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IMPROVEMENTS TO THE PRECISION PAN AND TILT HEAD(U)  
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MICROCOPY RESOLUTION TEST CHART

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ROYAL SIGNALS AND RADAR ESTABLISHMENT

Memorandum 3996

TITLE: IMPROVEMENTS TO THE PRECISION PAN AND TILT HEAD  
AUTHORS: J D Roberts, E C E Charlwood, P N Griffith and F Mansfield  
DATE: December 1986

SUMMARY

This Memorandum describes the drive and control improvements made to the heavy duty precision pan and tilt head previously reported in Memorandum 3691. The drive improvements have resulted in an increased maximum performance for the head to 4R/s<sup>2</sup> in acceleration and to 0.85 R/s in velocity. The improvements to the control circuitry have allowed adaption to computer control and two approaches have been assessed which represent two levels of complexity in the control algorithms.

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RSRE MEMORANDUM 3996

IMPROVEMENTS TO THE PRECISION PAN AND TILT HEAD

J D Roberts, E C E Charlwood, P N Griffith and F Mansfield

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1. INTRODUCTION

RSRE Memorandum 3691 described the mechanical and electronic design of a heavy duty precision pan and tilt head that was controlled in both axes by digital servos and was driven by stepper motors. The 15 bit absolute position encoders that provided the feedback for the servos were linked to the drive shaft by gear boxes and had an angular resolution of 0.1 mR. The drives to the head from the stepper motors, operating at 200 steps each revolution, were taken through single worm/wheel gears of ratio 328:1 to make each step of the motors equivalent to 50  $\mu$ R and thereby ensure stability of the head. The dynamic frequency response tests showed that the head had a maximum unlimited acceleration of 2.3 R/s<sup>2</sup> with a velocity of 0.12 R/s at 3 Hz and that these values could be reduced by the insertion of limiters in the velocity control circuit to 1.0 R/s<sup>2</sup> and 0.1 R/s. Two of the design improvements recommended in the Memorandum to give improved performance were to replace the existing drives with higher torque motors to increase the driving torque to the head and thereby increase the maximum velocity and acceleration, and to uprate the motor drive electronics so as to increase the number of steps each revolution and thereby increase the positional accuracy of the head. To capitalise fully on these improvements

it was considered necessary to make some improvements in the design of the worm drives to remove the backlash present. The design changes made to effect these improvements and the tests made to measure the performance improvement are presented in Section 2 of this Memorandum. The head was controlled by a digital servo system which can be operated in two modes; a position mode in which the positional demand was provided by a manual control and a velocity mode in which the velocity demand was provided by either a manual control or an auto-lock follow loop. The servo system being digital lends itself to computer control and modifications have been made to the control circuitry to interface both a simple low-cost personal computer and a more complex custom-built microprocessor system. These two systems have been programmed to implement very similar control techniques for the head. The design of the interface circuitry and the assessment of the effectiveness of these control techniques are presented in Section 3 of this Memorandum. Section 3 also contains an analysis of the control equations for the servo drives to the head in which the time constants and damping term are identified.

## 2. DRIVE IMPROVEMENTS

### 2.1 Modifications

It was found during the original test programme that the pan and tilt head could only just meet the design requirement for the slew rate to be 0.2 R/s with a load of 150 kg. To extend the design it was decided to improve the drive system to the head by increasing the drive torque to the head. The torque can be increased by the use of both a larger drive motor and a more efficient drive system. The drive motor chosen was the Unimatic type 21, reference 4270D200F03 which is capable of producing a torque at the load of 1640 Nm. This should be compared with the original motor Unimatic type 20, reference 3450D200F1.2 which produced a torque at the load of 656 Nm. In each of these reference numbers the D200 part refers to the number of steps to each revolution of the motor. The drive system chosen was the Unimatic type HD65 which had a micro-step facility. This facility allowed control of the amplitude of the current through the motor windings through a predetermined series of levels so that the motor could be driven at 2000 steps each revolution. This fineness of control permits the head in principle to be positioned to 10  $\mu$ R given the gear ratio remains at 328:1. The original drive system Unimatic type 1054 had a 400 step each revolution capability and the head could be positioned to 50  $\mu$ R although the encoder will only resolve to 0.1 mR. Drive type HD65 achieved the required velocities by driving 6.5 A pulses into the induction of the motor at a clock rate of the order of 40 KHz. If the cable feeding the motor was not screened then there was a significant level of RF interference. When the cable was screened, and the screening earthed at the drive end, feedback occurred between the input and output of the drive unit and made the system unstable. To prevent this instability the clocking pulses to the drive unit had to be fed via opto-isolators.

It was found after a period of operation that back-lash had developed between the drive motor and the head. This was traced to wear in the worm gear housing support pivot. The support pivot was replaced by a double thrust bearing which should have the additional benefit of having a longer life. The gear bearings were pre-loaded taper roller bearings and it was thought that these bearings were wedged up under thrust. These bearings were replaced by radial needle roller bearings to absorb the end thrust and journal ball bearings to support the worm shaft.

## 2.2 Tests

The performance of the modified system was tested by measuring the system frequency response. The measurement technique used was to feed the drive circuitry with a sine wave velocity demand of varying amplitude at a series of preset frequencies. Under these conditions the amplitude at which the head stalled was a measure of the maximum velocity possible for the accelerations imposed by the input sine waves. There were no limiter or lowpass filter present in the control circuitry. The results obtained for the three combinations of motor type with drive type are presented in Table 1.

Frequency (Hz)	Velocity (mR/s)		
	Combinations		
	1.	2.	3.
1	380		
2	210	350	370
3	120	270	250
4	90	170	180
5	70	130	120
6	50	90	100
7	40	80	80

TABLE 1

where combination 1 is motor type 20 with drive type 1054  
 combination 2 is motor type 21 with drive type HD65  
 combination 3 is motor type 20 with drive type HD65.

These values have been rounded to reflect the reproducibility in the measurements of +/-10.

From these values of maximum velocity it is possible to derive an experimental value for the acceleration for each of the combinations, which may be compared with that calculated from a knowledge of the inertia of the head and the torque of the motor. The experimental and theoretical values of acceleration are given in Table 2.

Combination	Inertia (Kg.m <sup>2</sup> )	Torque (N.m)	Acceleration (R/s <sup>2</sup> )	
			Exp.1	Theory
1	282	656	2.2	2.3
2	337	1640	3.9	4.8
3	282	1000*	3.9	3.5

TABLE 2

where the inertias of the individual components at the load were

motor type 21	73 Kg.m <sup>2</sup>
worm gear	14 Kg.m <sup>2</sup>
fly-wheel	150 Kg.m <sup>2</sup>
load	100 Kg.m <sup>2</sup>

The inertia transfer ratio is equal to the square of the gear ratio and this in the present case is equal to 107584:1. The torques are taken

from the manufacturer's data except for combination 3 where the motor is being driven in a non-standard way so the \* denotes that the value is an estimate.

A comparison of the theory and experiment values shows fair agreement especially when it is acknowledged that the effects of friction have not been allowed for in the theoretical values. The magnitude of the inertia transfer ratio is very important in system design. One design objective is to give the motor shaft more inertia than the load so as to maintain shaft motion and protect the gear teeth should the power fail. It can be seen from the above values that because of the transfer ratio the motor inertia contributes a significant component to the total inertia at the load. It can also be seen that the size of the fly-wheel is larger than is necessary and as such it does restrict the maximum acceleration obtained.

The conclusion that may be drawn from Tables 1 and 2 is that combination 2, the original motor type 20 and drive type 1054, exhibits the poorest response and performance with an acceleration of  $2.3 \text{ R/s}^2$  and a maximum velocity of  $0.12 \text{ R/s}$  at 3 Hz. The drive type HD65 gives a much improved performance irrespective of which motor is used and both motors give comparable results, an acceleration of  $4 \text{ R/s}^2$  and a maximum velocity of  $0.23 \text{ R/s}$  at 3 Hz.

### 2.3 Limitations

During the operation of the system it was found that motor type 21 and drive type HD65 when in the 2000 steps each revolution mode, sounded very harsh and induced vibration in the optical equipment mounted on the head. This contrasted with the motor type 20 under the same conditions which sounded quite smooth and did not induce any vibration. The drive type HD65 achieves its top performance by driving 6.5 A pulses at 40 KHz rates into the motor from a 165 V supply. The harshness for the motor type 21 is considered to be due to the increased efficiency of this motor due to improved magnetic materials, allowing it to respond to the higher frequencies present in the drive pulses. This interpretation is consistent with the experimental fact that the vibration reduced as the drive current was reduced. In operation it was found that the motor type 20 ran very hot although it did not exceed its rating. Motor type 21 was preferred for use on a continuous basis to ensure that the motor stayed well below its temperature rating but the current needed to be reduced to achieve smooth operation. This need to trade-off performance against vibration is a limitation of the head that will need to be corrected.

## 3. CONTROL IMPROVEMENTS

### 3.1 Computer Control

The digital circuits to control the position of the pan and tilt head compare the position of the head as read by a positional encoder with the demanded position as entered manually. The magnitude of the difference determines the frequency of the pulse train fed by the binary rate multiplier (BRM) to the stepper motor of the head drive. The input to the BRM is a six bit word. This design of circuitry lends itself to adaption to computer control and this Section reviews two approaches that have been implemented which represent two levels of complexity in the control algorithms.

### 3.1.1 Sinclair Spectrum based system

The Sinclair Spectrum computer is an eight bit system based on the Z80A CPU and is coupled to the pan and tilt head through a programmable interface type 8255A. The block diagram of the total interface is shown in Figure 1. An unused area of memory within the computer, the print buffer, is used to communicate with this interface, and the exchange takes place along 26 TTL compatible signal lines. These lines are divided into 16 address and mode control lines, 8 bi-direction data lines and 2 read and write lines. The commands PEEK and POKE are used to take in and output data from defined addresses in memory. The interface with the pan and tilt head is organised as three ports with 8 signal lines each. Port A and most of port B are used to read the position of the head. The head positional encoder outputs a 15 bit word and the eight least significant bits are read in at port A while the seven most significant bits are read in at port B. A line of computer code multiplies the high byte by 256 and adds it to the low byte. The resulting number is the angle of the head in units of  $50 \mu\text{k}$ . The eighth bit at port B is used to register an event recorded by the equipment mounted on the head. Port C is connected to the head stepper motor controller and the signal lines are separated into six bits to control the BRM, one bit to indicate direction and one bit to control single step movements. The six bit word into the BRM enables the BRM to output 64 frequencies between 0 and  $63/64$  of the clock frequency. The clock frequency normally used is 1 MHz which in combination with the divide by sixteen stage smoothes the output pulse train to the motor. For the present case using 400 steps each revolution (motor drive combination 1) the maximum usable frequency is 12.7 kHz which is equivalent to a head rate of 0.635 R/s. If a finer gradation in frequency is required then it is possible either to use BRMs in cascade when a twelve bit word will output 4096 frequencies between 0 and  $4095/4096$  of the clock frequency or to vary the frequency of the clock under software control. The single step movement is used when the velocity demand is set to zero and the head needs to be moved to its final position. All data are transferred in an asynchronous manner and no handshaking is involved. The azimuth and elevation control interfaces are identical and operate in parallel.

Programmes are written in Sinclair BASIC and are stored on a ZX Microdrive. One example of these programmes is the slewing of the head to a new position in the least time possible. To carry out this manoeuvre all the relevant data for the desired profile are entered into the programme through the keyboard. This data must include the maximum permissible acceleration, coasting and deceleration rates as well as the final position required. The maximum acceleration rate is determined by the rate at which the incremental frequency steps can be fed to the BRM without stalling the motor. A large number of small steps will give the smoothest performance. The updating commands occur at a rate of approximately 140 Hz. During this phase of the drive the control is essentially "open loop" as the actual position of the head cannot be read. Once the maximum slew rate of the head has been achieved then the command to read the position of the head can be issued again and the control reverts to "closed loop". When the head has reached a predetermined position, an equivalent deceleration is applied by reducing the frequency input to the motor. If this profile leaves the head away from the designated position then the single step facility will be operated through the OR gate to achieve this final

adjustment. During the "closed loop" part of this manoeuvre the event detection bit into port B is also being monitored. If this bit changes from 0 to 1 then the co-ordinates of the head are noted and displayed on the VDU.

The velocity control circuit for the head as described in RSRE Memorandum 3691 was independent of the position control circuit. It was analogue with a voltage to frequency converter to generate the pulse train to drive the motor. The voltage demand could be accepted from a wide range of sources including automatic lock-follow systems. In order to make this velocity control system more flexible a part of the circuit has now been replaced by a digital circuit to allow software control of the lock-follow loop. Figure 1 shows this modification as an OR gate on the input to port A. In the lock-follow mode this gate allows the interface to read an eight bit track error word in place of the eight least significant bits of the head position. This error word is fed into the control equation to determine the acceleration necessary from the BRM to reduce the error to zero. Such an error word can be generated by dividing up the field of view of the lock-follow sensor on the head into 255 bits in each plane. This modification will allow in principle the use of complex control equations, the adjustment of the time constants in these equations in a dynamic way and will also assist in removing the velocity errors that occurred during steady acceleration of the head using the analogue circuitry.

During the experimental testing of this system several modifications to improve the performance of the system were identified. The response time of the control system was limited by congestion at the input and output ports and the inherent slowness of BASIC. These limitations can be partially removed by introducing additional ports by using parallel programmable interfaces and operating critical parts of the programme in machine code. The time intervals for any one manoeuvre are determined by the length of the command loops involved; for example the slope of an acceleration ramp was dependent on the length of the command loop involved in incrementing the multiplication factor fed to the BRM. This led to irregularities in the slope and a lack of repeatability run to run. This limitation can be removed by introducing a real-time clock input to synchronise the issuing of the commands.

The main benefit in the use of a Sinclair Spectrum to control the head is that a fairly powerful and flexible capability can be obtained at low cost, £200. The main disadvantage is that it is an eight bit machine that is limited by a slow computational speed.

### 3.1.2 Motorola microprocessor based system.

The main disadvantage of the Sinclair Spectrum based system, that it is a 8 bit machine with a slow computational speed, can be overcome by the use of a 16 bit microprocessor based system. In order to permit future expansion into a multiprocessor environment a suitable architecture has to be adopted. The system chosen was the Motorola 68000 family operating on a VME bus; the interface block diagram is shown in Figure 2. The system is implemented on a Phillips PG2020 processor card. This card uses a 68000 microprocessor and provides 128 Kbytes of RAM and 128 Kbytes of EPROM space. The card has two serial input/output ports to enable connection to a terminal and to the host computer, a VAX 11/730 in the present case. The software

required was developed using the RAM space and then loaded into the EPROMs to enable the system to stand alone. The hardware interface to the head is an ELTEC APAL-1 parallel interface card on the VME bus. This card is based on two M68230 devices, each of which has a 16 bit port. Port 1 is used to input data from a positional encoder on the head while Port 2 is used to output 12 bit data to the two BRMs in cascade, together with a direction bit. The use of two BRMs in cascade permits a smoother output pulse train to the motor. Also located on the M68230 device is a 24 bit programmable timer. As before the azimuth and elevation controls are identical and operate in parallel.

It is very important to adopt the correct control strategy for the envisaged application and the one essential feature required for the control of the pan and tilt head is preemption. This is the ability of the controlling software to gracefully abort the present activity when a new command is received. This was implemented by the use of pSOS68K, a preemptive process scheduling kernel produced by Software Components Group Inc and is associated with their debugging system PROBE. The software was written in Pascal using OREGON PASCAL-2, a cross compiler assembler and linker package hosted on the VAX 11/730 computer and produced by Oregon Software Inc. The system consists of three separate processes operating under pSOS68K. The processes communicate by means of message exchanges and event flag signalling. The first process manages all the terminal inputs and outputs and passes commands to the second process, the sequencer, to sequence these commands and schedule their release to the third process, the controller. This third process checks that the demands made on it are executable and controls the head within defined arcs. Error reporting of such as moving outside the defined arc or demanding a rate in excess of the maximum rate is implemented by event flag signalling from the controller to the sequencer and the recovery necessary is effected in the sequencer. Event signalling is also used to synchronise the sequencer and the controller.

The control technique is best exemplified by describing an analogous manoeuvre to that presented in Section 3.1.1; the slewing of the head to a new position in the least time possible, but in this instance in such a way that it arrives at this position with the required velocity. The data inputs required are the final position and velocity since the initial and present values of both position and velocity can be obtained by reading the registers at the input/output ports at the relevant times during the manoeuvre. When the controller receives a message from the sequencer requesting a new position preemption occurs and any acceleration is stopped and the head allowed to continue moving at its present rate. This rate and the position are measured and, since the time taken to calculate the required velocity/time profile for the demanded manoeuvre is known, the position at which the manoeuvre should start is calculated. The velocity/time profile is stored as a 36 byte long nested PASCAL variant packed record structure and is capable of defining up to four phases for any one manoeuvre. It takes the form of a series of rate demands to be initiated at specific times or positions. The rate demands are requests to change from one rate to another at the maximum acceleration or deceleration. The main control loop executes each of the phases in turn, waiting for the required start condition of each phase. At each iteration of the loop the position of the head is read to ensure it is within the prescribed arc limits, the message exchange is checked for any new commands and the pulse rate to BRMs

altered if the start condition has been satisfied. If the start condition is calculated to occur within the following 2 ms then a loop is entered to await the start position and so ensure an accurate start to that phase of the manoeuvre. If an error condition occurs then the head is decelerated to a standstill and the condition signalled to the sequencer. In order to ensure accurate control of the rate at which the BRMs are incremented the timer on the M68230 device is used to lock the control loop at a 1 kHz rate. The maximum time lapse from receiving a new position message to making the first change in the new profile is 5 ms.

The velocity/time algorithm can generate three types of profiles which contain one, two or three phases to cover the possible range of manoeuvres and these are shown in Figure 3. The situation where the requirement can be satisfied by a single rate change is shown in Figure 3a. If this cannot be achieved then it is necessary to calculate an intermediate velocity and have two rate changes as shown in Figure 3b. If this intermediate velocity is in excess of the capability of the head then it is necessary to have a rate change to achieve the maximum permitted rate, then to continue at this rate until the calculated position to change the rate to reach the requirement as shown in Figure 3c. By careful attention to the implementation of this algorithm the position at which the required velocity is reached is repeated to within one position encoder bit, a repeatability of +/- 50  $\mu$ R. The listing of the programme written to achieve this algorithm is presented in Appendix A.

The main benefits in the use of a 16 bit M68000 microprocessor on a VME bus are speed, precision and expandability, which readily enables the integration of the control of the pan and tilt head into a multiprocessor environment. The main disadvantage is that the implementation is more expensive and requires significant microprocessor skills.

### 3.2 Control Equations

The equivalent circuit for the servo control circuitry to drive the head is given in Figure 4 and shows the three components that need to be considered; the integrator with its associated damping to ensure stability, the lag due to the limits placed on the motor velocity and acceleration and the converters  $K_1$  for voltage to velocity and  $K_2$  for position to voltage.

The Laplace transformed equivalent transfer function of this circuit is

$$P_O(s) = \left[ P_N(s) - P_O(s) \right] \left\{ D + \frac{1}{s\tau_1} \right\} \frac{1}{s\tau_2} \left\{ \frac{1}{1+s\tau_3} \right\}$$

where  $P_O(s)$  and  $P_N(s)$  are the transforms of the equivalent position output and input respectively

$D$  is the damping term =  $R_2/R_1$

$\tau_1$  is the time constant of the integrator =  $C_1R_1$

$\tau_2$  is the time constant of the converters =  $1/K_1K_2$

$\tau_3$  is the time constant of the lag due to motor limits =  $R_3C_2$

and  $s$  is the Laplace transform variable.

This equation may be rearranged,

$$P_o(s) = P_N(s) \left\{ \frac{(1+Ds\tau_1)}{\tau_1\tau_2s^2(1+s\tau_3)} \right\} \left\{ \frac{1+(1+Ds\tau_1)}{\tau_1\tau_2s^2(1+s\tau_3)} \right\}$$

Rewriting terms with  $a = \tau_1\tau_2$ ,  $b = \tau_3$  and  $c = D\tau_1$  then

$$\frac{P_o(s)}{P_N(s)} = \left\{ cs + 1 \right\} / \left\{ abs^3 + as^2 + cs + 1 \right\}$$

This last equation may be solved by numerical methods (1). Figure 5 shows a comparison between the theory using the time constants and damping term relevant to the servo circuitry and the experimentally measured response to step function input. A comparison of the two curves shows good agreement. The variation of these response curves with variations in the time constants has been found to depend on the ratio of the time constants rather than on the absolute values of the constants (2).

#### 4. CONCLUSIONS

This Memorandum has presented the drive and control improvements that have been made to the pan and tilt head. The drive improvements have resulted in an increase in both maximum acceleration and velocity of the head although the loading on and wear rates of the gears still limit the performance that can be achieved. The computer control assessments have shown that both a Sinclair Spectrum and a Motorola microprocessor based systems can be used to control the head; the choice between these being the computational speed required for the particular application balanced against the level of complexity and cost acceptable.

#### 5. ACKNOWLEDGEMENTS

The Authors wish to thank Mr D Bagshaw for advice and assistance in implementing the mechanical modifications to the head and Mr A Watkins for assistance during the building of the electronic circuitry.

#### 6. REFERENCES

1. W A Geckle Jnr, Electronic Design Vol 25 Dec 6 p114 1979.
2. P N Griffith and J D Roberts, to be published.

APPENDIX A

PASCAL IMPLEMENTATION OF THE VELOCITY PROFILE ALGORITHM

The following segment of Pascal code was used to generate the velocity profile. The principal variables are:

Profile - A user scalar defining the profile type, ie One\_step,  
Two\_step, Coast\_Vmin, or Coast\_Vmax  
Pf - Demanded final position to be achieved  
Vf - Demanded velocity at Pf  
Ps - Position at which manoeuvre is to start  
Vs - Velocity at start of the manoeuvre  
Vmax - Maximum permitted head speed for the manoeuvre  
accel - Value of acceleration and deceleration used  
hf\_pd - Half the time taken to execute the main control loop  
Vs\_sq - Square of Vs  
Vf\_sq - Square of Vf  
Vmax\_sq - Square of Vmax  
Vl - The required intermediate velocity to achieve demands  
Pl - The position at which last rate change must occur if the  
manoeuvre is a coast at Vmax of Vmin

```

Stot := Pf - Ps;           {total displacement demanded}
Sl := (Vf_sq - Vs_sq) * 0.5 / accel; {resulting displacement from a
                                   single rate change}

IF Vf < Vs THEN           {Slowing down or reversing}
  Sl := - Sl;

IF Stot <> Sl THEN         {need at least a two rate change manoeuvre}
  BEGIN
  Profile := Two_step;
  IF Stot > Sl THEN       {demand requires more than Sl}
    BEGIN
    Vl := sqrt((Vf_sq + Vs_sq) * 0.5 + accel * Stot);
    END
  ELSE                   {demand requires less than Sl}
    BEGIN
    Vl := - sqrt((Vf_sq + Vs_sq) * 0.5 - accel * Stot);
    END;
  IF Vl < - Vmax THEN    {need to coast at -(Vmax)}
    BEGIN
    Pl := Pf - (Vf_sq - Vmax_sq) * 0.5 / accel - Vmax * hf_pd;
    Profile := Coast_Vmin;
    END
  ELSE IF Vl > Vmax THEN {need to coast at Vmax}
    BEGIN
    Pl := Pf - (Vmax_sq - Vf_sq) * 0.5 / accel + Vmax * hf_pd;
    Profile := Coast_Vmax;
    END;
  END
ELSE
  BEGIN
  Profile := One_step;
  END;

```

The 'Vmax \* hf\_pd' factor in the calculation of Pl shifts the start point of the last rate change to minimise quantization errors.

SPECTRUM INTERFACE BLOCK DIAGRAM

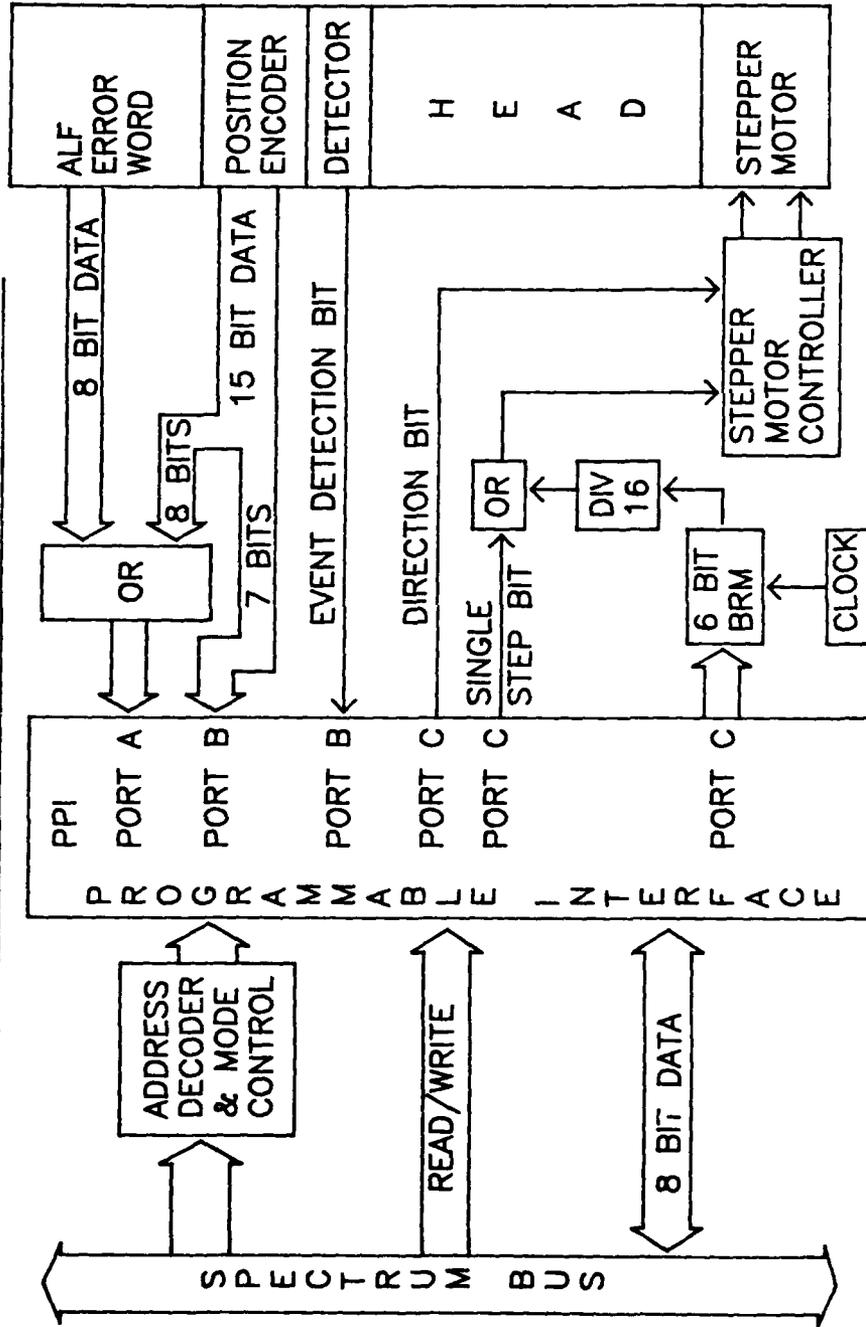


FIG 1

MICROPROCESSOR INTERFACE BLOCK DIAGRAM

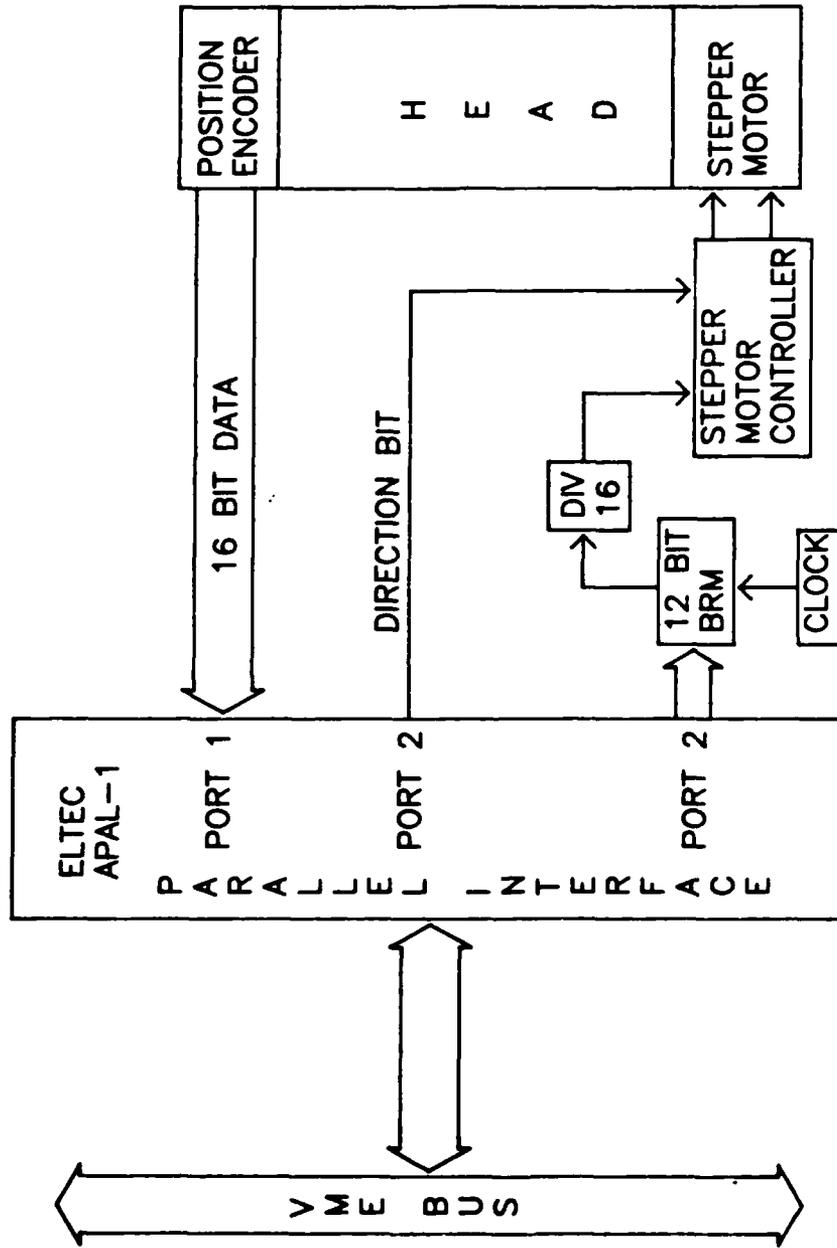
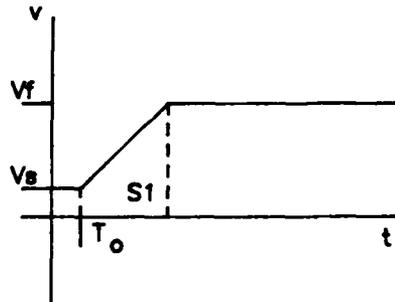
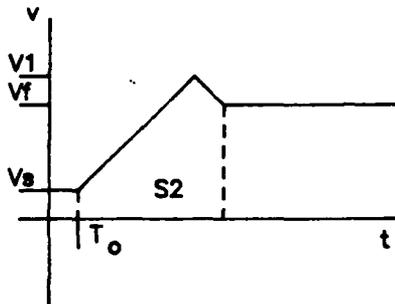


FIG 2

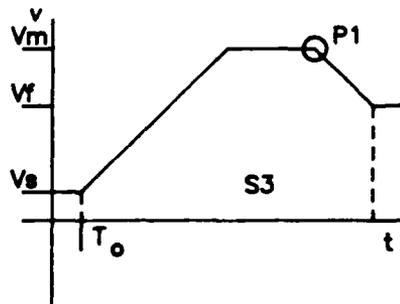
## VELOCITY/TIME PROFILES



a) Single Rate Change Profile



b) Two Rate Change Profile



c) Coast at  $V_{max}$  Profile

**Key:**

$V_s$  = Velocity at start of the manoeuvre  
 $V_f$  = Velocity required at the demanded Final Position

$V1$  = Intermediate Velocity necessary to achieve the Demanded Position

$V_m$  = Maximum permitted Velocity

$S1$  = Area representing displacement resulting from a Single Rate Change

$S2$  = Area representing displacement where demand >  $S1$

$S3$  = Area representing displacement where demand >  $S1$  and computed  $V1 > V_m$

$T_o$  = The Time at which the manoeuvre Start Position is achieved

$P1$  = Position at which the final rate change must start

FIG 3

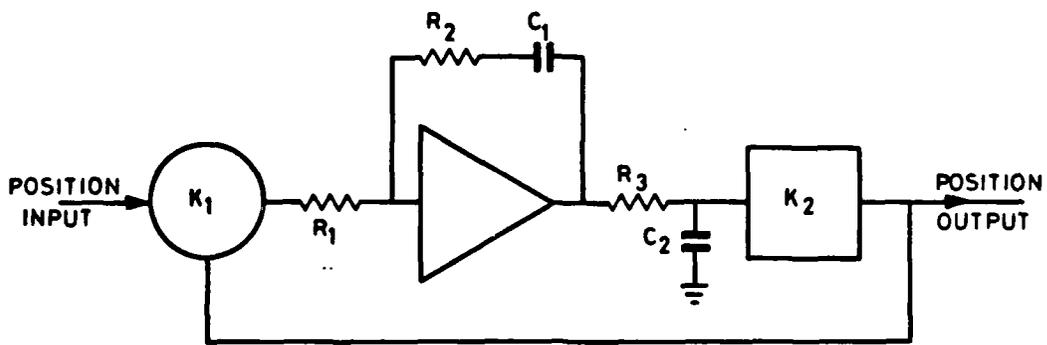
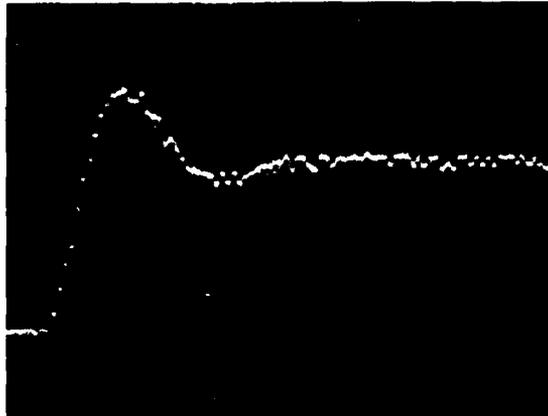
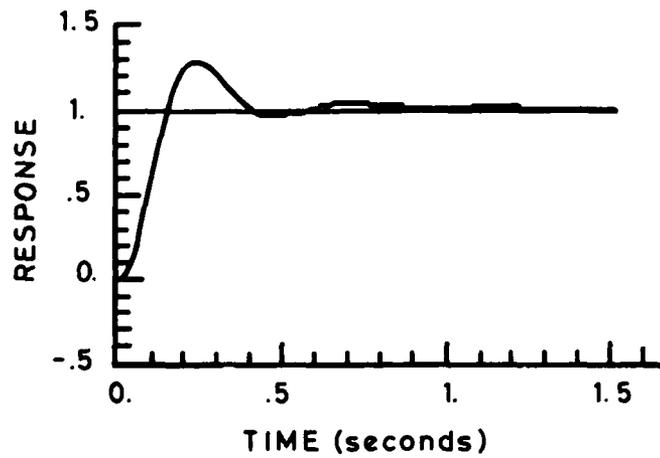


FIG. 4. SERVO CONTROL EQUIVALENT CIRCUIT



(a) MEASURED RESPONSE



(b) CALCULATED RESPONSE

FIG. 5. SERVO PERFORMANCE

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