Position and Velocity Measurement by Optical Shaft Encoders

Kasturi V. Rangan

CMU-RI-TR-82-8

Robotics Institute
Carnegie-Mellon University
Pittsburgh, Pennsylvania 15213

23 June 1982

This work is sponsored by The Office of Naval Research
(Contract No. N00014-81-K-0503)

Table of Contents

Abstract

Accurate measurement of the angular position and angular velocity of the joints is essential in the control of a robot manipulator. This report analyses in detail the design and implementation of a measurement system for the CMU Direct Drive Arm using High Resolution Optical Shaft Encoders. Two methods of angular velocity measurement--*velocity by change of position* and *velocity by frequency*--are analysed and compared.

Introduction

This report describes the principles involved in using optical shaft encoders to measure angular position and velocity. The design,implementation and performance analysis of a measurement system built for the CMU Direct Drive Arm are presented in detail.

The control of a Robot Manipulator involves reading the current state of the manipulator, computing the desired state and implementing a control algorithm to achieve the desired state. The current state includes joint angles, joint angular velocities, joint angular accelerations, forces and moments, proximity to a workpiece etc. The quantitative measurement of these parameters is done using transducers.

We are concerned here with the measurement of joint angles and joint angular velocities. In robot manipulators where joint links are connected to drive motors through gears and other transmission mechanisms, the angular displacement of the motor shaft is many times that of the joint link. This makes possible high resolution joint parameter measurement using low resolution shaft encoders. In the *CMU DD ARM* the joint axes are directly coupled to the rotors and stators of the drive motors without any gearing or other means of transmission [1]. The maximum angular displacement of a motor, therefore, is less than 360 degrees. The maximum angular velocity is of the order of *2 to 3 rad./sec.*. High resolution Optical Shaft Encoders are required for accurate measurements under these conditions. The measurement system has been designed so that the shaft encoder outputs can be processed and position and velocity values made available to the control system directly or through the computer. *FIG.*1.shows the functional position of such a measurement subsystem in the overall system [2].

The design takes into account the present configuration of the CMU DD Arm and hardware limitations and attempts to maximise the resolution and accuracy under these conditions. Two different methods of velocity measurement -- *velocity by change of position* and *velocity by frequency* -- are analysed and compared. Performance of the measurement system for *Joint 6* of the CMU Direct Drive Arm is presented. In the appendix is given a brief summary of the different transducers used for measurement of angular displacement and angular velocity.

1. The Measurement System

This section describes the position and velocity measurement system implemented for the CMU DD Arm. The measurement system as shown in *FIG.4* has one subsystem for each joint consisting of the optical encoder and processing hardware. The individual units output analog voltages proportional to the angular position and angular velocity of the corresponding joint and are interfaced to the processor through the Sampling Control and Interface hardware.

1.1 Optical Shaft Encoders

The measurement system for the CMU DD Arm uses two types of Optical Shaft Encoders: *Incremental* encoders and *Absolute* or *Shaft Position* encoders [6]. Joints 1,3,5 and 6 have incremental encoders and joints 2 and 4 have absolute encoders. In the home position, the axes are vertical for joints 1,3 and 5; and are horizontal for joints 2,4 and 6 [1].

1.1.1 Incremental Shaft Encoders

This type of encoder consists of a circular glass disc imprinted with a circular row of slots all the same size and distance apart.(*FIG.*2.) An additional slot may serve as a reference slot. Two sensors are focussed on the slots and are one-half slot-width apart. Light shining through the slots activate the sensors and the output of the encoder is as shown in the figure. The outputs A and B are 90 deg. out of phase with each other. A leads **B** for one direction of rotation and **B** leads A for the other. These quadrature waveforms can be resolved into UP and DOWN count pulses as shown.

The number of cycles of either A or **B** is proportional to the angle of rotation and the frequency of the waveform is proportional to the rate of change of angle. Resolution of these encoders depends upon the number of slots per revolution. Larger discs enable higher resolution.

1.1.2 Absolute Shaft Encoders

In this type of encoder the circular disc has a number of rows of slots and corresponding number of sensors.(*FIG.*3.) The pattern of light on the sensors and therefore the pattern of activated sensors directly gives a unique encoding of the angle of the shaft (to within a given angular resolution). The slots may be arranged so that the output code is binary or Gray Code. The Absolute Shaft Encoder outputs the data in parallel. The number of bits in the data word depends on the angular resolution of the encoder.

Reading the angle of the shaft from the encoder involves a simple strobe and a handshaking routine as shown in *FIG.*3.

The Absolute Encoders used here have two parts: *The Optical Unit* and the *Electronics Unit* [3]. The signals from the optical unit is processed by the electronics unit to provide the parallel data as mentioned before.

1.2 Position Measurement

The quadrature outputs from the Incremental Encoders are decoded to derive **UP** and **DOWN** count pulses. These pulses are counted by a set of counters. The output of the counters are stored in latch buffers after each counter transition as shown in *FIG.5.* These latch buffers are included to protect the counting process while data is being read by the computer or the data is transferred to the Digital to Analog Converters for feedback. Clocking of the latch buffers is disabled during HOLD mode when data is being read.

Data from the Absolute Encoders is stored in similar latch buffers. Parallel binary data is available whenever requested by the STROBE, after a delay of 100 μS.

The six encoders (4 Incremental and 2 Absolute) in this system are sequentially addressed by the control hardware through the Encoder Select Address.

Digital to Analog Converters are directly connected to the counter outputs in the case of Incremental Encoders and the analog voltage output is continuously variable. For joints with Absolute Encoders the **D to** A converters are connected to the data bus and hence the analog voltage output changes once every sampling interval.

1.3 Velocity Measurement

Joint velocity may be measured in two ways:

- Measure change of position between samples. This value is proportional to the velocity.
- Measure the Period of either **A** or **B** output. This value is inversely proportional to the velocity. The instantaneous frequency of the quadrature output which is proportional to the instantaneous velocity is the inverse of the period.

Incremental encoders provide the necessary output for both modes of velocity measurement. Change of position in Absolute Encoders can be obtained by subtracting previous position from current position. The absolute encoders used here in joint 2 and joint 4 also have quadrature sinusoidal outputs. These sinusoidal outputs are converted into squarewave outputs by detecting zero crossing, and subsequently used as before in velocity measurement.

The first mode of velocity measurement is done by counters similar to those in position measurement but are cleared at each sampling after transferring the count to latch buffers. The value of the counter output also depends on the sampling interval.

The second mode requires a separate clock of adequate frequency to provide high enough resolution. The cycle period of the encoder output is measured as an integer multiple of the clock period. Counters are used to count the number of clock cycles for one encoder cycle. A 'D' flip-flop synchronises the encoder output to the clock edge.The count is transferred to latch buffers and counters cleared(*FIG*.6.). Thus the count is available at the end of every encoder cycle and is independent of sampling interval. The joint velocity is inversely proportional to this value and inversion is done by a lookup table in a **Read Only Memory.**

2. Design

In this section the factors affecting the design of the system is presented and a mathematical analysis is carried out.

2.1 Configuration of joint motors and shaft encoders

The construction of the manipulator imposes many constraints on the range of angles of rotation as well as the velocity of each joint. One factor is the ratio of the gear driving the shaft encoder. This ratio affects the resolution available in angle measurement and also the frequency of the encoder outputs. The optical encoders used in the CMU DD ARM are the ***ITEK RI 13/15MQ*** incremental encoder and the ***ITEK MICROSERIES*** *μS 15/16(S)* shaft position encoder [4] [3]. **Table 1** gives the present configuration of the **CMU DD ARM**.

TABLE 1

(K = 1024)

JOINT NO.	ENCODER RESOL. PER REV. & TYPE	GEAR RATIO	RANGE OF ROTATION DEGREES (APPROX)	ANGLE RESOL.	NO. OF BITS OF ANGLE OUTPUT	NO. OF ENC. CYCLES FOR VEL. MEAS.
1.	8 K (inc)	8:1	-160 to +160	64 K /rev.	16	16 K /rev.
2.	32 K (abs)	2:1	- 90 to + 90	64 K /rev.	15	8 K /rev.
3.	8 K (inc)	8:1	- 90 to + 90	64 K /rev.	15	16 K /rev.
4.	32 K (abs)	2:1	- 90 to + 90	64 K /rev.	15	8 K /rev.
5.	8 K (inc)	4:1	-160 to +160	32 K /rev.	15	8 K /rev.
6.	8 K (inc)	4:1	- 90 to + 90	32 K /rev.	14	8 K /rev.

2.2 Hardware Limitations

The position counters are 16 bits wide and therefore do not pose any limits for the above configuration. Counter widths for velocity differ for the two modes of measurement. In the first case, where the change in position is counted, the width is 8 bits, with an additional bit being the sign bit. In the second mode a 12 bit counter and an additional sign bit is used.

The **Read Only Memory** lookup table has a 12 bit address (4096 addressable locations). As the sign bit is the MSB of the address input, the LSB of the counter is unused. This has the effect of reducing the clock frequency by a factor of two.

The **Digital to Analog Converters** for position measurement has a resolution of **12** bits and an output range from -10 volts to +10 volts. This limits the voltage resolution of position feedback to **9.77 mV**. The **D/A** converter for velocity accepts **8** bit data and has a range from -5 volts to +5 volts limiting the resolution of velocity feedback to **39.1 mV**.

The D/A converters accept offset binary code as input. The counters as well as the absolute encoders generate 2's complementary binary code. The difference is the MSB which is complemented in the offset binary code.

2.3 Angle(Position) Measurement

The computation of the angle of the joint from the value read by the processor is simple and straightforward.

$$P = \frac{X \cdot A}{2^{N-1}}$$

where,

P = Angular position of the joint in degrees
X = Value read by the processor
A = Magnitude of the range of the joint divided by two
(The range of the joint in degrees is from -A to +A)
N = Maximum width of the counter output

2.4 Velocity by Change of Position

The equation for the velocity of the joint is:

$$V = \frac{n}{N \cdot T}$$

where,

V = Angular velocity in revs./sec.
n = change of position in one sampling interval given by the counter (counting *UP* and *DOWN*)
N = Number of *UP* or *DOWN* count pulses per revolution of the joint; same as the Angle Resolution given in **Table 1**
T = Sampling Interval in Seconds

The range of velocities that can be measured by this mode depends on the value of T if we assume that the counter width is fixed. The smallest measurable velocity is obtained by substituting **n = 1**.

$$V_{min} = \frac{1}{N.T}$$

The largest measurable velocity is:

$$V_{max} = \frac{n_{max}}{N.T}$$

where,

n_{max} = Maximum count possible = $2^{(\text{counter width})} - 1$

Accuracy at smaller velocities is poor in this mode of measurement.

This method has the advantage that the counter output is directly proportional to the velocity and it is easily implemented.

2.5 Velocity by frequency measurement

The second method of velocity measurement makes use of the property of the quadrature outputs that their frequency is proportional to the joint velocity. Though the outputs A and B in *FIG.*2. can be resolved into UP and DOWN count pulses with a repetition rate four times that of either A or B, while measuring periods a complete cycle is used. This is because of the uncertainty of the duty cycle of these outputs at a constant velocity [4]. *FIG.*2. illustrates this uncertainty.

The velocity of the joint may be computed as follows:

Time period for one encoder cycle = n . t
Time period for one joint revolution = N . n . t

$$V = \frac{1}{N.n.t} = \frac{f}{N.n}$$

where,

V = joint velocity in revs./sec.
n = counter output = cycle period as an integer multiple of clock period
t = clock period in seconds
f = clock frequency = 1 / t Hz.
N = Number of Encoder Cycles per joint revolution

From the above the maximum and minimum velocities measurable can be computed:

$$V_{max} = \frac{f}{N} \text{ revs./sec. } (n = 1)$$

$$V_{min} = \frac{f}{N \, . \, n_{max}} \text{ revs./sec.}$$

The frequency of the clock is chosen so that V_{max} is within reason for the particular manipulator. A second important factor in selecting f is the accuracy of measurement at or around maximum velocity. If f is chosen equal to V_{max} . N, we see that,

for $n = 1, V = V_{max}$

for $n = 2, V = \frac{V_{max}}{2}$

It is seen that making f large entails having to use a wider counter to measure the same minimum velocity. This also involves the requirement of a larger Read Only Memory since the counter output forms the address to the ROM.

Having selected a clock frequency, n_{max} is computed from the minimum velocity required to be measurable. This may depend on the characteristics of the control system. Overflow of the counter sets the counter to its maximum count and this is converted as zero velocity by the lookup table. Setting of the counter due to overflow is asynchronous to the encoder cycle and as a result the immediately next velocity sample will be of zero value. A change in direction of rotation also asynchronously sets the counters and the velocity samples are of zero value till the sample after the end of the next completed encoder cycle.

Updating of velocity samples need not occur for every sample due to the fact that the encoder cycle period may be larger than the sampling period. Updating occurs at the sample immediately after the completion of an encoder cycle. *FIG.7* illustrates this. For an accelerating joint, the successive updating will occur after a decreasing number of samples and for a decelerating joint, after an increasing number of samples. The value of the velocity sample V_i obtained will be,

$V_i = 0$ if $n >= n_{max}$ in the last sampling interval
$= V_{i-1}$ if no encoder cycles completed in the last sampling interval
$= V_i$ if encoder cycle completed in the last sampling interval

Inversion of the counter output can be done either by the processor or by hardware such as the **ROM.** Having a lookup table in hardware makes for high speed inversion and processor independent control of the manipulator. The size of the ROM is determined by both n_{max} and the number of bits of the D/A input. The number of addresses is **$2.(n_{max} + 1)$** allowing for negative velocities. This is generally equal to **2^{k+1}** where **k** is the width of the counter. The width of the ROM output is determined by the input requirements of the D/A converter as well as the data format of the processor. The ROM used in the above system is **4 K X 16**, with the higher order byte as the input to the D/A converters.

The ROM can be programmed to provide the required gain in the analog output of the D/A converter. The voltage output should saturate at the limits of the range of the D/A converter as shown in *FIG.7*. This can be achieved by programming the ROM appropriately.

3. Implementation and Performance

In this section the implementation of some of the salient features described above is discussed. Design modifications due to poor performance are also described.

3.1 Position Measurement

The D/A converters for position feedback were connected to the data bus and strobed at every sampling pulse. It was found that the control system could not function at its best and therefore the inputs of the D/A converters were connected directly to the output of the counters. In the case of the absolute encoders, the poorer performance was overcome by increasing the overall sampling frequency to **1 kHz**.

3.2 Velocity Measurement

With a sampling frequency of **1 kHz**. the first mode of velocity measurement was infeasible because the minimum measurable velocity was,

$$V_{min} = \frac{1}{32768 \times 10^{-3}} \text{ rev./sec.}$$

$$\begin{aligned} &= 10.986 \text{ deg./sec for joints 5,6 and} \\ &\quad 5.493 \text{ deg./sec for joints 1,3 and} \\ &\quad 43.944 \text{ deg./sec for joints 2,4} \end{aligned}$$

The ROM output which is the input to the D/A converter is computed by the relationship,

$$\text{Output Number} = \text{Integer part of } \frac{3200 \times 256}{n}$$

where,

n = number obtained by making the MSB of the address word '0'
(The MSB is the sign bit.)

The magnitudes of V_{max} and V_{min} are as follows.

$$\text{for } V = V_{max},\ n = \frac{3200}{128} = 25. \text{ (} \pm \text{ 128 is the range of the D/A input in bipolar mode of operation)}$$

$$V_{max} = \frac{100000}{8192 \times 25} \text{ rev./sec.}$$

= 175.78 deg./sec. for joints 2,4,5,6 and
87.89 deg./sec. for joints 1,3

Note: The D/A output saturates to ± 5 volts for
velocities exceeding the above values.

$$V_{min} = \frac{100000}{8192 \times 2047} \text{ rev./sec.}$$

= 2.147 deg./sec. for joints 2,4,5,6 and
1.073 deg./sec. for joints 1,3

Note: The D/A output is 0 volts for velocities
less than the above values.

A conversion relationship

$$\text{ROM output value} = \frac{400 \times 256}{n}$$

was tried initially but was found to have poor control performance because the maximum and minimum measurable velocities were eight times the above computed values. There was no velocity feedback at very small velocities.

The velocity feedback signal is in discrete steps. Filtering may be incorporated to smooth out the signal if required. The relatively high sampling frequency overcomes the absence of filtering to a certain extent.

3.3 Hardware Features

The measurement system shown in *FIG*.4. incorporates the following features:

- The mode of velocity measurement is independently jumper selectable for each joint. It has to be noted that the velocity feedback gain is different for the two modes and necessary correction has to be made in the servo controller.

- The sampling period may be set to any value between *10 μS.* and *99.99 mS.*

- Different modes of sampling control:

    1. **Hardware(Analog) control** : This uses the programmable clock to do sampling so that the Manipulator may be controlled without a processor. The processor may read the joint angles and velocities for display or to be stored in a file. The file may be read back to the manipulator control system so that the manipulator can execute a predefined motion. The D/A converters are strobed at every sample.

2. **Processor(Digital) Control** : The Control Hardware allows the processor to do the sampling by reading the joint angles and velocities. The D/A converters are strobed as before. Under digital control, the servo controller is replaced by a control algorithm in the processor and the actuating signal inputs to the servo amplifiers are directly from the processor.

The system has been designed in a modular fashion. The position and velocity measurement circuits for each joint is housed in a separate printed circuit board. The **ROM** lookup table is shared between all the encoders. The bus structure of the backplane permits addition of more joints limited only by the **Encoder Select Address Lines.**

In the **CMU DD ARM** measurement system, Encoder Select Address is 3 bits wide. A fourth bit selects between Position and Velocity Latch Buffers for each joint. The absolute address of each joint is individually selectable by jumpers on each circuit. The joints can be addressed at random and this facility allows the incremental encoders to be read while the processor is waiting for the absolute encoders to reply to the STROBE, thus reducing the total sampling duration to about 100 μS.

Another feature provided in the absolute encoder circuits is that the *Data Ready* signals generate an interrupt request to the processor which the processor can use.

3.4 Noise Reduction in Encoder Signals

Though it does not have any direct effect on the measurement methods or analysis, achieving reliable performance requires that the signals from the shaft encoders be protected adequately from electrical noise. The design here tries to minimise the susceptibility to noise by using *Line Drivers* shown in *FIG.4* at appropriate locations and ensuring that the lengths of wires carrying low level signals are minimum possible for the physical configuration of the manipulator.

The Incremental Encoders have the necessary electronic circuitry to provide TTL compatible outputs in the same package as the optical unit. The line drivers for these are mounted on the base frame close to the first joint. The measurement hardware is in the same rack as the processor and is electrically about *4 meters* away from the line drivers.

The Absolute Encoders have their electronics in a separate package and the optical unit which is driven by the joint motor generates very low level signals. The manufacturer of the Encoder recommends that the signal lines from the optical unit to the electronic package be no more than *18 inches.* Therefore the Encoder electronic package along with line drivers are placed within the prescribed distance of the optical unit.

3.5 Performance Analysis

Figures 8 and 9 show plotted values of the position and velocity D/A converter outputs for *joint 6* using an oscillograph. The performance of the position measurement system has not been evaluated because a reference system of higher accuracy and resolution has not been available and also because installing such a system would be difficult. However the accuracy of position measurement is well demonstrated by the results obtained in the positional repeatability tests on joints 1,4 and 6. The standard deviation measured for joint 6 is

0.003 degree [1]. Thus in the computations shown in *FIG.*9, the position measurement is assumed to be accurate. Angular velocities are computed graphically as shown.

*FIG.*8. shows sinusoidal variations in angle and corresponding sinusoidal variations in angular velocity. The velocity curve is 90 deg. out of phase with the position curve. Three ranges of V_{max} are presented. The dead zone at zero velocity is observable in *FIG.*8-c. The smallest increment in the output is the resolution of the D/A converter and is equal to 39.1 mV.

*FIG.*9. shows D/A output curves for approximately constant rate of change of position. Computed value of the Velocity D/A output is shown alongside. In each of the graphs the zero velocity line has been drawn. This is different from the zero volt line because of a d-c offset at the Digital to Analog converter. The velocity output is not a flat line corresponding to the apparently straight portion of the position output because the motion of the joint is a little jerky due to the effect of friction at these velocities. However, the mean value of the output allowing for the d-c offset is equal to the computed value.

*FIG.*10 is a plot of values read by the processor. The position input, the measured position and the measured velocity are all shown for a squarewave type of joint motion. It is seen from the flat parts of the velocity curve that the joint velocity has exceeded the measurable value. The diagram demonstrates that the measurement of velocity is instantaneous.

4. Conclusion

Optical encoders provide a reliable and practical means of measuring angular position and angular velocity with accuracies required in robot manipulator applications. It is seen that the principles involved in measurement using these transducers are simple and the various mathematical relationships are easily implemented in hardware.

The measurement system described in the above sections has been built and installed. It has shown very good reliability and consistency in operation. However, the performance of the system may be improved in a number of ways. The resolution of the D/A converters can be increased to 16 bits for position and to 12 or 16 bits for velocity. If it is desired that the range of measurable velocities for each joint be different for control reasons, one way to achieve this would be to have different clock rates; one per joint being the most flexible.

Acknowledgements

I thank Dr.Takeo Kanade, Dr.Haruhiko Asada, Edward C.Kurtz, Ichiro Takeyama, Regis Hoffman, Neil Schwartz and Dr.James L.Crowley for their cooperation and help.

I. A Brief Review of Transducers

This appendix very briefly describes the principles of operation of different transducers used for measurement of angular displacement and angular velocity [5] [7].

I.1 Angular Displacement Transducers

The following are ***Analog Displacement Transducers.***

Rotary Resistance Potentiometer:. Change in Angle causes a proportional change in resistance which in turn generates a proportional voltage. Multiturn potentiometers generally have a linear resistance element with the wiper sliding along a helical screw. Wiper tracks are susceptible to wear and linearity is of the order of *0.1%.*

Strain-Gage Angular-Displacement Transducer:. Most of these incorporate a bending beam. Angular displacement converted to deflection of a beam results in strain that is transduced into resistance change by strain gages. Either two or four strain gages may be connected in a *Wheatstone Bridge* circuit.

Capacitive Displacement Transducer:. In this not very common type of transducer, angular displacement is converted into change of capacitance. This is done essentially by changing the interactive area between two plates. Additional signal conditioning circuitry provides d-c output proportional to the angular displacement.

Differential Transformer:. A primary coil is inductively coupled to two secondary coils by a movable core. The differential output from the two secondary coils is proportional to the angular displacement of the core.

Inductance Bridge:. Two coils and a movable core are so arranged that the inductance of one coil increases while the inductance of the other decreases with the movement of the core. The matched set of two coils forms two arms of an a-c bridge. These are normally designed for a range of ± 45 degrees.

Synchro Transformers:. This is a family of transducers which are essentially transformers where one winding is rotated to vary the coupling between them. Three forms of synchro are described. The first two are transformers in the conventional sense and the third one is solid state using Hall Effect.

1. One commercially available synchro transformer that provides a voltage proportional to the shaft angle is the *linear variometer.* There is one secondary winding and the voltage output is linear for a range of ± 85 degrees.

2. *Three Phase Synchro Transformer* has three secondary windings which are 120 degrees apart physically. Solid State converters are available that convert the three phase outputs to a d-c voltage proportional to the angle of the rotating winding.

3. *Hall Effect Synchros* make use of the phenomenon of Hall Effect by rotating the semiconductor plate about the axis of current flow in the perpendicular magnetic field. The induced voltage across the plate is proportional to the cosine of the angle by which the axis of the magnetic field deviates from a vertical to the plate.

Resolver:. Resolvers are similar to synchros in design. They differ mainly in the number and spacing of their windings. A two-phase stator(two stator windings 90 degrees apart) with two rotor windings also 90 deg. apart is one design. When used as a transducer one of the rotor windings is shorted.

Digital Transducers also called *Digital Shaft Encoders* have outputs that represent angular displacement by a number of discrete increments. They exist in two forms.

Incremental encoders measure angular displacement with respect to a starting point. In the basic form these have the shaft attached to a disc or other form of rotor which is divided near its circumference into a number of equal sectors. The disc rotates past a reading device fixed in position which generates an electrical output for each sector passing it. These electrical pulses may be counted and accumulated to obtain a number representing the angular displacement.

Absolute Encoders measure angular displacement with respect to an internal reference point. The output is a coded representation of the angular position of the shaft. These are similar in operation to incremental encoders except that the disc has a number of tracks with each track divided into sectors. The division into sectors is generally designed to generate a binary or a Gray code at the reading devices.

Generating an electrical output for each passing sector may be accomplished by: **i.** a contacting brush sliding over metal plates; **ii.** a flux sensitive coil or head activated by ferromagnetic material; and **iii.** a photodetector placed behind alternately opaque and transparent sectors and activated by light incident upon it through the transparent sectors. The third type, commonly referred to as Optical Shaft Encoders has very high resolution in a relatively small size. Another advantage is that they are comparatively free from noise.

Another type of optical encoder with a very high degree of resolution is a measuring system using *interfering patterns.* The "N + 1" pattern is used mainly with coded disc elements. One of two concentric discs having N sectors is attached to the sensing shaft. The other stationary one has $N+1$ sectors. Light intensity transmitted through the discs will be maximum at one point on the disc circumference and minimum at a point 180 degrees away. The output of an Optical Sensor due to this light intensity is modulated in a quasi-sinusoidal fashion.

The *Moire pattern* or *Moire fringe* has been used to improve resolution in displacement measurement. The essential element of a Moire fringe system is a length of transparent material engraved with a precisely known number of lines per unit angle of rotation. When two similarly engraved sections are superimposed at a slight angle, a beam of light projected through the twin layers produces a dark area or a fringe. Travel of one of the sections at right angles to the engraved lines produces a fringe movement along the lines. Reversal of travel also reverses the fringe movement. One complete movement of the fringe across the field represents travel of one line division. Linear resolutions of 1.2 μM in 250 mm travel are attainable.

I.2 Angular Velocity Transducers *(Tachometers)*

Analog tachometers are essentially generators of either d-c or a-c voltages.

The **D-C Tachogenerator** has a permanent magnet stator and a wound rotor. The output voltage varies linearly with rotary speed. In the **A-C Induction Tachometer**, The primary (input) winding is excited by an a-c voltage. The amplitude of the output from the secondary varies with rotor speed. The **A-C Peramnent Magnet Tachometer** uses the magnetic interaction between a permanent magnet rotor and a stator winding to provide an a-c output voltage. The amplitude as well as the frequency are proportional to the rotor speed.

Digital Tachometers are similar to the Incremental Encoders described in the previous section. The number of electrical pulse outputs in a time interval may be counted to obtain a number proportional to the angular velocity. A second method to compute angular velocity is to measure the time interval between two pulses; this value is inversely proportional to the angular velocity of the rotor. Direction of rotation can be detected by placing two sensors or reading devices such that they produce electrical outputs which are 90 degrees out of phase with each other and decoding the state sequence of these quadrature outputs. *FIG.2.* illustrates this for the optical incremental encoder.

References

[1] Haruhiko Asada, Takeo Kanade, Ichiro Takeyama.
Control of a Direct Drive Arm.
Technical Report CMU-RI-TR-82-4, The Robotics Institute, Carnegie Mellon University, April, 1982.

[2] Haruhiko Asada, Takeo Kanade et al.
Control of a Direct Drive Arm.
Internal Technical Report.

[3] *ITEK, Installation & Operation Manual, MicroSeries uS−/16& us−/23 Shaft Position Encoders*
1980.
Manual No. 2990, Rev.(-), ITEK Corporation, Measurement Systems Division, Christina Street, Newton, MA-02161.

[4] *ITEK,Operation and Maintenence Manual, DIGISEC, RI−/15C Series Encoders*
1980.
Manual No. 2750, Revision O, ITEK Corporation, Measurement Systems Division, Christina Street, Newton, MA-02161.

[5] Harry N. Norton.
Handbook of Transducers for Electronic Measuring Systems.
Prentice-Hall, inc., 1969.

[6] Snyder W.E. and Schott J.
Using Optical Shaft Encoders.
Robotics Age, Fall, 1980.

[7] E.J.Wightman.
Instrumentation in Process Control.
Butterworth & Co. Ltd., London., 1972.

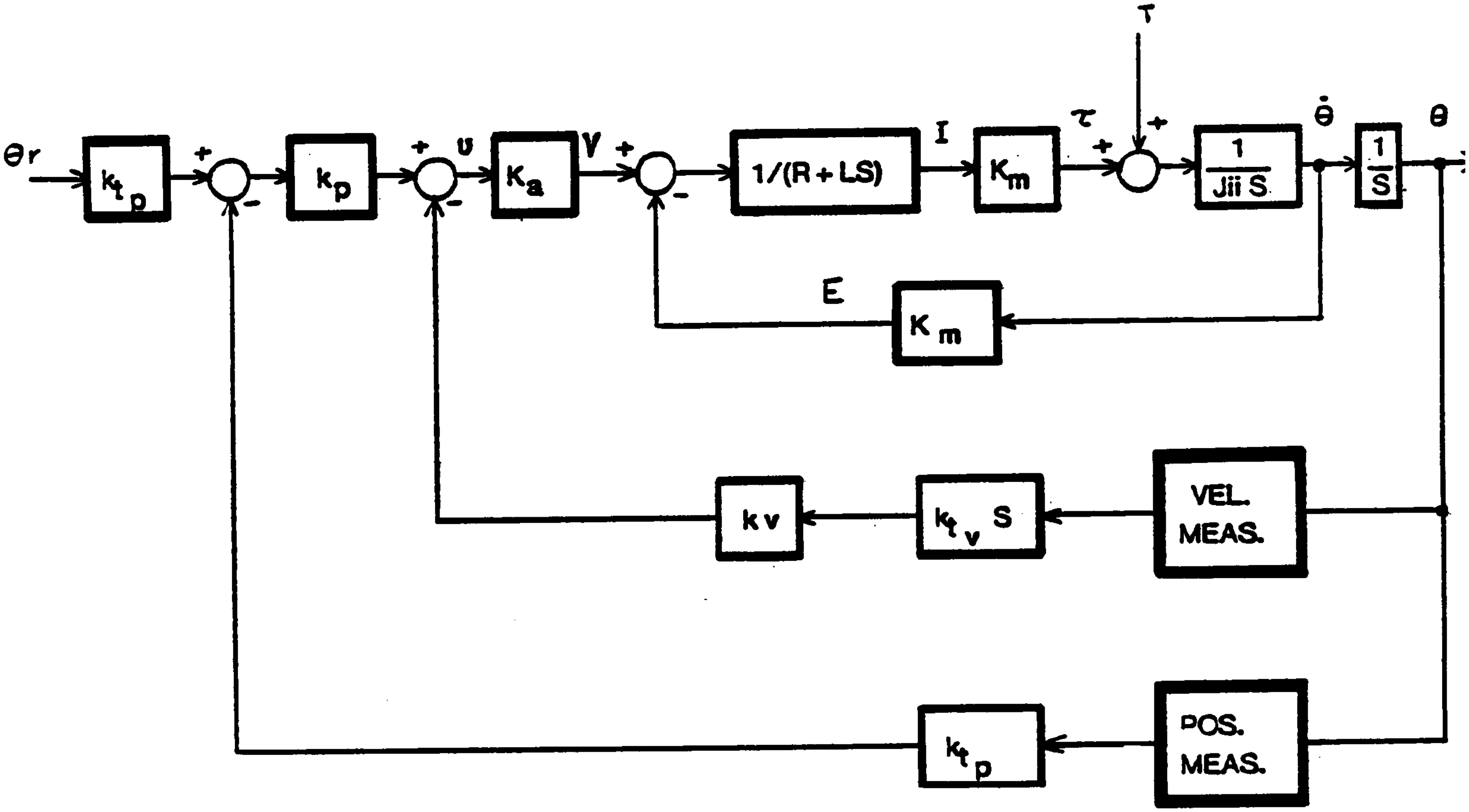
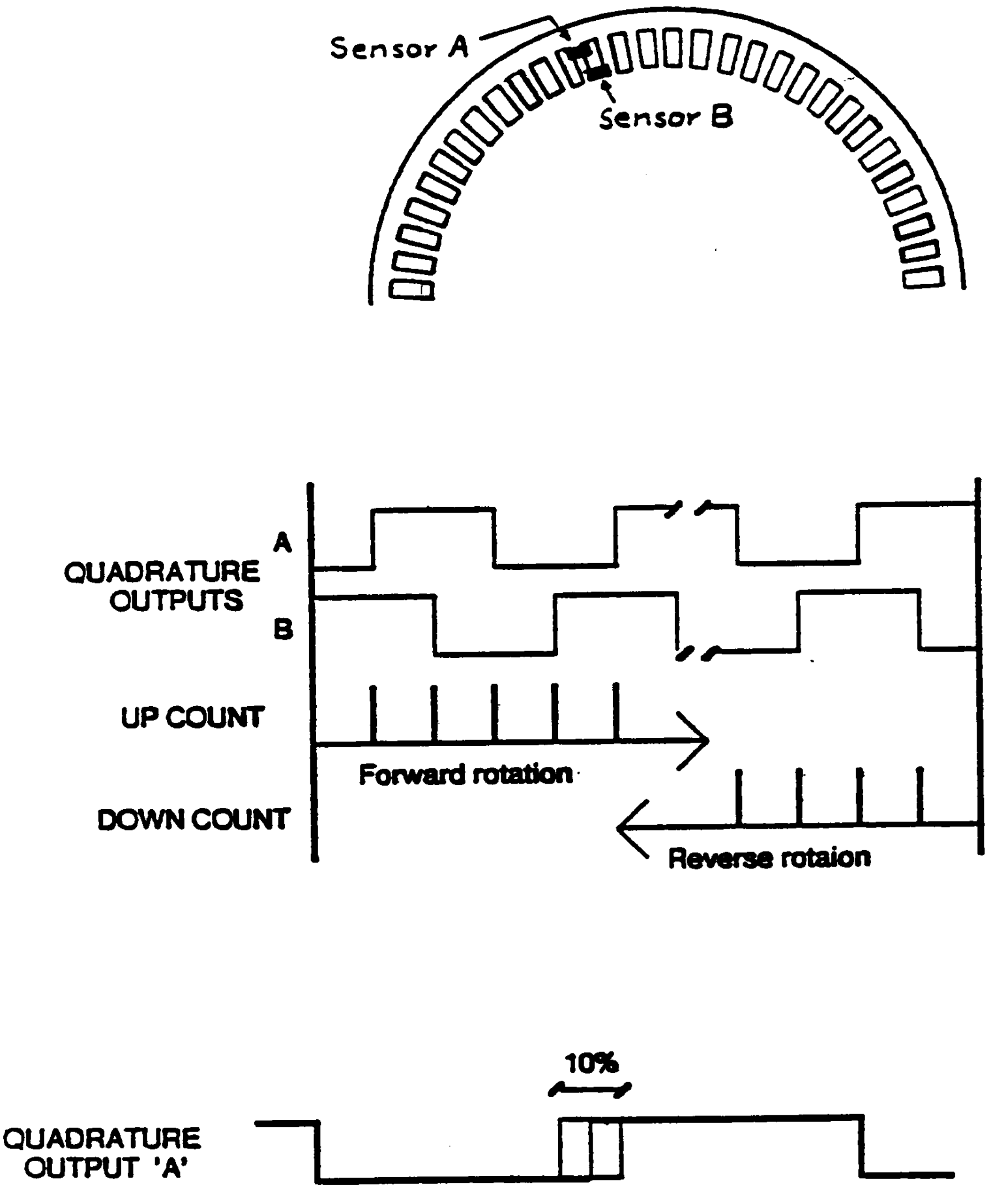
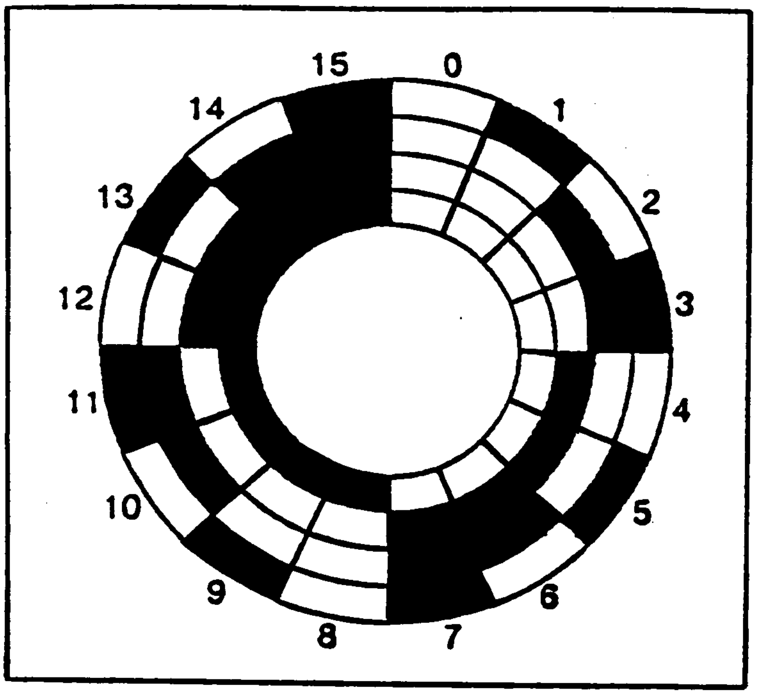


FIG. 1. BLOCK DIAGRAM OF A SINGLE LINK DRIVE SYSTEM [1]

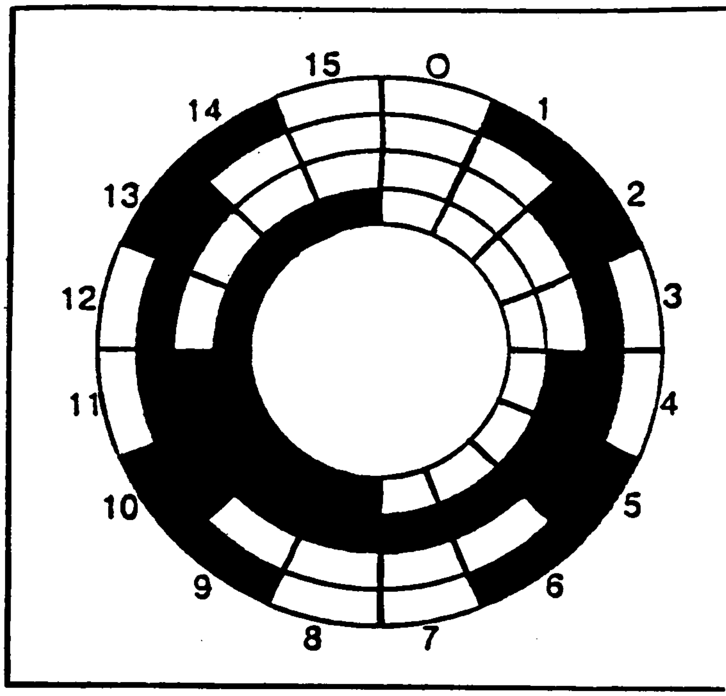


UNCERTAINTY IN DUTY CYCLE [3]

FIG.2. INCREMENTAL ENCODER



An absolute shaft encoder utilizing a binary code.



An absolute shaft encoder utilizing a grey code.

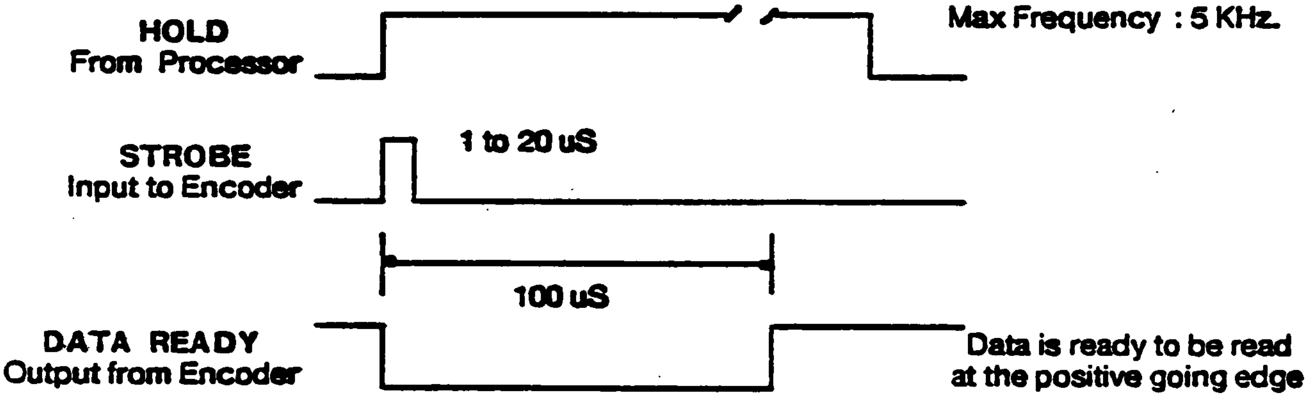


FIG.3. ABSOLUTE ENCODER

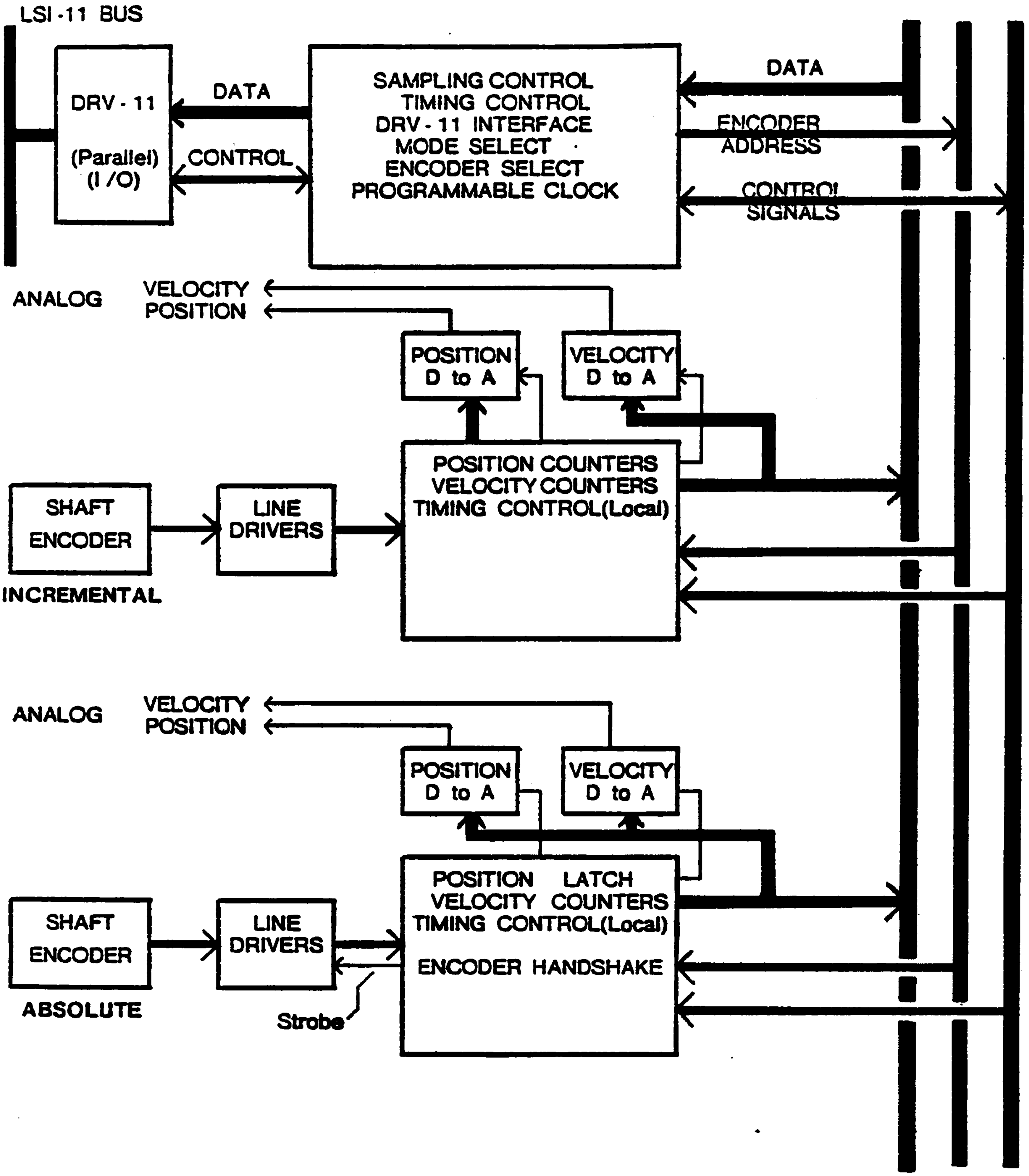


FIG.4. POSITION AND VELOCITY MEASUREMENT SYSTEM (BLOCK DIAGRAM)

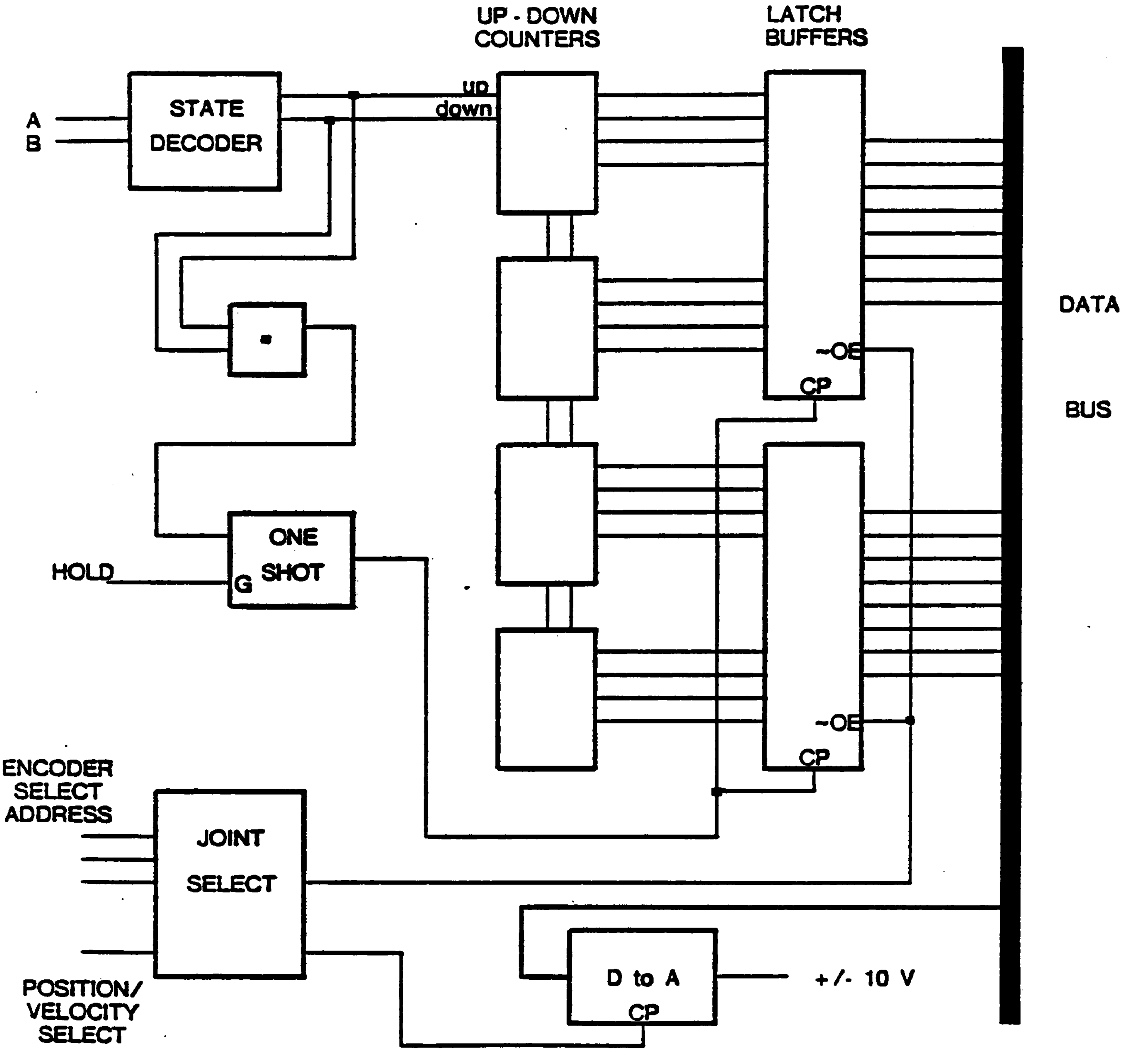


FIG.5. POSITION MEASUREMENT

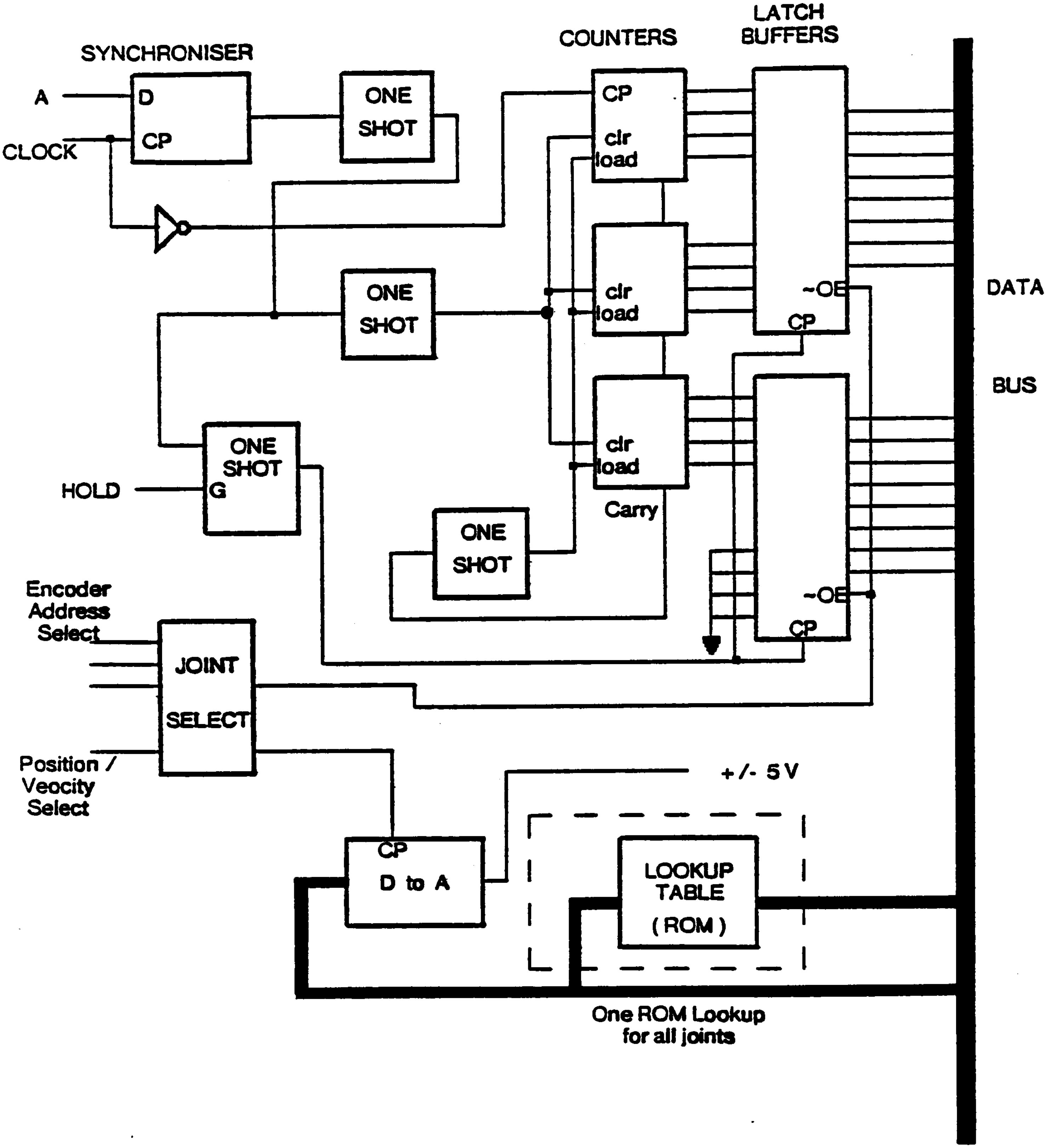
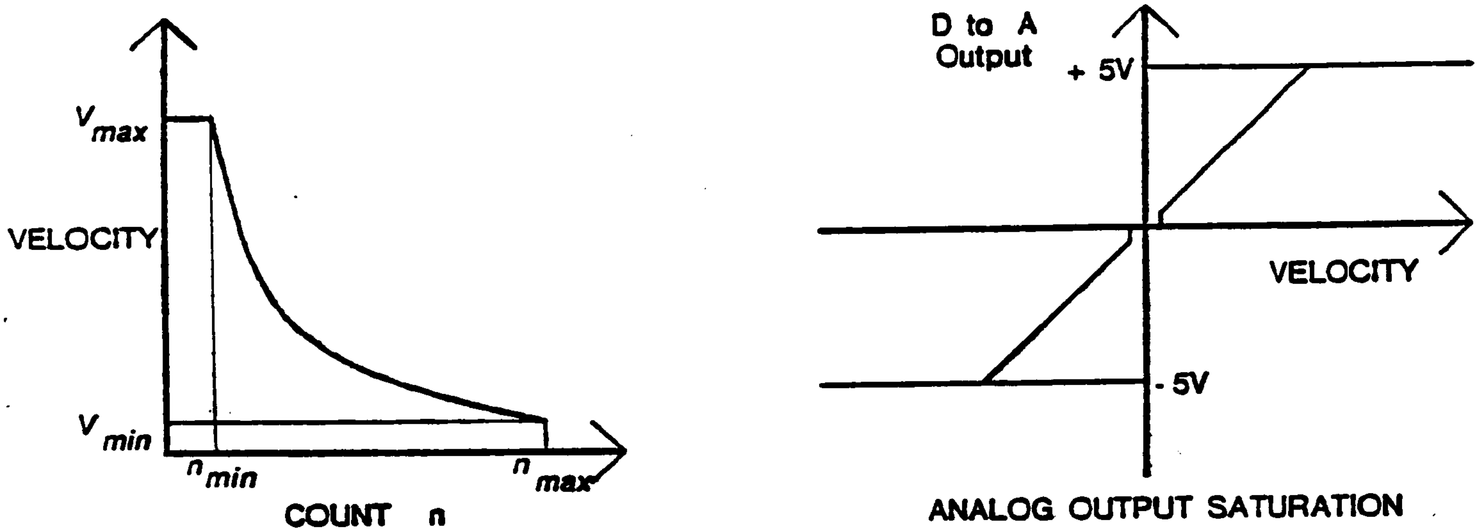
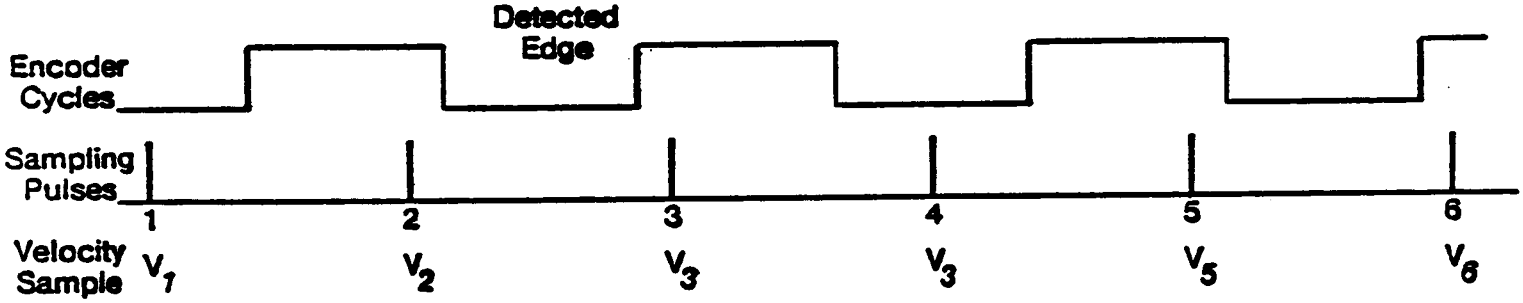


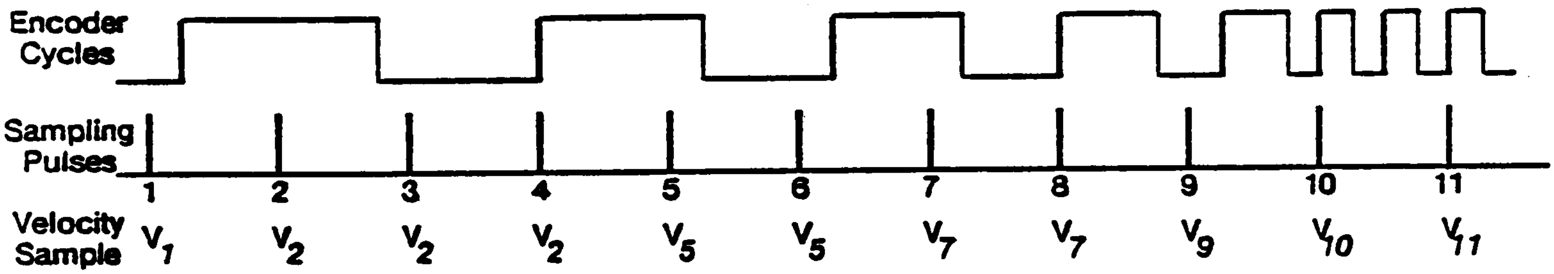
FIG.6. VELOCITY MEASUREMENT (ROM LOOKUP)



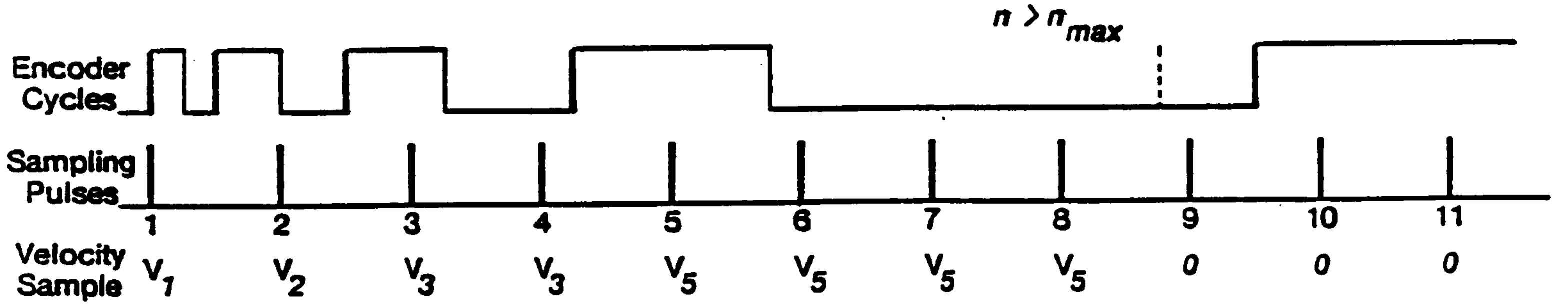
ANALOG OUTPUT SATURATION



CONSTANT VELOCITY OF ROTATION

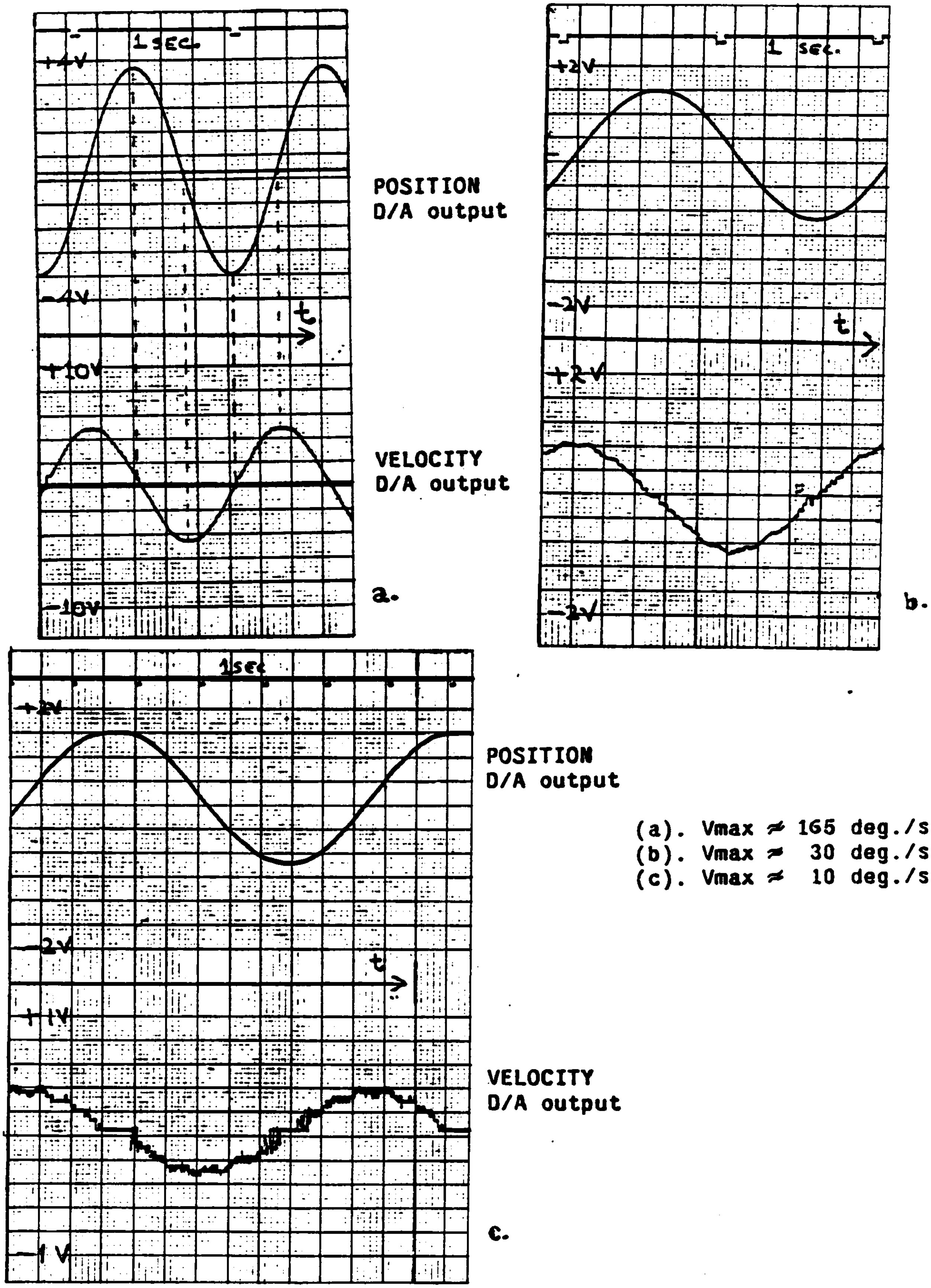


ACCELERATING JOINT



DECELERATING JOINT

FIG.7. SAMPLING AND VELOCITY MEASUREMENT



(a). Vmax ≠ 165 deg./sec
(b). Vmax ≠ 30 deg./sec.
(c). Vmax ≠ 10 deg./sec.

FIG.8. SINUSOIDAL VARIATION IN POSITION AND VELOCITY. (JOINT-6)

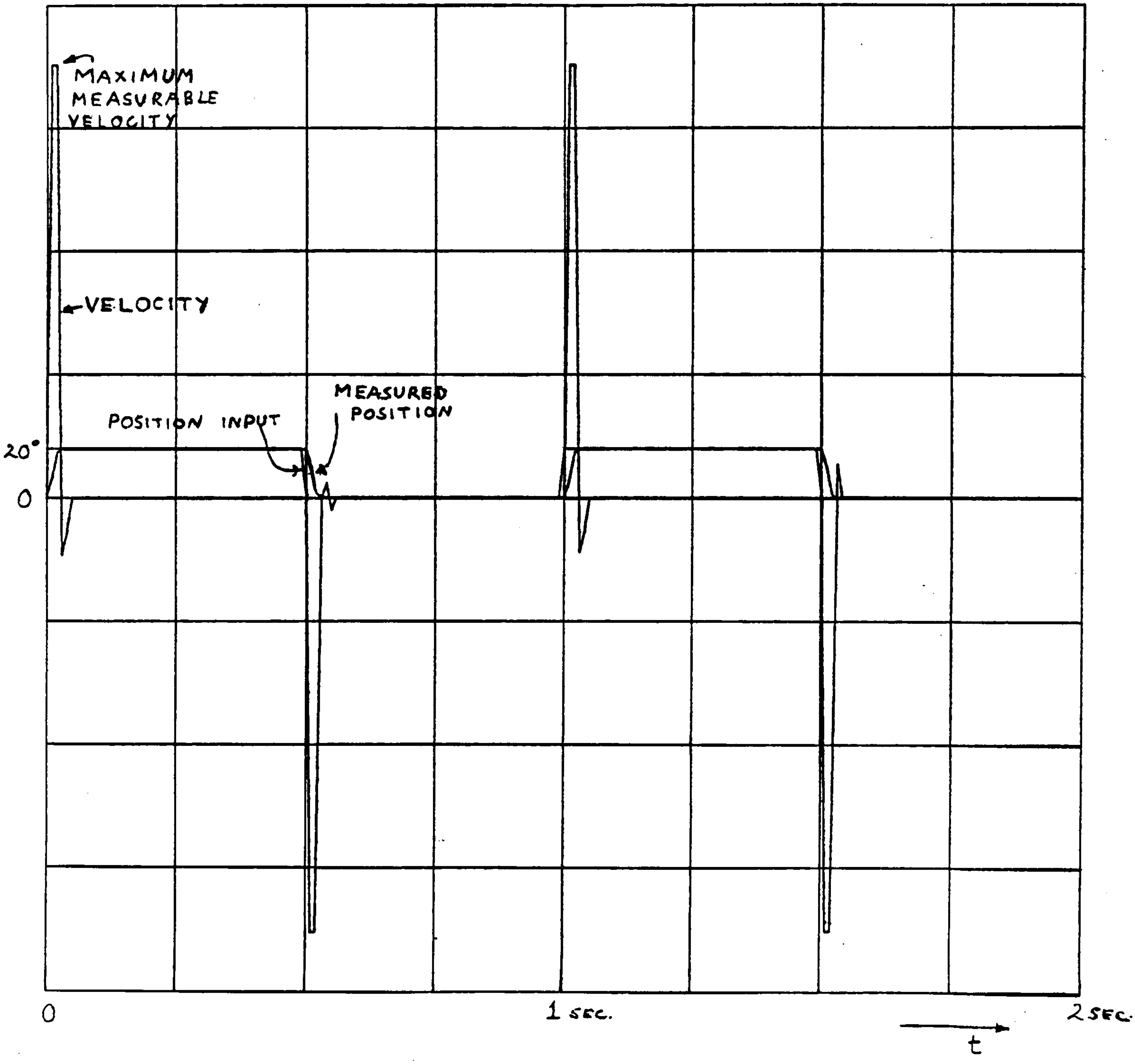
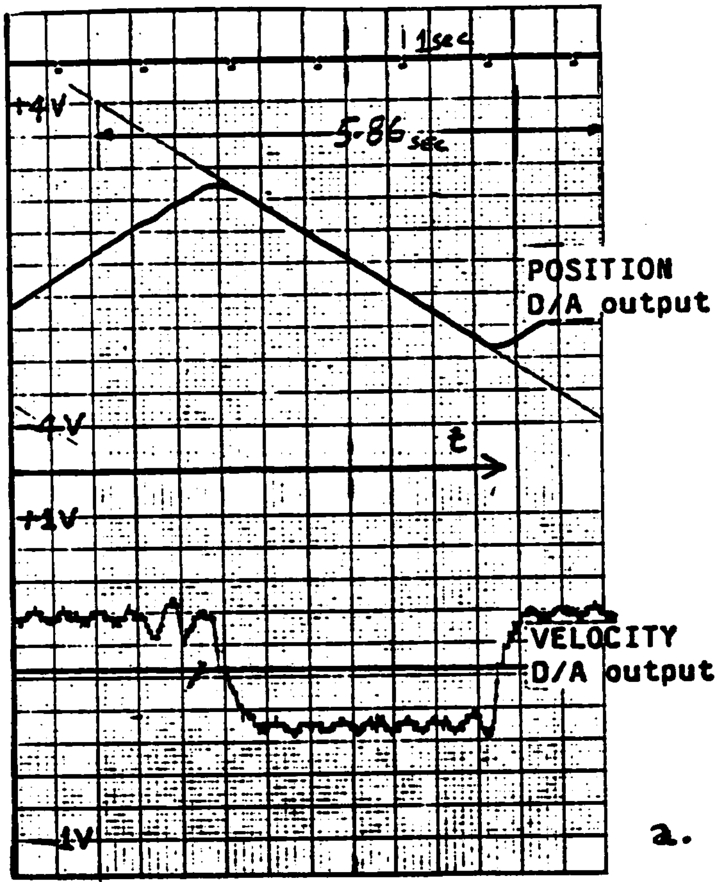
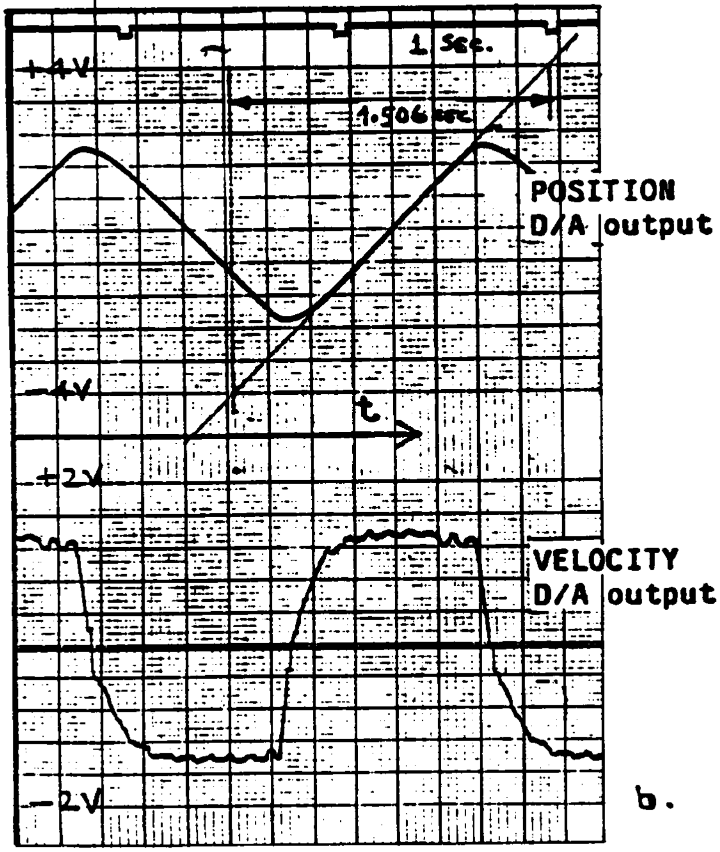


FIG. 10. JOINT 6 - SQUAREWAVE MOTION



V = 180/20 • -8/5.86 deg./sec.
= -12.287 deg./sec.
= -279.59 cycles/sec.
(3576.67 uS/cycle (-ve))
n = 357 (-ve)

ROM output = 3200/357
= 8.96 = 8 (-ve)
D/A outut = -8 • 5v/128
= -0.3125 volts



V = 180/20 • 8/1.506 deg./sec.
= 47.808 deg.sec.
= 1087.9 cycles/sec.
(919.19 uS/cycle)
n = 91

ROM output = 3200/91
= 35.16 = 35
D/A output = 35 • 5v/128
= 1.367 volts

FIG.9. CONSTANT RATE OF CHANGE OF POSITION (JOINT-6)