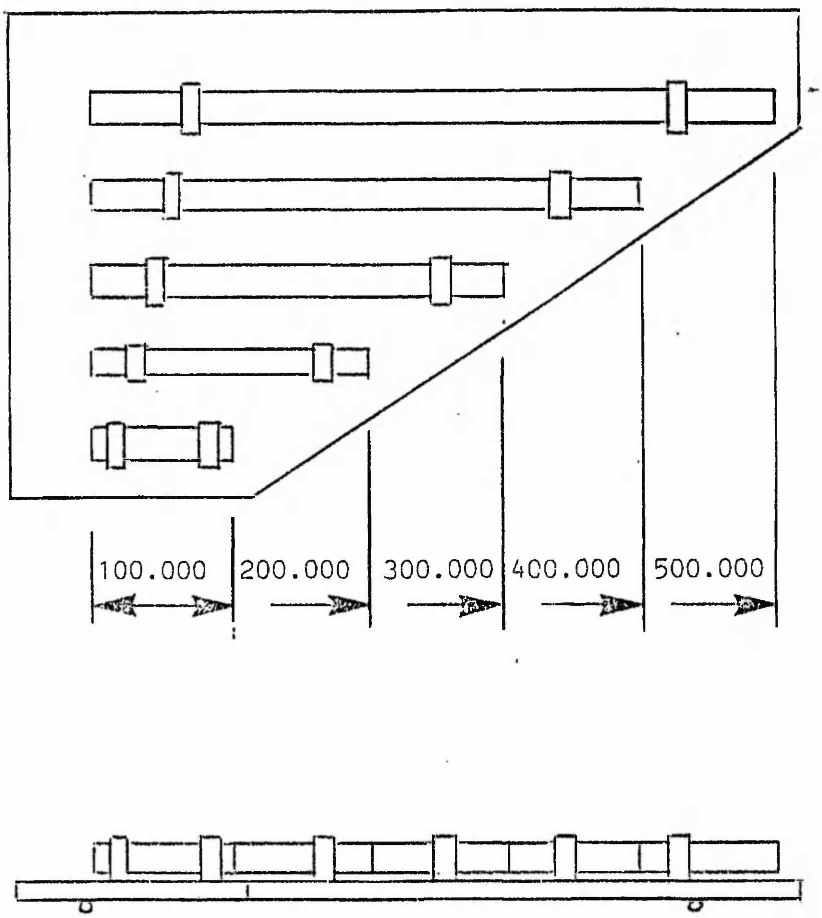
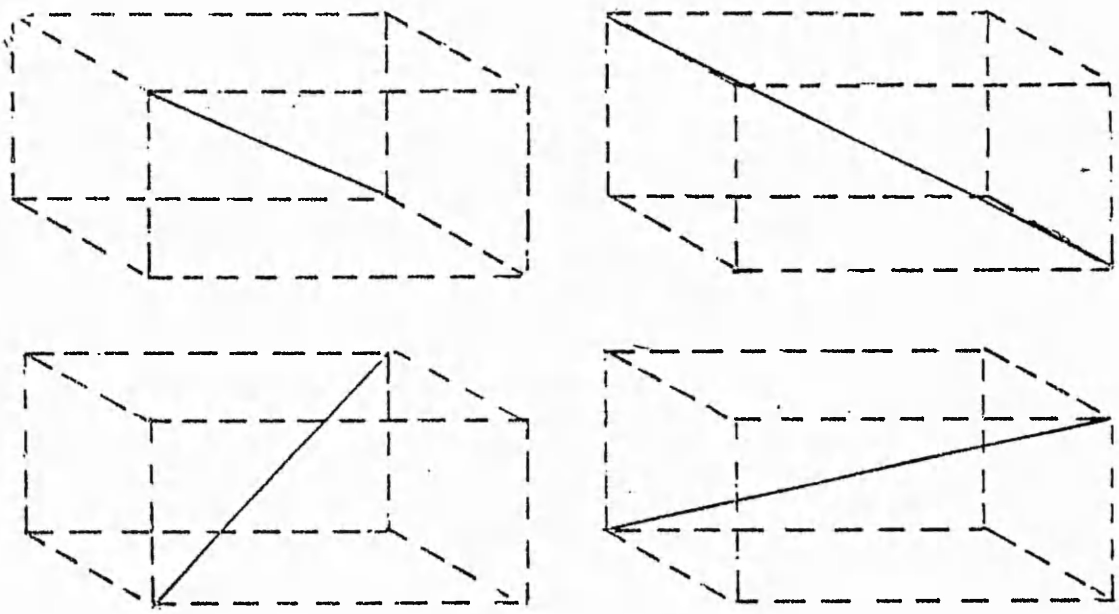
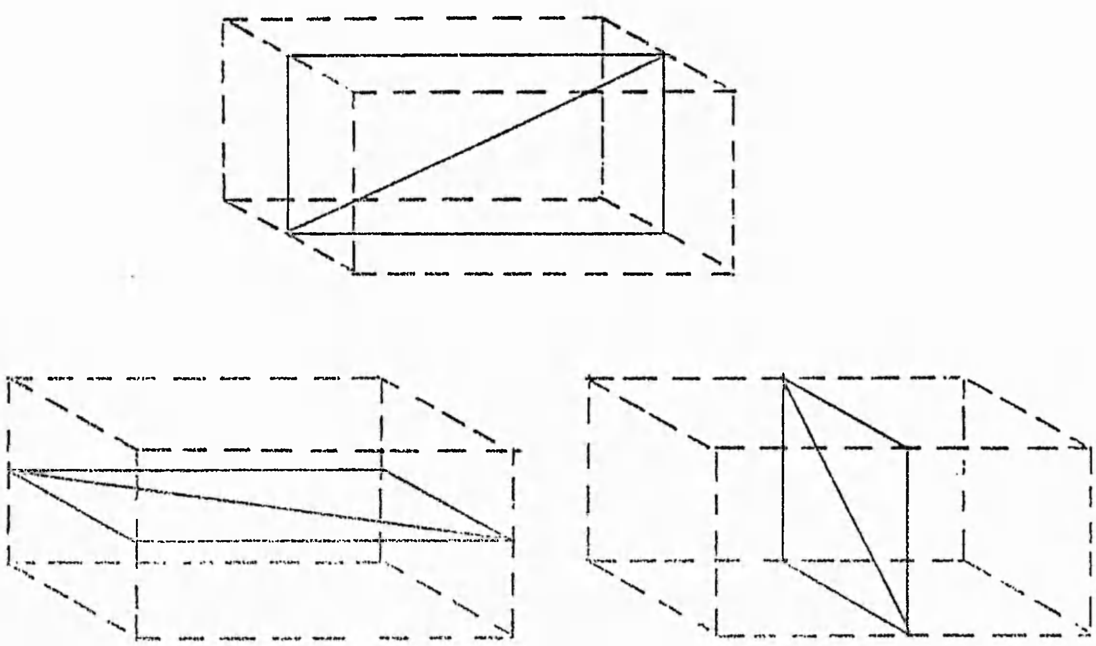


FIG 1: DIAGRAMMATIC VIEW OF REFERENCE STANDARD FIXTURE.
CAN BE INCLINED BY UP TO 45° TO THE CMM TABLE.



2 (a): CROSS DIAGONAL POSITIONS OF CALIBRATION.



(b): IN-PLANE DIAGONAL CALIBRATION POSITIONS - ADDITIONAL OPTION.

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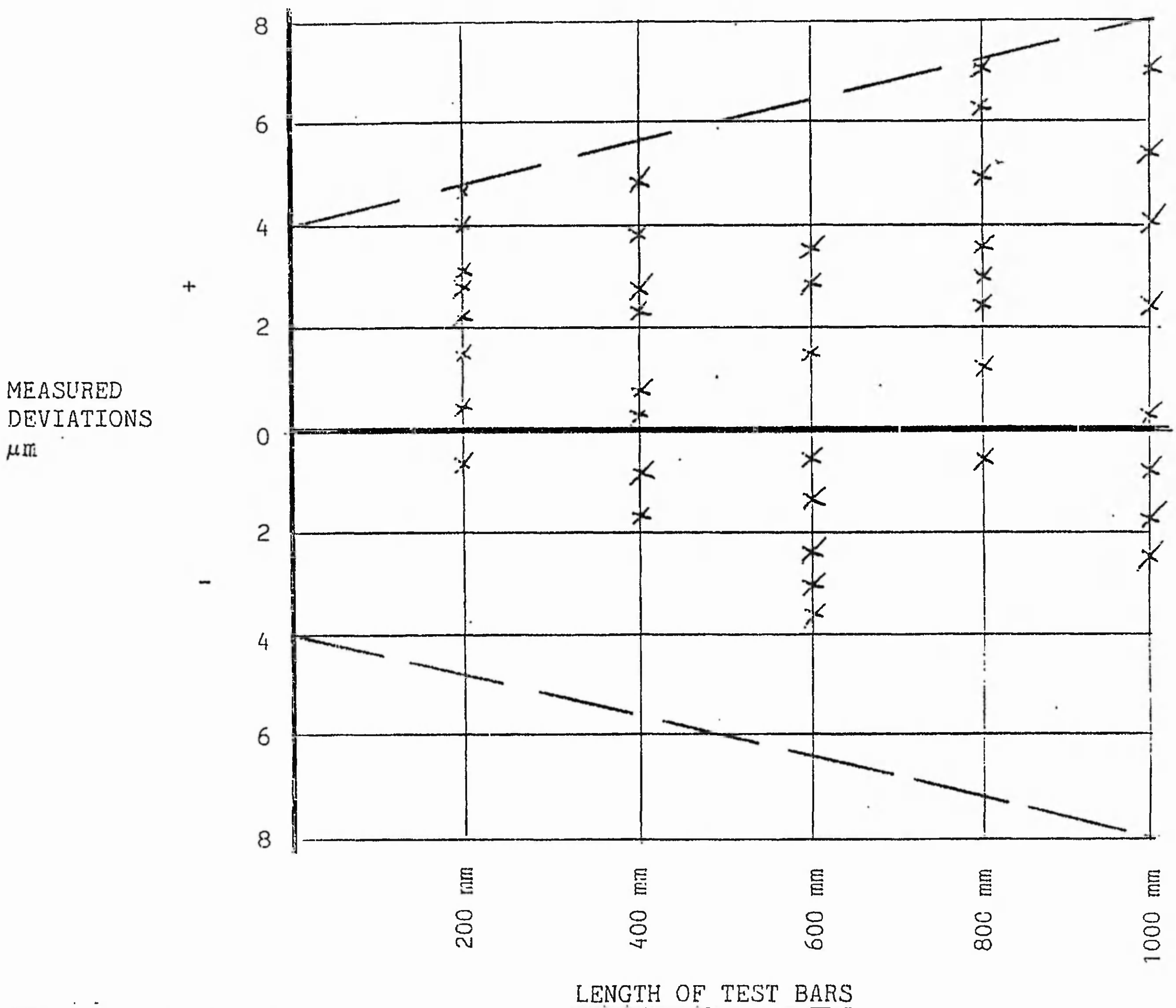
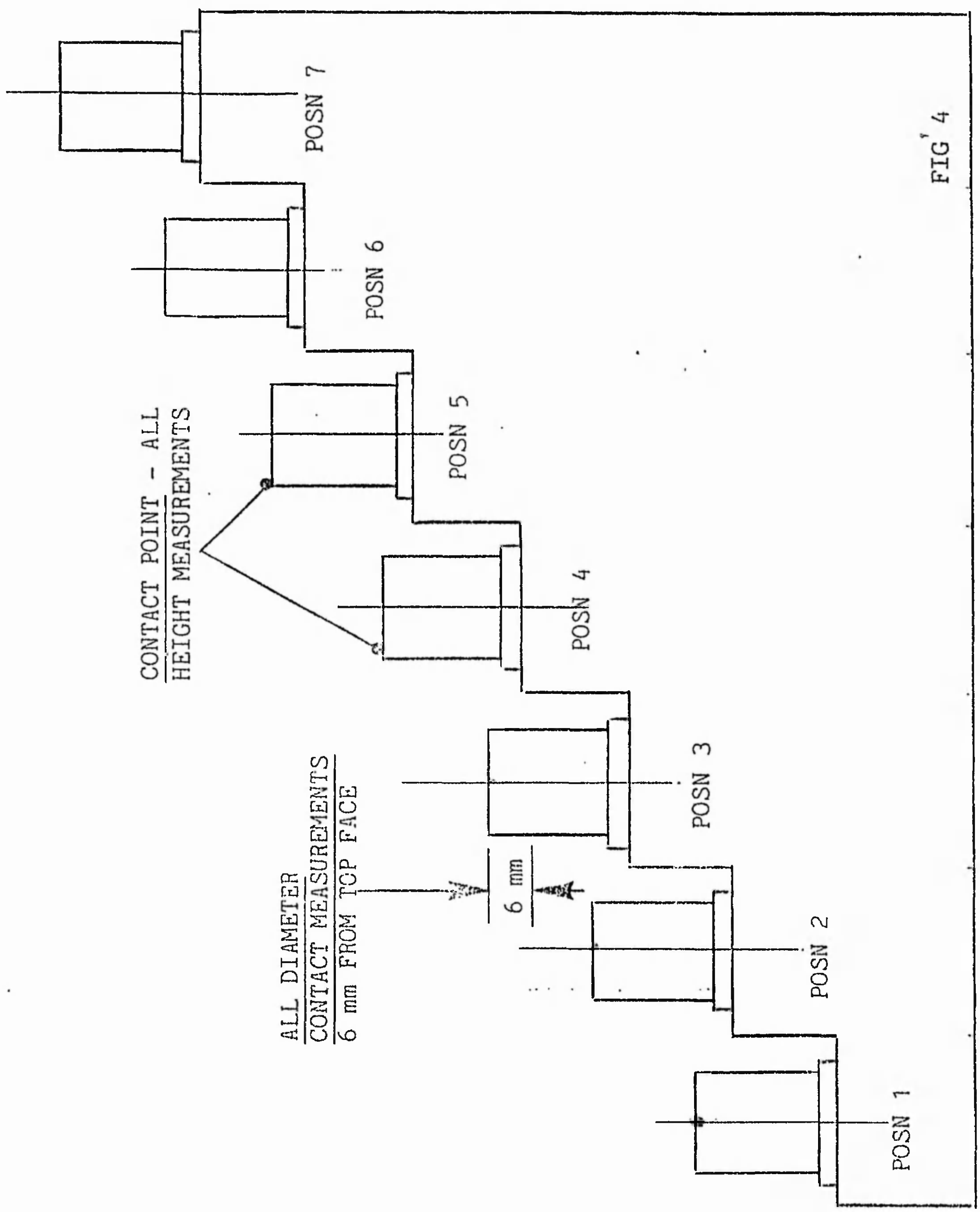


FIG 3: 5 TEST BARS.
MEASURED AT 4 DIAGONAL POSITIONS.
BOUNDARY LINES EQUALLY SPACED ABOUT ZERO ENCOMPASSING ALL MEASURED POINTS.
VOLUMETRICX ACCURACY $U_3 = 4 + \frac{L}{250}\ \mu m$

PITCH AND HEIGHT MEASUREMENTS FROM O/D^{S} AND TOP FACES



FIG' 4

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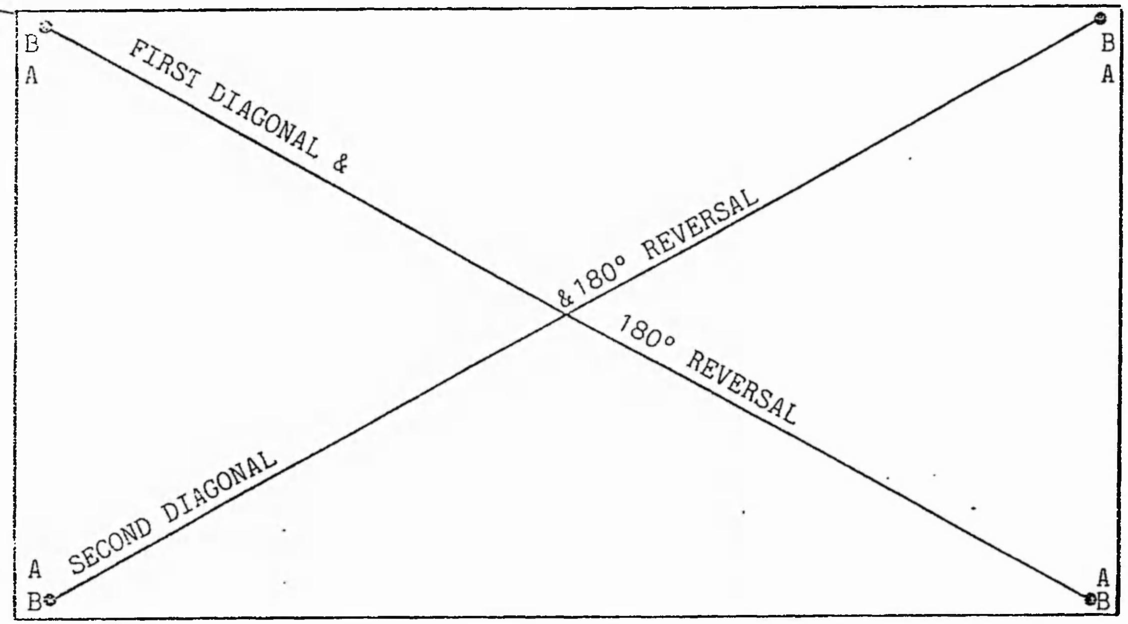


SEQUENCE 1	FIRST DIAGONAL	A TO B
2		B TO A
3	REVERSAL	A TO B
4		B TO A
5	SECOND DIAGONAL	A TO B
6		B TO A
7	REVERSAL	A TO B
8		B TO A

FIG 5

POSITION FOR MAGNETIC CLAMPS. THE CLAMPS SHOULD ONLY CONTAIN THE CALIBRATOR AND NO DOWNWARD CLAMPING PRESSURES SHOULD BE EXERTED UPON IT.

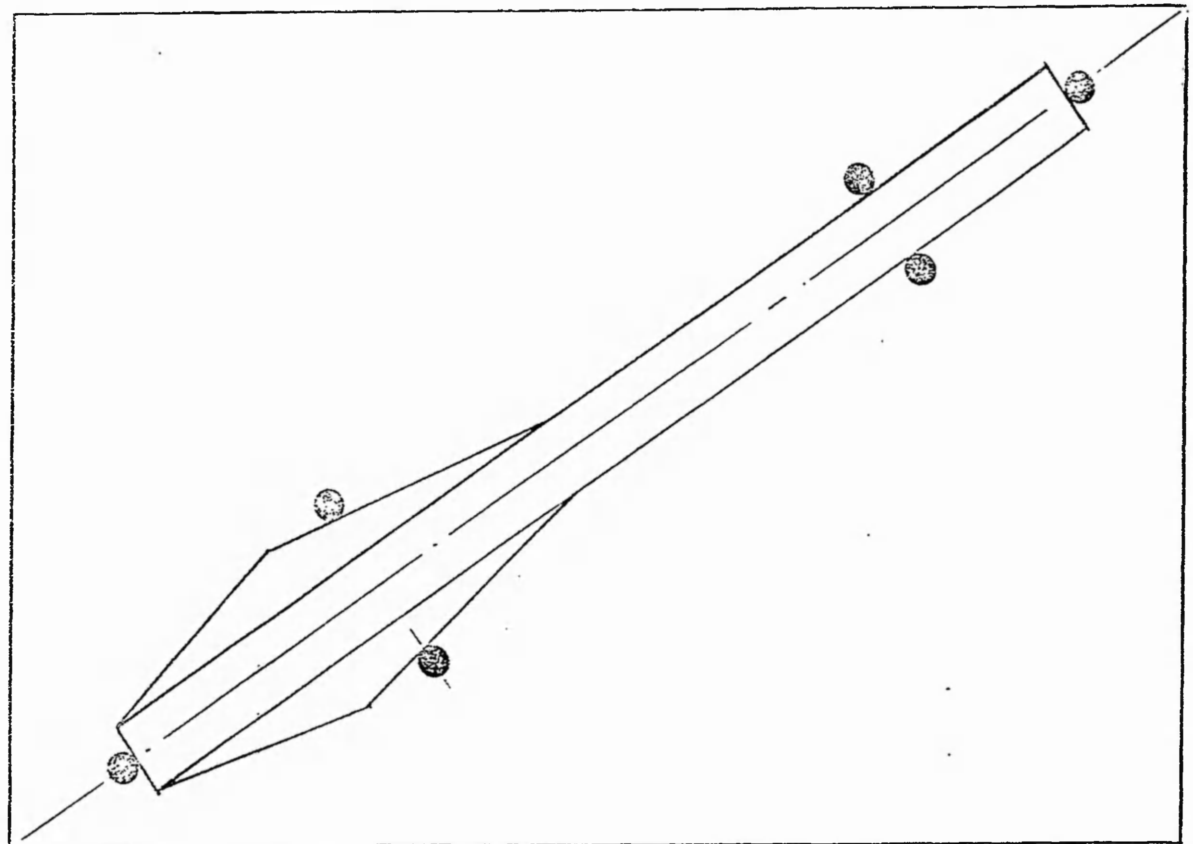


FIG 6

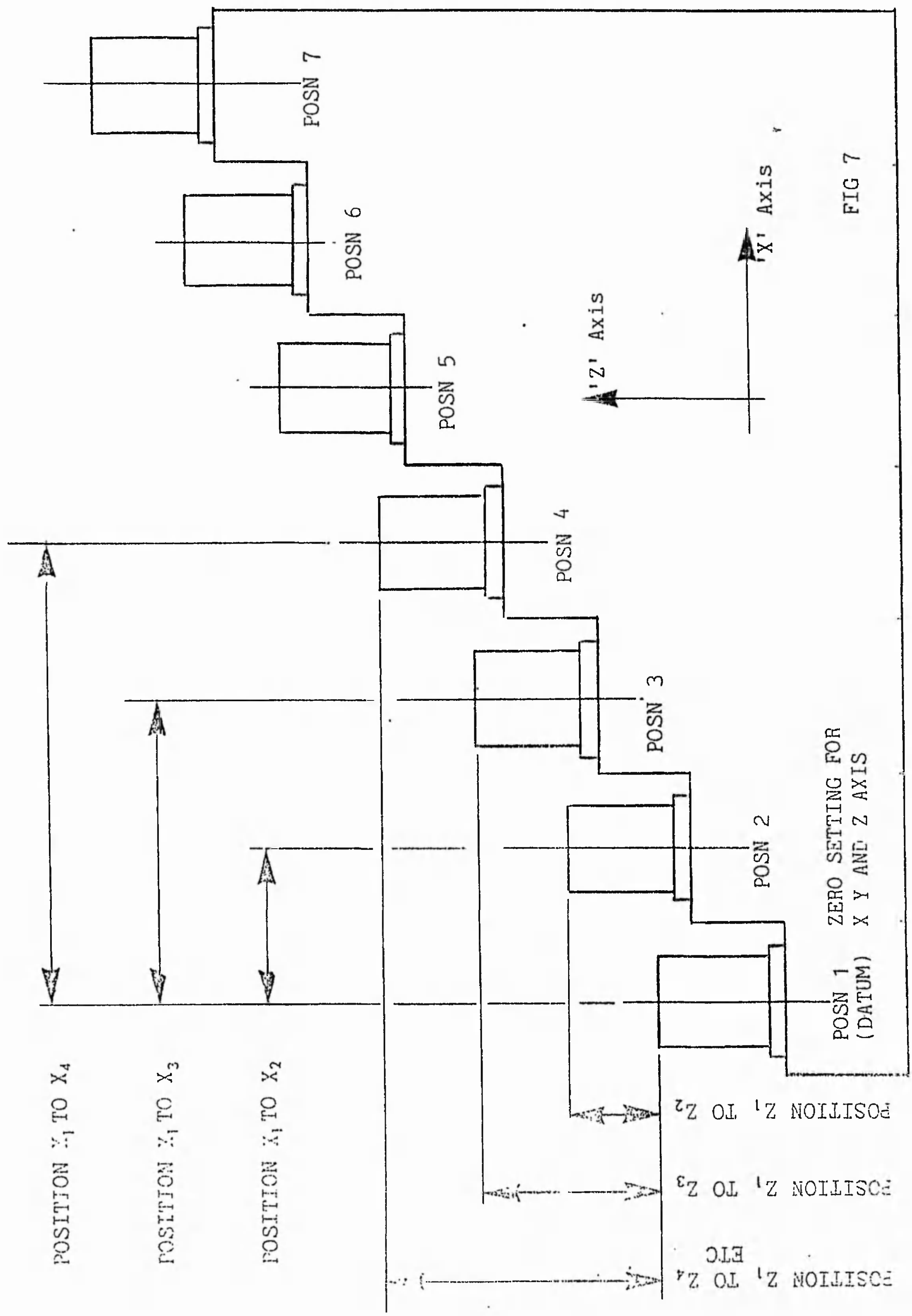
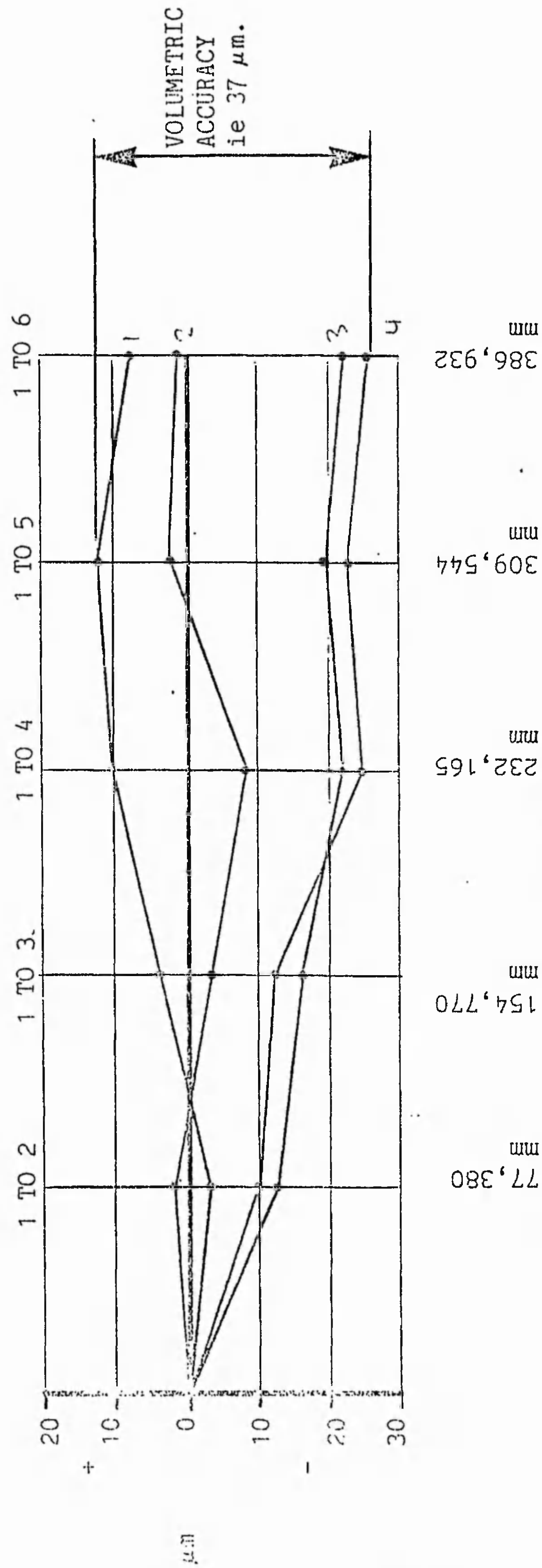

POSN 7
POSN 6
POSN 5
POSN 4
POSN 3
POSN 2
POSN 1 (DATUM)
ZERO SETTING FOR X Y AND Z AXIS
'Z' Axis
'X' Axis
POSITION X_1 TO X_4
POSITION X_1 TO X_3
POSITION X_1 TO X_2
POSITION Z_1 TO Z_2
POSITION Z_1 TO Z_3
POSITION Z_1 TO Z_4 ETC

FIG 7

TYPICAL EXAMPLE



PLOTTED DEVIATIONS

FIG 8

APPENDIX 2

Readout Test Software

```
--{{{F newprobe.occ     proc new.probe.hit
--:::F NEWPROBE.OCC
--}}}
--{{{F newcntr.occ     proc new.counters
--:::F NEWCNTR.OCC
--}}}
--{{{F csmultpx.occ
--:::F CSMULTPX.OCC
--}}}
--{{{F rocomms.occ     proc ro.comms
--:::F ROCOMMS.OCC
--}}}
--{{{F cscomms.occ     proc cs.comms
--:::F CSCOMMS.OCC
--}}}
--{{{F roprot.inc     protocols
--:::F ROPROT.INC
--}}}

--{{{  #use & #includes
#INCLUDE "linkaddr.inc"
#INCLUDE "hostio.inc"
#INCLUDE "roprot.inc"
#USE "cscomms.c4h"
#USE "csmultpx.c4h"
#USE "rocomms.c2h"
#USE "newprobe.c2h"
#USE "newcntr.c2h"
--}}}
--{{{  declarations
CHAN OF SP       fs, ts:
CHAN OF READOUT  from.readout:
--}}}

--{{{  placed pars
PLACED PAR

  PROCESSOR 0 T4
    PLACE fs           AT link0.in:
    PLACE ts           AT link0.out:
    PLACE from.readout  AT link2.in:
    CHAN OF READOUT     from.mult:
    PAR
      cs.comms          (fs, ts, from.mult)
      readout.multiplex  (from.readout, from.mult)


  PROCESSOR 1 T212
    PLACE from.readout  AT link1.out:
    CHAN OF SENDQUAD    t.chan:
    CHAN OF SENDQUAD    event.chan:
    PAR
```

```
    ro.comms        (t.chan, from.readout, event.chan)
    new.probe.hit   (event.chan)
    new.counters    (t.chan)

--}}}

#INCLUDE "linkaddr.inc"
#INCLUDE "roprot.inc"
PROC new.probe.hit (CHAN OF SENDQUAD event.chan)

  --{{{  ports & channels
  CHAN OF ANY debug.chan:
  PLACE debug.chan AT link3.out:
  --{{{  declarations for A/D memory mapped ports
  CHAN OF BYTE      probe.event:

  PORT OF BYTE Y6.event.reset:
  PORT OF BYTE dummy, dummy1:
  PORT OF BYTE x.sin.port, x.cos.port:
  PORT OF BYTE y.sin.port, y.cos.port:
  PORT OF BYTE z.sin.port, z.cos.port:
  PORT OF BYTE r.sin.port, r.cos.port:

  PLACE probe.event      AT event.in:
  PLACE Y6.event.reset   AT (#8000 >< #0060) >> 1:

  --{{{  portdec
  PLACE dummy            AT (#8000 >< #0000) >> 1:  --0
  PLACE dummy1           AT (#8000 >< #0002) >> 1:  --0
  PLACE x.sin.port       AT (#8000 >< #000C) >> 1:  --2
  PLACE x.cos.port       AT (#8000 >< #0002) >> 1:  --0
  PLACE y.sin.port       AT (#8000 >< #000C) >> 1:
  PLACE y.cos.port       AT (#8000 >< #0002) >> 1:
  PLACE z.sin.port       AT (#8000 >< #000C) >> 1:  --E
  PLACE z.cos.port       AT (#8000 >< #0002) >> 1:  --4
  PLACE r.sin.port       AT (#8000 >< #000C) >> 1:  --6
  PLACE r.cos.port       AT (#8000 >< #0000) >> 1:  --6
  --}}}
  --}}}
  --{{{  declarations for counter memory mapped ports
  PORT OF BYTE x.lsb, x.middle, x.msb:
  PORT OF BYTE y.lsb, y.middle, y.msb:
  PORT OF BYTE z.lsb, z.middle, z.msb:
  PORT OF BYTE r.lsb, r.middle, r.msb:

  PLACE x.lsb        AT (#8000 >< #0086) >> 1:
  PLACE x.middle     AT (#8000 >< #0084) >> 1:
  PLACE x.msb        AT (#8000 >< #0082) >> 1:

  PLACE y.lsb        AT (#8000 >< #00C6) >> 1:
  PLACE y.middle     AT (#8000 >< #00C4) >> 1:
  PLACE y.msb        AT (#8000 >< #00C2) >> 1:

  PLACE z.lsb        AT (#8000 >< #0026) >> 1:
```

```
PLACE z.middle      AT (#8000 >< #0024) >> 1:
PLACE z.msb         AT (#8000 >< #0022) >> 1:

PLACE r.lsb         AT (#8000 >< #0046) >> 1:
PLACE r.middle      AT (#8000 >< #0044) >> 1:
PLACE r.msb         AT (#8000 >< #0042) >> 1:
--}}}
--}}}
--{{{ type declarations
BYTE hit, throw.away:
[3]INT16 small.position, add.quad, sub.quad, q.mult:
[3]INT16 counter.quad, out.quad, slip.check:
[3]INT32 f.position, position, quad.check, c.quad:
INT32 set.counter.quad, count:
[4]INT16 set.quad:
[9]BYTE temp:
[6]BYTE sincos, atemp:
[6]INT16 ref, max, min, sinc:
[3]INT16 sin, cos, old.sin, old.cos:
[20]INT16 q.arctan:
[3]INT sin.over.cos.tan, cos.over.sin.tan:
BOOL sin.pos.cos.pos, sin.neg.cos.neg:
BOOL sin.pos.cos.neg, sin.neg.cos.pos:
BOOL going:
[3]BOOL setup, q.sign:
TIMER clock:
INT time, event.time, start, end, total.time:
VAL INT event.delay IS 1:
VAL INT pause IS 1:
--}}}

PAR
  --{{{F yutredcv
  --:::F YUTREDCV
  --}}}
  debug.chan ! 0(BYTE)
:

#INCLUDE "linkaddr.inc"
#INCLUDE "roprot.inc"
PROC new.counters (CHAN OF SENDQUAD t.chan)

  --{{{ ports & channels
  CHAN OF ANY debug.chan:
  PLACE debug.chan AT link3.out:
  --{{{ declarations for A/D memory mapped ports
  CHAN OF BYTE     probe.event:

  PORT OF BYTE Y6.event.reset:
  PORT OF BYTE dummy, dummy1:
  PORT OF BYTE x.sin.port, x.cos.port:
  PORT OF BYTE y.sin.port, y.cos.port:
  PORT OF BYTE z.sin.port, z.cos.port:
  PORT OF BYTE r.sin.port, r.cos.port:
```

```
PLACE probe.event      AT event.in:
PLACE Y6.event.reset   AT (#8000 >< #0060) >> 1:

--{{{ portdec
PLACE dummy1           AT (#8000 >< #0002) >> 1:  --0
PLACE x.sin.port       AT (#8000 >< #000C) >> 1:  --2
PLACE x.cos.port       AT (#8000 >< #0002) >> 1:  --0
PLACE y.sin.port       AT (#8000 >< #000C) >> 1:
PLACE y.cos.port       AT (#8000 >< #0002) >> 1:
PLACE z.sin.port       AT (#8000 >< #000C) >> 1:  --E
PLACE z.cos.port       AT (#8000 >< #0002) >> 1:  --4
PLACE r.sin.port       AT (#8000 >< #000C) >> 1:  --6
PLACE r.cos.port       AT (#8000 >< #0000) >> 1:  --6
--}}}
--}}}
--{{{ declarations for counter memory mapped ports
PORT OF BYTE x.lsb, x.middle, x.msb:
PORT OF BYTE y.lsb, y.middle, y.msb:
PORT OF BYTE z.lsb, z.middle, z.msb:
PORT OF BYTE r.lsb, r.middle, r.msb:

PLACE x.lsb            AT (#8000 >< #0086) >> 1:
PLACE x.middle         AT (#8000 >< #0084) >> 1:
PLACE x.msb            AT (#8000 >< #0082) >> 1:

PLACE y.lsb            AT (#8000 >< #00C6) >> 1:
PLACE y.middle         AT (#8000 >< #00C4) >> 1:
PLACE y.msb            AT (#8000 >< #00C2) >> 1:

PLACE z.lsb            AT (#8000 >< #0026) >> 1:
PLACE z.middle         AT (#8000 >< #0024) >> 1:
PLACE z.msb            AT (#8000 >< #0022) >> 1:

PLACE r.lsb            AT (#8000 >< #0046) >> 1:
PLACE r.middle         AT (#8000 >< #0044) >> 1:
PLACE r.msb            AT (#8000 >< #0042) >> 1:
--}}}
--}}}
--{{{ type declarations
BYTE hit, throw.away:
[3]INT16 small.position, add.quad, sub.quad, q.mult:
[3]INT16 counter.quad, out.quad, slip.check:
[3]INT32 f.position, position, quad.check, c.quad:
INT32 set.counter.quad, count:
[4]INT16 set.quad:
[9]BYTE temp:
[6]BYTE sincos, atemp:
[6]INT16 ref, max, min, sinc:
[3]INT16 sin, cos, old.sin, old.cos:
--[21]INT16 q.arctan:
[3]INT sin.over.cos.tan, cos.over.sin.tan:
BOOL sin.pos.cos.pos, sin.neg.cos.neg:
BOOL sin.pos.cos.neg, sin.neg.cos.pos:
```

```
[3]BOOL setup, q.sign:
TIMER clock:
INT time, event.time, start, end, total.time:
VAL INT event.delay IS 1:
VAL INT pause IS 1:
--{{{
VAL []INT16 q.arctan IS
          [  0(INT16), 8(INT16),
          16(INT16),  24(INT16),  32(INT16),
          40(INT16),  47(INT16),  54(INT16),  62(INT16),
          68(INT16),  75(INT16),  81(INT16),  87(INT16),
          93(INT16),  99(INT16), 104(INT16), 109(INT16),
          114(INT16), 118(INT16), 123(INT16), 127(INT16) ]:
--}}}
--}}}

PAR
  SEQ
    --{{{  set reference
    --{{{  initialise vars
    count := 0(INT32)
    q.sign := [ TRUE, TRUE, TRUE ]
    setup := [ TRUE, TRUE, TRUE ]
    SEQ
      SEQ k = 0 FOR 6
        ref[k], max[k], min[k] := 128(INT16), 0(INT16), 255(INT16)
      SEQ k = 0 FOR 3
        SEQ
          slip.check[k] := 0(INT16)
          add.quad[k] := 0(INT16)
          sub.quad[k] := 0(INT16)
          position[k] := 0(INT32)
    --}}}
    --{{{  tset quadrants
    --x.lsb ? temp[2]
    --x.middle ? temp[1]
    --x.msb ? temp[0]
    --SEQ j = 0 FOR 3
      --position[0] := (INT32 temp[j]) V (position[0] << 8)
    --set.counter.quad := (position[0] /\ #00000300(INT32)) >> 8
    --SEQ i = 0 FOR 4
      --set.quad[((INT set.counter.quad) + i) REM 4] := (INT16 i) + 1(INT16)
    --}}}
    --{{{  setmax min & reference readings
    --WHILE  count < 1000000(INT32)
      --SEQ
        --{{{  read a/d
        --dummy1 ? throw.away
        --{{{  no ops delay of approx 3.5microsecs 3 is 3.5, now on 6
        --SEQ i = 0 FOR 3
          --SKIP
        --}}}
        --x.sin.port ? atemp[0]
        --{{{  no ops delay of approx 3.5microsecs 3 is 3.5, now on 6
```

```
--SEQ i = 0 FOR 3
 --SKIP
--}}}
--x.cos.port ? atemp[1]
--}}}
--{{{  change max, min, ref
--SEQ i = 0 FOR 2
 --SEQ
  --IF
   --(INT16 atemp[i]) > max[i]
    --max[i] := (INT16 atemp[i])
   --TRUE
    --SKIP
  --IF
   --(INT16 atemp[i]) < min[i]
    --min[i] := (INT16 atemp[i])
   --TRUE
    --SKIP
  --ref[i] := (max[i] - min[i]) / 2(INT16)
--}}}
--count := count + 1(INT32)
--}}}
--}}}
WHILE TRUE
 SEQ
  --{{{  read x, y, z byte counter positions
  x.lsb ? temp[2]
  y.lsb ? temp[5]
  z.lsb ? temp[8]
  x.middle ? temp[1]
  y.middle ? temp[4]
  z.middle ? temp[7]
  x.msb ? temp[0]
  y.msb ? temp[3]
  z.msb ? temp[6]
  --}}}
  --{{{  read a/d
  dummy ? throw.away
  --{{{  no ops delay of approx 3.5microsecs 3 is 3.5, now on 3
  SEQ i = 0 FOR 3
   SKIP
  --}}}
  dummy1 ? throw.away
  --{{{  no ops delay of approx 3.5microsecs 3 is 3.5, now on 3
  SEQ i = 0 FOR 3
   SKIP
  --}}}
  x.sin.port ? sincos[0]
  --{{{  no ops delay of approx 3.5microsecs
  SEQ i = 0 FOR 3
   SKIP
  --}}}
  x.cos.port ? sincos[1]
  --{{{  no ops delay of approx 3.5microsecs
```

```
SEQ i = 0 FOR 3
 SKIP
--}}}
y.sin.port ? sincos[2]
--{{{ no ops delay of approx 3.5microsecs
SEQ i = 0 FOR 3
 SKIP
--}}}
y.cos.port ? sincos[3]
--{{{ no ops delay of approx 3.5microsecs
SEQ i = 0 FOR 3
 SKIP
--}}}
z.sin.port ? sincos[4]
--{{{ no ops delay of approx 3.5microsecs
SEQ i = 0 FOR 3
 SKIP
--}}}
z.cos.port ? sincos[5]
--}}}
--{{{ convert counter readings to 32bit ints
SEQ f = 0 FOR 3
 position[f] := 0(INT32)
SEQ i = 0 FOR 3
 SEQ j = 0 FOR 3
  position[i] := (INT32 temp[j + (3*i)]) V (position[i] << 8)
--SEQ i = 0 FOR 3
 --position[i] := position[i] << 8

--}}}
--{{{ interpolate A/D readings
--{{{ limit sin & cos to between -128 & 127
SEQ i = 0 FOR 3
 SEQ
  cos[i] := (INT16 sincos[(2*i)+1]) - ref[(2*i)+1] --cos
  sin[i] := (INT16 sincos[2*i]) - ref[2*i] --sin
SEQ i = 0 FOR 3
 SEQ
  sin[i] := ((sin[i]) Λ (#FFFC(INT16)))
  cos[i] := ((cos[i]) Λ (#FFFC(INT16)))
--}}}
SEQ i = 0 FOR 1
 SEQ
  --{{{ assign lookup table values and boolean quad variables
  sin.pos.cos.pos, sin.neg.cos.neg := FALSE, FALSE
  sin.pos.cos.neg, sin.neg.cos.pos := FALSE, FALSE
  --}}}
  --{{{ determine a/d quadrant
  IF
   (sin[i] >= 0(INT16))
    --{{{ either set.quad 0 or 1
    IF
     (cos[i] >= 0(INT16))
      SEQ
```

```
      out.quad[i] := 0(INT16)
      sin.pos.cos.pos := TRUE
    TRUE
     SEQ
      out.quad[i] := 1(INT16)
      cos[i] := -cos[i]
      sin.pos.cos.neg := TRUE
  --}}}
 TRUE
  --{{{  either set.quad 2 or 3
  IF
   (cos[i] <= 0(INT16))
    SEQ
     out.quad[i] := 2(INT16)
     cos[i] := -cos[i]
     sin[i] := -sin[i]
     sin.neg.cos.neg := TRUE
   TRUE
    SEQ
     out.quad[i] := 3(INT16)
     sin[i] := -sin[i]
     sin.neg.cos.pos := TRUE
  --}}}
IF
 sin[i] = 0(INT16)
  sin[i] := 1(INT16)
 TRUE
  SKIP
IF
 cos[i] = 0(INT16)
  cos[i] := 1(INT16)
 TRUE
  SKIP

--}}}
--{{{  calculte s.pos
IF
 (sin[i] <> 0(INT16)) AND (cos[i] <> 0(INT16))
  --{{{  calculate small.position
  SEQ
   sin.over.cos.tan[i] := (INT((sin[i] * 200(INT16)) / cos[i]))
   sin.over.cos.tan[i] := ((sin.over.cos.tan[i] + 5(INT)) / 10(INT))
   cos.over.sin.tan[i] := (INT((cos[i] * 200(INT16)) / sin[i]))
   cos.over.sin.tan[i] := ((cos.over.sin.tan[i] + 5(INT)) / 10(INT))
   IF
    (sin.pos.cos.pos OR sin.neg.cos.neg)
     SEQ
      IF
       cos[i] >= sin[i]
        small.position[i] := q.arctan[sin.over.cos.tan[i]]
       TRUE
        small.position[i] := (256(INT16) - q.arctan[cos.over.sin.tan[i]])
    (sin.pos.cos.neg OR sin.neg.cos.pos)
     SEQ
```

```
        IF
          sin[i] >= cos[i]
            small.position[i] := q.arctan[cos.over.sin.tan[i]]
          TRUE
            small.position[i] := (256(INT16) - q.arctan[sin.over.cos.tan[i]])
    --}}}
   TRUE
     SKIP
 --}}}
 --{{{  setup quadrant routine
 IF
   setup[i]
     IF
       ( ( (sin[i] > (-25(INT16)) ) AND (sin[i] < 25(INT16)) ) OR
         ( (cos[i] > (-25(INT16)) ) AND (cos[i] < 25(INT16)) ) )
         SKIP
       TRUE
         SEQ
           setup[i]  := FALSE
           c.quad[i] := (position[i] /\ #00000003(INT32))
           q.mult[i] := out.quad[i] - (INT16 c.quad[i])
           --{{{  calculate multiplier
           IF
             q.mult[i] = 3(INT16)
               q.mult[i] := 1(INT16)
             q.mult[i] = 1(INT16)
               q.mult[i] := 3(INT16)
             q.mult[i] < 0(INT16)
               q.mult[i] := (-q.mult[i])
             TRUE
               SKIP
           --}}}
   TRUE
     SKIP
 --}}}
 --{{{  quadrant check
 IF
   setup[i]
     SKIP
   TRUE
     SEQ
       --{{{  counter quadrant
       quad.check[i] := (position[i] /\ #00000003(INT32))
       CASE (INT quad.check[i])
         0
           counter.quad[i] := 0(INT16) - q.mult[i] --3(INT16)
         1
           counter.quad[i] := 1(INT16) - q.mult[i]
         2
           counter.quad[i] := 2(INT16) - q.mult[i]
         3
           counter.quad[i] := 3(INT16) - q.mult[i]
         ELSE
           counter.quad[i] := 0(INT16)
```

```
            counter.quad[i] := (counter.quad[i] /\ #0003(INT16))
            --}}}
            --{{{  sslippp check for slippage
            add.quad[i] := 0(INT16)
            slip.check[i] := counter.quad[i] - out.quad[i]
            IF
              slip.check[i] = (-3(INT16))
                slip.check[i] := 1(INT16)
              slip.check[i] = 3(INT16)
                slip.check[i] := (-1(INT16))
              TRUE
                SKIP
            --{{{  frigger add quad
            IF
              (slip.check[i] < (-1(INT16))) OR  (slip.check[i] > 1(INT16))
                SKIP
                --CAUSEERROR()
              (slip.check[i] = (-1(INT16)))
                add.quad[i] := (50(INT16))
              (slip.check[i] =  1(INT16))
                add.quad[i] := -50(INT16)
              TRUE
                SKIP
            --}}}
            --}}}
        --}}}
      --}}}
      --{{{  combine counter and A/D readings & output
      SEQ i = 0 FOR 1
        IF
          setup[i]
            SEQ
              small.position[i] := 0(INT16)
              f.position[i] := (position[i] * 50(INT32))
              t.chan ! sincos; position; small.position; f.position
          TRUE
            SEQ
              f.position[i] := (position[i] * 50(INT32)) + (INT32 add.quad[i])
              t.chan ! sincos; position; small.position; f.position
      --}}}
    debug.chan ! 0(BYTE)
:

#INCLUDE "roprot.inc"
PROC readout.multiplex (CHAN OF READOUT from.readout, from.mult)

  [6]BYTE d:
  [3]INT32 a:
  [3]INT32 e:
  [3]INT16 b, c:

  SEQ
    WHILE TRUE
      SEQ
```

```
    from.readout ? CASE
      r.data; d; a; b; e
        from.mult ! r.data; d; a; b; e
      r.p.hit; d; a; b; e
        from.mult ! r.p.hit; d; a; b; e
:

#INCLUDE "linkaddr.inc"
#INCLUDE "roprot.inc"
PROC ro.comms (CHAN OF SENDQUAD t.chan, CHAN OF READOUT from.readout,
          CHAN OF SENDQUAD event.chan)

  --{{{ declarations
  [3]INT32 position:
  [3]INT16 small.position:
  [3]INT32 hit.position:
  [3]INT32 f.position:
  [3]INT16 c.quad, a.quad:
  [6]BYTE sincos:
  --}}}

  WHILE TRUE
    ALT
      event.chan ?  sincos; position; small.position; f.position
        from.readout ! r.p.hit; sincos; position; small.position; f.position
      t.chan ? sincos; position; small.position; f.position
        from.readout ! r.data; sincos; position; small.position; f.position
:
PROTOCOL READOUT
  CASE
    r.data; [6]BYTE; [3]INT32; [3]INT16; [3]INT32
    r.p.hit; [6]BYTE; [3]INT32; [3]INT16; [3]INT32
:

PROTOCOL ADQUAD IS INT16; INT16:

PROTOCOL SENDQUAD IS [6]BYTE; [3]INT32; [3]INT16; [3]INT32:
--PROTOCOL SENDQUAD IS [3]INT32:

PROTOCOL COUNTERDQUAD IS INT32; INT:
```