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The development and application of an opto-electronic technique for analysis of body movements

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THE DEVELOPMENT AND APPLICATION OF AN OPTO-ELECTRONIC TECHNIQUE FOR ANALYSIS OF BODY MOVEMENTS

By

D. L. MITCHELSON

Supervisors:

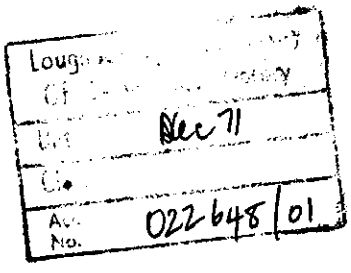
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Thesis submitted for the Degree of

Master of Science of

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ABSTRACT

The relative merits of the most commonly used techniques for analysis of human movement are briefly outlined. The performance characteristics of the ideal instrumentation for recording movement are listed. As a consequence of these considerations, an opto-electronic technique which makes use of polarised light is developed for measuring angular orientation of limb and body segments.

This technique is used to study patterns of upper arm abduction during a simple lifting task, and to study the relationship between arm and trunk movements during a task which requires reaching to various distances on a table surface.

The merits of the opto-electronic technique are discussed in the light of the experience gained from the experimental applications, and recommendations are made for the future development of the instrumentation.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

A great deal of information about the static anthropometric characteristics of individuals and population groups has been gathered during the last fifty years (Refs. 1, 23). In addition to basic data on structure, weight, limb dimensions and somatotype, many measurements have been made of maximum ranges of movement for the various body segments, and the maximum forces which can be exerted at different points within the range (Refs. 3, 25). By comparison, measurement and analysis of the way in which body and limb segments move in relation to each other as a function of time, that is to say dynamic anthropometry, has been a relatively neglected area of the human sciences. Although the first attempts to study the characteristics of human movement date back to the nineteenth century, the history of scientific study in this area since then is not very extensive.

As early as 1887, E. Muybridge had published nearly 800 photographic plates showing sequences of various kinds of human movement, such as walking and running. The photographs were taken at time intervals of 70 to 200 milliseconds by an elaborate arrangement of batteries of up to 48 cameras, all linked electrically to a sequential timing device. The subjects were not fitted with any landmarks, although in some cases they were shown walking in front of a reference grid on a background board.

Since that time, several techniques for recording different aspects of movement have been developed. Motion picture analysis, however, was until recently the only method available for studying the relationships between the movement of all body and limb segments simultaneously. Unfortunately, this technique is extremely time consuming, with the

result that research into the nature of the time patterns of displacement, velocity and acceleration of limbs during movement has been rather fragmentary. This is perhaps also due to the lack of any comprehensive taxonomy of movement which takes into account the detailed characteristics of movement-time patterns.

The taxonomies so far in use are such as that developed by Roebuck (1968) as a means of describing modes of movement while wearing a space-suit. It is, in effect, simply an elaboration of the conventional classification of directions of movement such as flexion, extension, abduction, and so on. One taxonomy which comes closer to describing the qualities of the movements themselves is due to Laban (1963), and is intended to describe movements employed in ballet. But this is still too vague to be of much value as a scientific system of movement classification.

There remains a need for a practical taxonomy of movement which adequately describes the hierarchical set of relationships between the movement time patterns of the various body and limb segments. At this stage it is not at all certain that such a taxonomy is possible. It may be that the relationships involved are too fluid to be forced into a stable classification system. However, this will not be known until much more experimental data of the kind sought in this project has been gathered.

Despite these problems, greater understanding of the characteristics of human movement is required in the psychological, industrial and medical spheres of interest. Of the small amount of work so far accomplished in this field, the instrumentation used, the data analysis procedures, and even the working definition of the movement, have tended to reflect the special interests of those carrying out the research.

1.1. Psychological Studies of Movement

Experimental psychologists have studied movement either from the behaviourist viewpoint as the response part of a stimulus-response paradigm, or as a means of discovering the characteristics of the central nervous processes which result in movement. Thus, Taylor and Birmingham (1948) have studied continuous and step function tracking performance as a means of understanding the nature of corrective response movements. They found that the dynamic response movements were little affected by moderate increases in the weight which were used to load the subject's hand or by changes in the required amplitude of the movement.

The most important factor in the control of movement appears to be time. This is borne out by Fitts (1954), Crossman (1957), and Fitts and Peterson (1964). Their results showed that the movement time is governed by the amount of information which must be processed by the central nervous system in order to make the movement with a given level of accuracy.

This general view of movement time has been fairly well supported by experimental evidence. Other workers such as Crossman (1957), Knight and Dagnall (1967) have proposed slightly different formulations than Fitts' original one, but they all support the information processing theory of movement time.

Most psychological research on human movement has concentrated on measuring what might be described as the end result of the movement. In the case of Fitts' reciprocal tapping experiment, it is the rate of tapping, width and distance between targets and the successful hits on the target which are measured. In tracking tasks it is the position of

an external control such as a joystick that is measured. This kind of approach has certainly produced results which have increased our knowledge of the central processes involved in control of movement. However, it may be argued that a careful study of the time patterns of body segment movements will yield further valuable information on the way in which programmes of motor output are learned and co-ordinated. Such studies would provide a natural complement to electromyographic analysis of motor activity.

1.2. Industrial Studies of Movement

In industry it is important to supplement considerations of static anthropometry with a knowledge of movement characteristics in order to design the layout of workplaces and plan the optimum time pattern of work skills. This applies particularly when speed and accuracy of movement are essential elements of the work.

The traditional methods of time and motion study employed in the detailed analysis of industrial tasks do not provide much insight into the nature of the complete space-time pattern of the movement. Again, these methods are only concerned with the overall result of the movement as defined by its starting and finishing points and duration.

A more advanced method of analysing movement which has been developed primarily to yield results of interest to industry is a system called 'Unopar' due to Nadler and Goldman (1958). This employs the doppler effect, using high frequency sound. A small sonic generator is attached as a 'landmark' to the limb segment whose motion is to be recorded. The velocity and direction of the movement is then continuously measured via a three-dimensional array of microphones and a sophisticated electronic signal processor. Provision is made for

recording position, velocity and acceleration simultaneously.

This system has been used by Kattan and Nadler (1969) to derive a polynomial equation for the path through which subjects' hands travelled while performing point to point tapping tasks. Although this system eliminates the time consuming work of taking measurements from film, thus enabling many subjects to be studied, it does have some disadvantages. These are associated with decreasing accuracy at low values of limb velocity and also positional uncertainty during reversals of movement.

1.3. Medical Studies of Movement

In the field of medicine there is a requirement for reliable techniques of assessing the nature and degree of various types of physical disability, both as a check on the effectiveness of therapeutic treatment and as a means of determining good design specifications for prosthetic devices. The time patterns of limb and body movements have been employed in various ways to help meet these requirements.

Beasley (1961) has developed a technique for the quantitative testing of the degree of spasticity in the affected muscle groups of spastic patients. The amplitude and frequency of muscle tremor are measured quasi-isometrically and the resulting records used for purposes of diagnosis and for planning the most effective kinds of treatment. Although this technique is well adapted for its specific purpose, it must be classified with the many other studies in which it is not the free movement of the limb in three-dimensional space that is measured, but only the one-dimensional movement experienced by a mechanical transducer attached to one point of the limb.

McWilliam (1965) comes closer to studying the time patterns of the movement of whole limb segments. In work carried out at the Powered Limbs Research Unit in West Hendon, the time patterns of humeral and forearm rotation were measured, using an electrogoniometer. The movements were made at the subject's own pace and without the need for positional accuracy. McWilliam found that while the total movement time and the peak velocity varied with the distance moved, the general shape of the velocity vs time waveform remained the same. An interesting result of the work is that oscillations in the amplitude of the velocity occurred when the velocity was less than about 1 radian per second. This was true at the end of moderately fast movements, and also when the subjects were instructed to make a deliberately slow movement.

These results are in agreement with Peters and Wenborne (1936), who found that the plots of distance travelled against time were very nearly constant for different directions and extents of movement, and that when movements made as fast as possible were compared with those made at moderate speed, then all phases changed to about the same proportional extent.

Furnée (1967) has outlined a method of movement analysis, using television cameras, which was intended for assessing the functional effectiveness of artificial limbs. Three cameras were mounted so that the subject was viewed along each of the three mutually perpendicular axes. The signal from each camera was processed in an appropriate way and then recorded on magnetic tape for input to a computer for subsequent analysis. Unfortunately, no results of this work have yet been published.

As part of an orthetics research project, Pearson et al. (1963) have carried out an analysis of arm movements in the saggital plane, using a multiple exposure photographic technique. The angular displacement-time measurements for each arm segment were used as input data to a computer. Angular velocity and acceleration were computed using the method of finite differences. Then, using the free-body diagram technique described by Dempster (1961), the forces and torques experienced at the axis of the shoulder and of the elbow were computed. The results were presented graphically, showing displacement, velocity, acceleration, force and torque for each segment as a function of time.

This work appears to be one of the most advanced studies so far accomplished in the field of dynamic anthropometry. However, it is confined to illustrating the virtues of the analysis techniques which were employed by using a small sample of experimental data. Apparently there has been no further published work giving details of more comprehensive experimental results.

The most promising recent developments in instrumentation for analysis of angular movements come from Grieve (1969) and from Reed and Reynolds (1969). They report the simultaneous and separate development of apparatus which makes use of polarised light for on-line measurement of angular displacements of limb and body segments.

Grieve as well as Reed and Reynolds reports a time resolution of 50 Hz and an angular resolution of the order of 1 to 2 degrees provided that their polarised light projector and the transducer mounted on the subject are within 15 to 20 degrees of the correct angular alignment to the plane in which the experimental movements are to be made.

There is no reason why the time resolution cannot be improved quite

considerably according to the above authors.

Grieve's technique, called Polgon, is well suited to a convenient graphical mode of movement representation he has outlined (Grieve, 1969b). In this, the absolute angular positions of any two limb segments are plotted against each other rather than against time. When this is done for cyclical movements such as walking, a 'shape' is generated, which is unique to a particular speed of walking for each person. Pathological conditions of the legs can radically alter this shape, thus providing clinicians with a valuable means of assessment of the course of disease or the effect of therapy.

One great advantage of these developments is that on-line recordings of the relative angular positions of several non-adjacent body segments may be made. However, the same line-of-sight limitations of film analysis apply to this kind of apparatus.

In summary, as pointed out by Dempster (1961) and Welford (1968), very little work has been done specifically on the subject of the inter-relationship of the time patterns of free limb movement in three dimensions. While many references have been pursued which promised some information in this area, few of them proved relevant.

It seems evident that real progress in the field of dynamic anthropometry must await the development of instrumentation which will permit rapid accumulation of accurate measurements of limb and body segment positions as a function of time, and in a form which can be immediately fed to a digital computer for analysis.

2. DEVELOPMENT OF OPTO-ELECTRONIC INSTRUMENTATION

2.1. Basic Requirements

In determining the most important attributes required of instrumentation for analysis of human movement, it is perhaps most helpful to state what the ideal piece of apparatus should do. It then becomes a matter of using known technologies in order to approach this ideal as closely as possible within the constraints of cost.

To provide maximum flexibility as a laboratory tool, the instrumentation would need to possess the characteristics listed below:

a) The movement record should be produced as movement occurs and should be permanent. It is particularly important to eliminate intermediate stages of data analysis which occur, for example, in the various film techniques.

b) The record should be continuous in time. This would eliminate time skewing errors that can occur when the movement is sampled at finite intervals of time. If continuous recording is not possible, then the sampling frequency should be as high as possible.

c) The record should be in a form readily usable either for computational analysis or visual display,
Such a facility would enable selected parameters of the movement to be displayed to an experimental subject, thus providing him with immediate feedback for purposes of improved learning of motor skills.

d) The band width of the apparatus should be high enough to provide good resolution of the fastest movements under study. In this context, good resolution means that which is required to ensure adequate support for experimental hypotheses according to pre-

-determined levels of confidence.

e) The instrumentation should be capable of simultaneously measuring angular and linear displacements, velocities and accelerations in 3 dimensions of as many of the limb and body segments as required.

f) The human subject under study should be relatively free from any physical encumbrance due to the apparatus.

g) In some cases it may be advantageous if the instrumentation were portable so that field studies may be carried out. A reduction in the size and weight of the equipment should be possible if less than whole body movement analysis is required. Under certain experimental conditions this may be done without sacrificing any of the performance characteristics which are required for a particular application.

This list of characteristics represents the most that may be required for any one experimental condition. Usually the requirements will be somewhat less stringent than this, as when, for example, the movement patterns of only one limb are being investigated.

2.2. Alternative Design Possibilities

It is considered that there are a limited number of physical principles which may be exploited in the design of instrumentation for movement analysis. These may be broadly categorised as electro-mechanical, accoustic, magnetic and optical.

The techniques which have been used to date have employed most of these principles. Those most commonly used, however, have been electro-mechanical devices in the form of electrogoniometers,

accelerometers and force transducers, and optical techniques using cine film in one way or another. Each of these methods has its own advantages and disadvantages. Table 1 summarizes the relative merits of the most important and frequently used techniques.

The main limitation encountered in using electrogoniometers is that in order for their output to relate directly to the angular attitude of adjacent limb segments, they must be mounted exactly over a fixed axis of rotation to the joint between the two segments. This restricts the use of the goniometer to the few joints possessing well defined axes of rotation such as the elbow, knee and hip.

Linear and angular accelerometers have considerable usefulness in analysis of human movement. Their light weight and small size mean a minimum of interference with freedom of movement. When carefully calibrated they can provide highly accurate measurements of acceleration. In addition the devices available today have very great dynamic range and bandwidths from near D.C. up to several hundred KHz. This means that any acceleration, from very fast, high amplitude transients to relatively long, small accelerations may be recorded.

It is possible to obtain measurements of velocity and displacement by integrating the output from an accelerometer once and twice respectively. However, this approach to complete movement analysis has the great disadvantage that it is very difficult to establish absolute values of velocity and position. This is because the constants of integration are not determined by the electronic process of integration.

The accoustic technique called Unopar, described by Goldman and Nadler appears to have some use in the study of linear velocities, however, it suffers from a similar disadvantage as accelerometers in

TABLE 1. RELATIVE MERITS OF VARIOUS TECHNIQUES FOR MOVEMENT ANALYSIS

TECHNIQUE	TYPE OF MEASUREMENT WHICH IS POSSIBLE							COMMENTS
	ON-LINE	ANGULAR MOVEMENT		LINEAR MOVEMENT		ADJACENT SEGMENTS	MANY SEGMENTS	
		ABSOLUTE	RELATIVE	ABSOLUTE	RELATIVE			
CHRONOCYCLOGRAPH		*	*	*	*	*	*	Very time consuming analysis limitations of line-of-sight
CINE ANALYSIS		*	*	*	*	*	*	" "
ELECTROGONIOMETER	*		*			*		Can hinder free movement, least expensive
ACCELEROMETERS	*	?		?		*	*	Uncertainty in position
UNOPAR	*			?		*	*	" "
POLGON	*	*	*			*	*	

that absolute positions cannot be defined.

It may be feasible to build a system which uses a magnetic field as the basic reference grid for movement analyses. Such a system would require either strong permanent magnets or electro-magnets to be set up in some carefully selected spatial relationship so that every point in a predetermined volume of space could be uniquely identified by the strength and direction of the magnetic field. The subject under study would then be placed in this volume of space to perform the experimental task. If selected landmarks on the subject's body were fitted with small Hall effect transducers, then in principle it would be possible to determine the positions of each landmark by appropriate electronic signal processing. This approach would completely eliminate the line-of-sight difficulties common to many optical techniques.

The main drawback to such a system would be the great difficulty of calibrating the outputs. This would arise from the fact that the magnetic field would necessarily be of complex geometry and strength, so that translation of the transducer signals to outputs representing a linear, three-dimensional cartesian co-ordinate system would prove particularly difficult. Another problem would occur if the system were moved to differing locations, in that the configuration of ferro-magnetic materials in the vicinity of the working volume would necessarily affect the pattern of the magnetic field, thus disturbing the calibration.

Of the possible optical techniques for studying movement, the traditional one of cine film analysis may be rejected as a practical modern tool owing to the very lengthy analysis time involved. This view is backed up by the author's experience in using cine analysis for

a short research project carried out at the Department of Ergonomics and Cybernetics at L.U.T. in 1970. The work involved analysing film of upper and lower arm movements which lasted a total of only 14 seconds. The film was shot at 80 frames per second. Subsequent measurement and recording of four landmark co-ordinates in each frame took a total of 60 hours of extremely tedious work.

The use of a modified closed circuit T.V. system as outlined by Furnée would certainly be useful in studying relatively slow movements. However, if a resolution of, say, .1% in X and Y co-ordinate position were needed, at a frame repetition rate of 100 Hz, then the bandwidth of the system would have to be in excess of 100 MHz. This is an unrealistically high value. A further problem with this system is that of variable time skewing of the co-ordinate data. That is, the time which the position of a particular landmark is recorded within each frame scan would depend upon its position in the field of view. This would introduce errors into any measurements wh ich required comparison of the position of different landmarks as a function of time.

It would seem that the situation might be improved if the optical system was not required to scan the visual field in which the subject was placed but could provide an immediate signal representing the position of the landmark.

As stated in Section 2.1, any apparatus capable of comprehensive movement analysis should have the facility to record both linear and angular movements. One physical phenomenon which immediately presents itself in connection with angular measurements is polarized light. It seems that a system which made use of the properties of polarized light would be the most fruitful one to attempt to develop. Consequently,

the instrumentation described in the following section was developed.

The work of Grieve (1969a) and Reed and Reynolds (1969) did not come to the author's notice until the instrumentation had been built. This occurred because the main emphasis in searching the literature had been in the fields of biomechanics ergonomics, human factors, athletics and prosthetics. It was thought that physiology journals would be less relevant to the field of movement analysis. In fact, it was in journals of physiology that the above authors published their papers.

2.3. Final Design of the Opto-electronic Instrumentation

2.3.1. Angular Displacement Circuitry

After a period of consideration of the various ways in which polarised light may be employed in analysis of angular movements the basic design which was finally chosen is illustrated in Figure 1.

The light emitted from a D.C. light source is polarized by transmission through a disc of linearly polarizing filter. The disc is mounted on the drive shaft of a small electric motor and made to rotate at a rate of 150 revolutions per second. The beam of light which is thus transmitted is plane polarized, with its plane of polarization being rotated through one complete revolution every .0067 seconds. The light is then received by a transducer which consists of a photo-cell in front of which is mounted a small disc of polarizing filter of the same type as used in the large rotating disc. As the plane of polarization of the light beam rotates, alternate extinction and transmission takes place at the filter in the transducer, thus producing a sinusoidal light flux into the detecting photo-cell. Since the extinction and transmission occur twice for each revolution of the

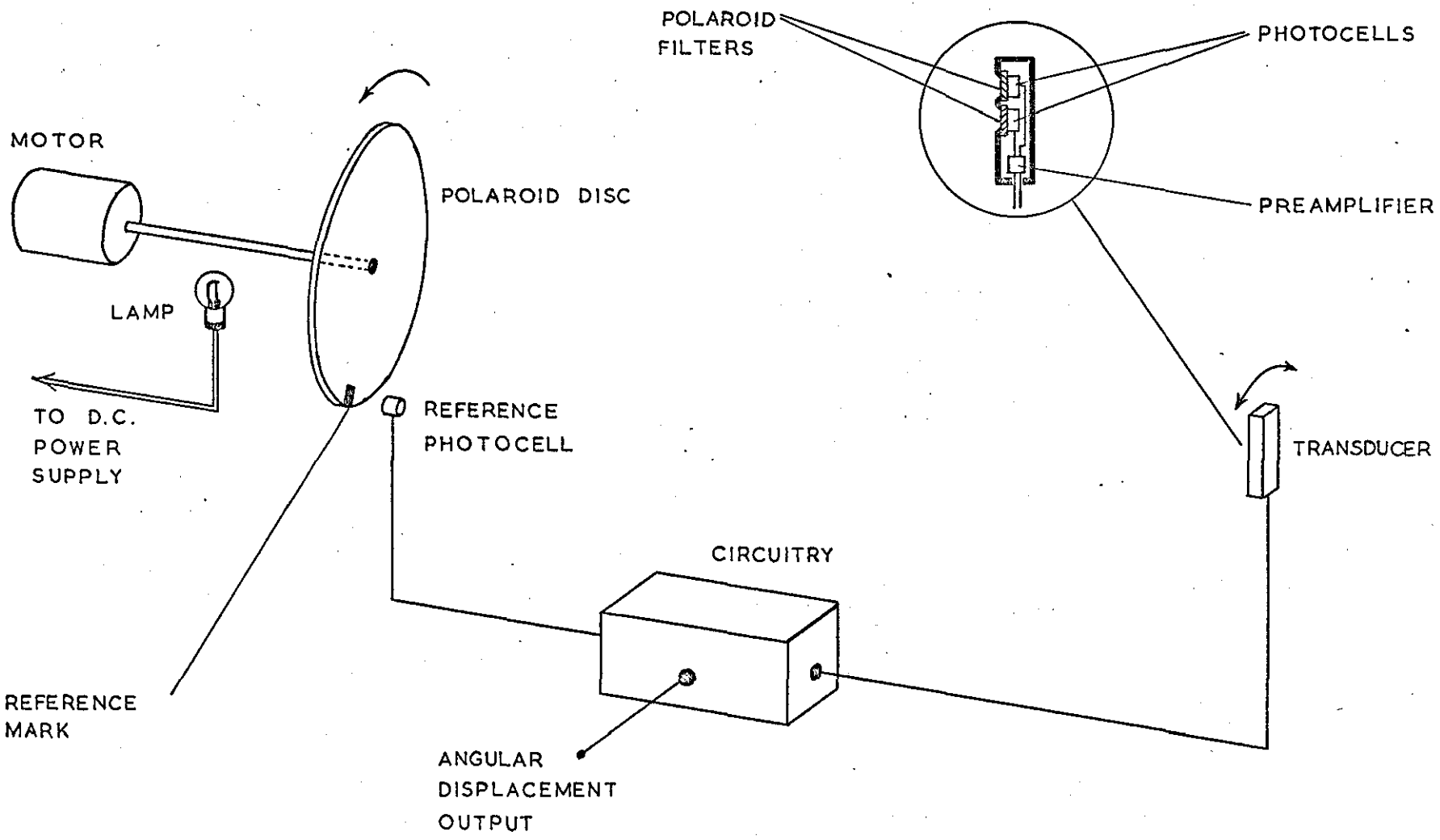


FIG. 1 SCHEMATIC DIAGRAM OF ANGLE SENSING APPARATUS

disc, the frequency of the signal received at the photo-cell is twice the rate of revolution of the disc.

A small rectangular opaque reference mark is mounted on the edge of the rotating disc, and another photo-cell is fixed near the edge of the disc in line of sight to the filament of the light source. Consequently, every time the reference mark on the disc passes in front of the photo-cell, obscuring the light, a pulse is generated in the photo-cell.

Both the reference pulse and the sinusoidal signal from the transducer are passed to an electronic circuit which measures the elapsed time between the reference pulse and the following zero crossing of the sinusoidal signal. This time measurement is then converted to a D.C. voltage which is proportional to the angular displacement between the polarizing axis of the filter in the transducer, and the angular position of the photo cell which senses the reference mark.

The essential elements of the circuitry are illustrated in block diagram form in Figure 2. The signal from the transducer is first fed to an amplifier which has a twin-T filter net-work in its feed-back loop. This allows the amplifier to be tuned to the frequency of the incoming sinusoidal signal, thus reducing the unwanted frequency components of the signal which may arise from room lighting and mains pick-up. The amplified and filtered signal is then fed to a comparator. The output from the comparator is a square wave which switches from a logic level of 0 to a logic level of 1 each time the sine wave input crosses the zero reference voltage level in a negative going sense. The comparator output switches from logical 1 to logical 0 when the sine wave crosses zero in the positive direction.

Meanwhile the signal from the photo-cell which senses the reference mark on the polarising disc is first fed to an amplifier and then to a

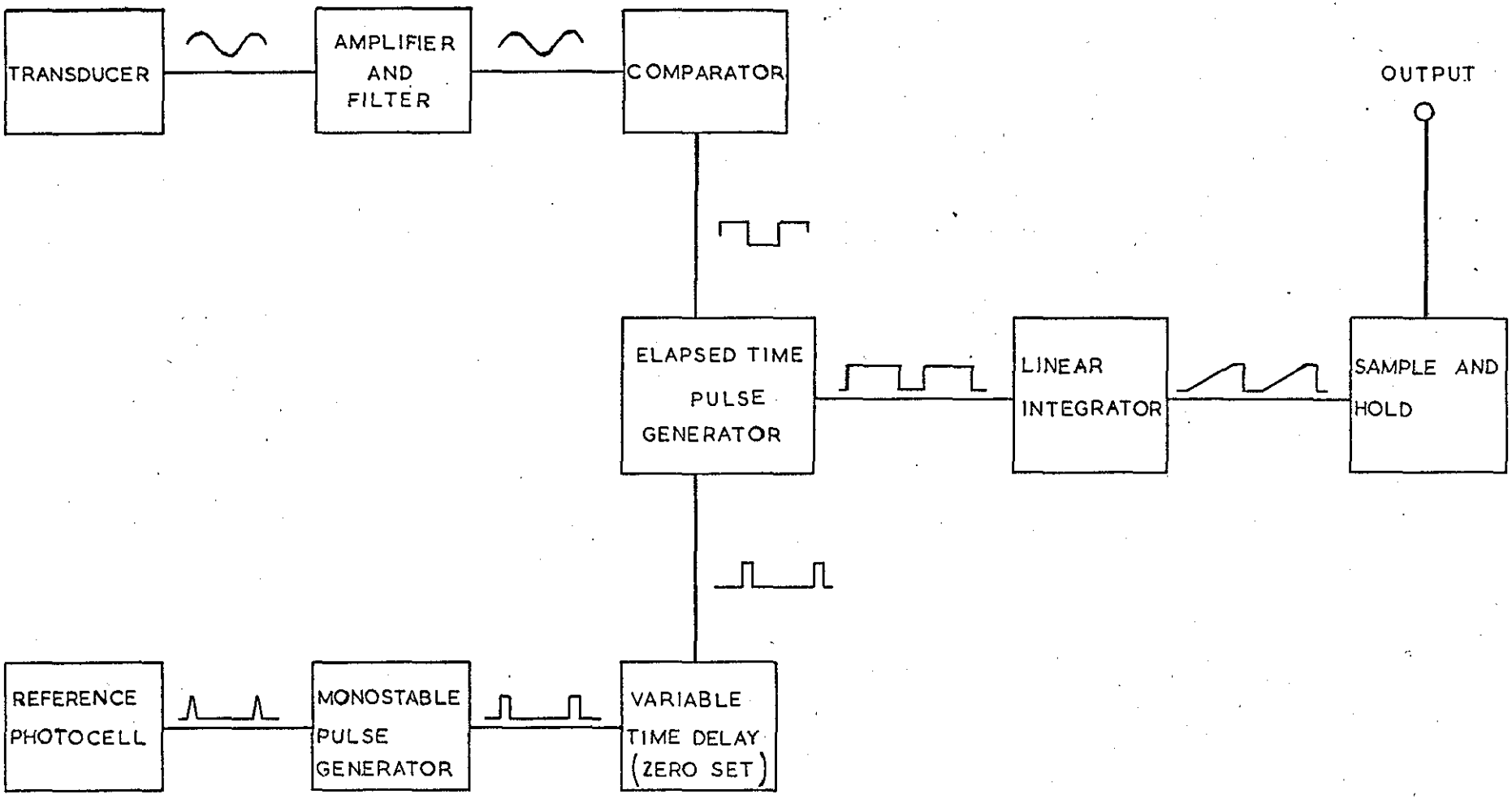


FIG. 2 BLOCK DIAGRAM OF ANGULAR DISPLACEMENT CIRCUITRY

monostable logic circuit which produces a short duration pulse, which is compatible with the other logic input requirement of the circuit. This signal is then fed to another monostable element whose time constant may be adjusted by means of a variable resistor. The effect of this is to introduce a time delay between the generation of the reference pulse and its transmission to later stages of the circuitry. It will be appreciated from the following description that the ability to adjust this time delay effectively provides a zero setting function by which the output signal of the circuit may be offset to any desired initial angular value.

Both this reference pulse and the output from the comparator are fed to the input of a bistable logic circuit which is set to logical 1 by the reference pulse and to logical 0 by the next negative going edge of the square wave from the comparator. The resulting output from the bistable element is a square wave signal which remains in the logical 1 state for a period of time which is proportional to the angular displacement of the transducer from the angular position of the reference photocell at the instant when the light input to the transducer is at half its maximum value. This elapsed time signal is then used to control the length of time for which a linear integrator is allowed to ramp up from zero volts.

The slope of the ramp is determined by a fixed input voltage of - 1.8 volts and by the value of the input resistor R and feed-back capacitor C which have values of 56 KΩ and .047 u F respectively. The formula for the value of the integrator output E_o is:-

$$E_o = -\frac{1}{RC}\int_0^t E_i \, dt$$

Hence $$\frac{d\,E_o}{dt} = -\frac{E_i}{RC} = \frac{1.8}{5.6 \times 4.7 \times 10^{-4}}$$

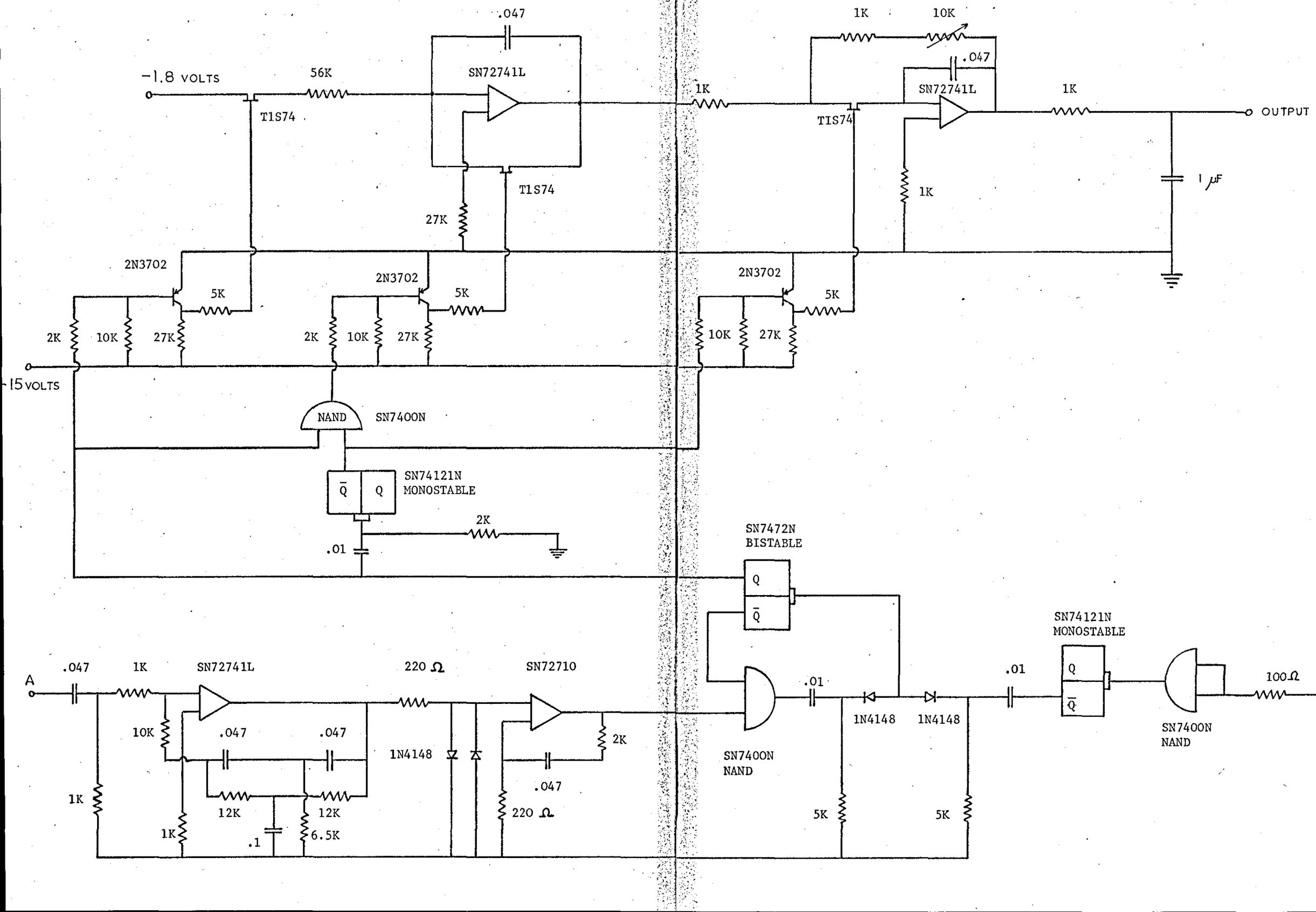
$$= .68 \text{ volts/millisecond}$$

The amplitude which the ramp has reached at the end of the elapsed time signal is then maintained for 2 milliseconds by keeping the integrator in the 'hold' condition. The integrator is then re-set to zero ready for the next ramping period. During this 2 millisecond period, the amplitude of the output level of the integrator is sampled by a sample and hold element. This D.C. level is then held constant at the output of the sample and hold circuit until the next 2 millisecond sampling period when it is adjusted to the peak level of the next ramp from the integrator.

The output from the circuit is thus a D.C. voltage proportional to the angular displacement of the transducer at that instant, within one revolution period of the polarizing disc, at which the light arriving at the photo-cell of the transducer is at its half maximum value. It is also apparent that the output level is updated once in each revolution period of the disc. When the transducer is made to rotate in a plane parallel to the disc, then the output appears as a 'staircase' signal of step length equal to one period of revolution of the disc.

The detailed circuit diagram is shown in Figure 3. As may be seen, the switching functions which control the state of the integrator and the sample and hold circuit are provided by FET transistors. Since these require voltage swings of zero to - 15 volts at their gates in order to achieve full switch-on and switch-off characteristics, the FET's were controlled by 2N3702 transistors operating from the zero and - 15 volt power supply lines. The 2N3702 transistors were in turn switched by the logic levels provided by the bistable and monostable logic elements.

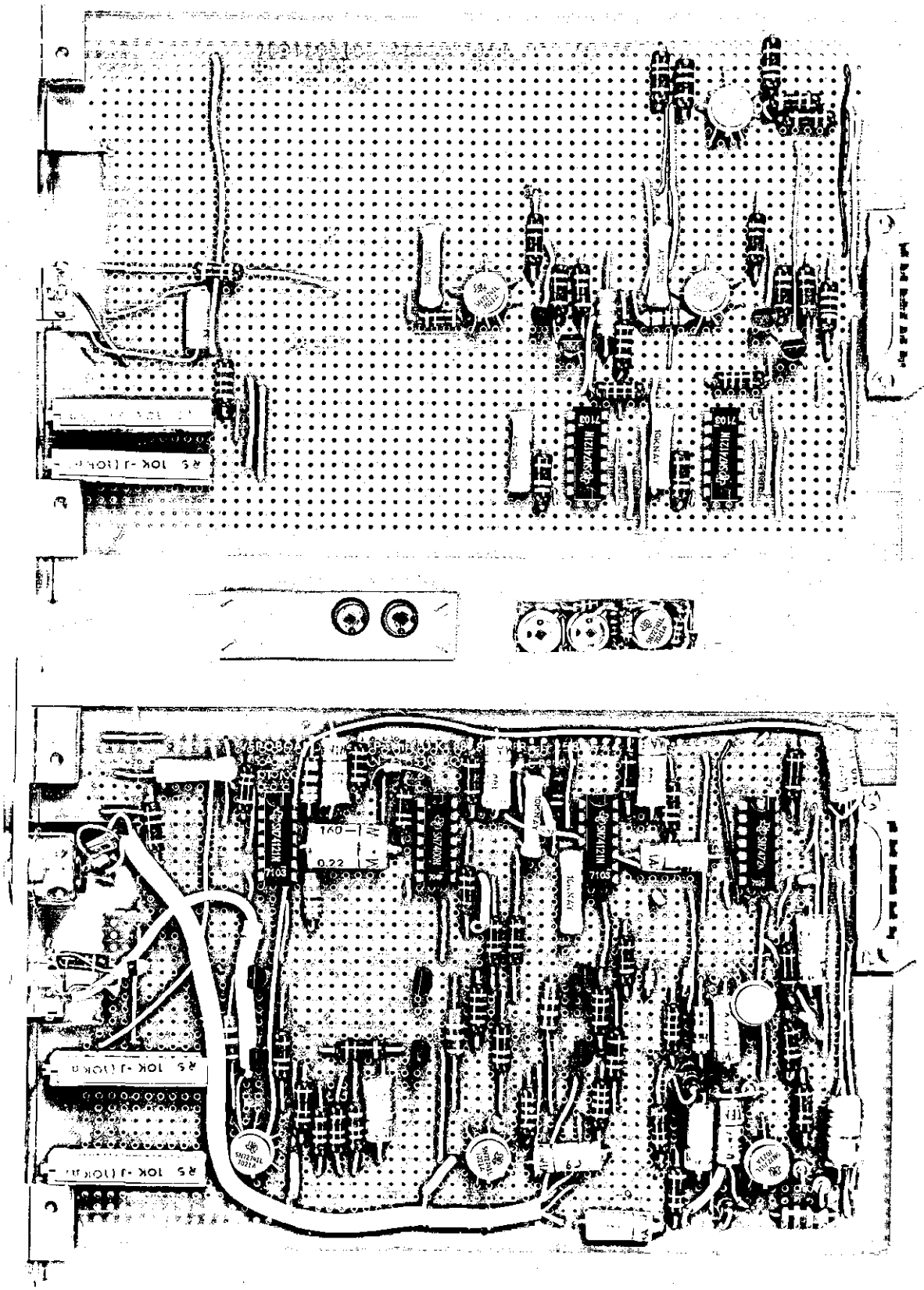
FIG. 3 : CIRCUIT DIAGRAM OF ANGLE ANALOGUE COMPUTER



The physical layout of the circuit boards is shown in the photograph on page 22a, together with a transducer shown with and without its aluminium case.

The design of the transducer required considerable care in order to ensure a minimum of unwanted noise due to mains and radio pick-up and due to extraneous light signals being received at the photo-cells. The latter effect was greatly reduced by use of a pair of photo-cells which were closely matched for sensitivity. The circuit of the transducers is shown in Figure 4. It can be seen that the photo-cells are connected so that their outputs work in opposition to each other. The entrance window of each photo-cell is covered by linearly polarizing filter, with the plane of polarization of the filters being at right angles to each other within the same plane. This design means that any non-polarized light which is incident on the two photo-cells is transmitted in equal amounts to each, and the resulting signals from the two cells thus cancel each other. On the other hand, the polarized beam of light which is incident at the photo-cell is first transmitted to one cell and extinguished at the other, and then vice-versa, as the plane of polarization of the beam rotates. The signals from the two cells are thus complementary and an overall doubling of the signal results at the input of the transducer amplifier.

All of the components in the transducer were of miniature type so that the overall physical dimensions were kept to 5 x 1.5 x .5 cm. and the weight was kept down to 15 gm. It was felt that it was important to keep the size and weight of the transducer down to this level in order to minimize the extent to which they would interfere with the normal movement patterns of the subject.



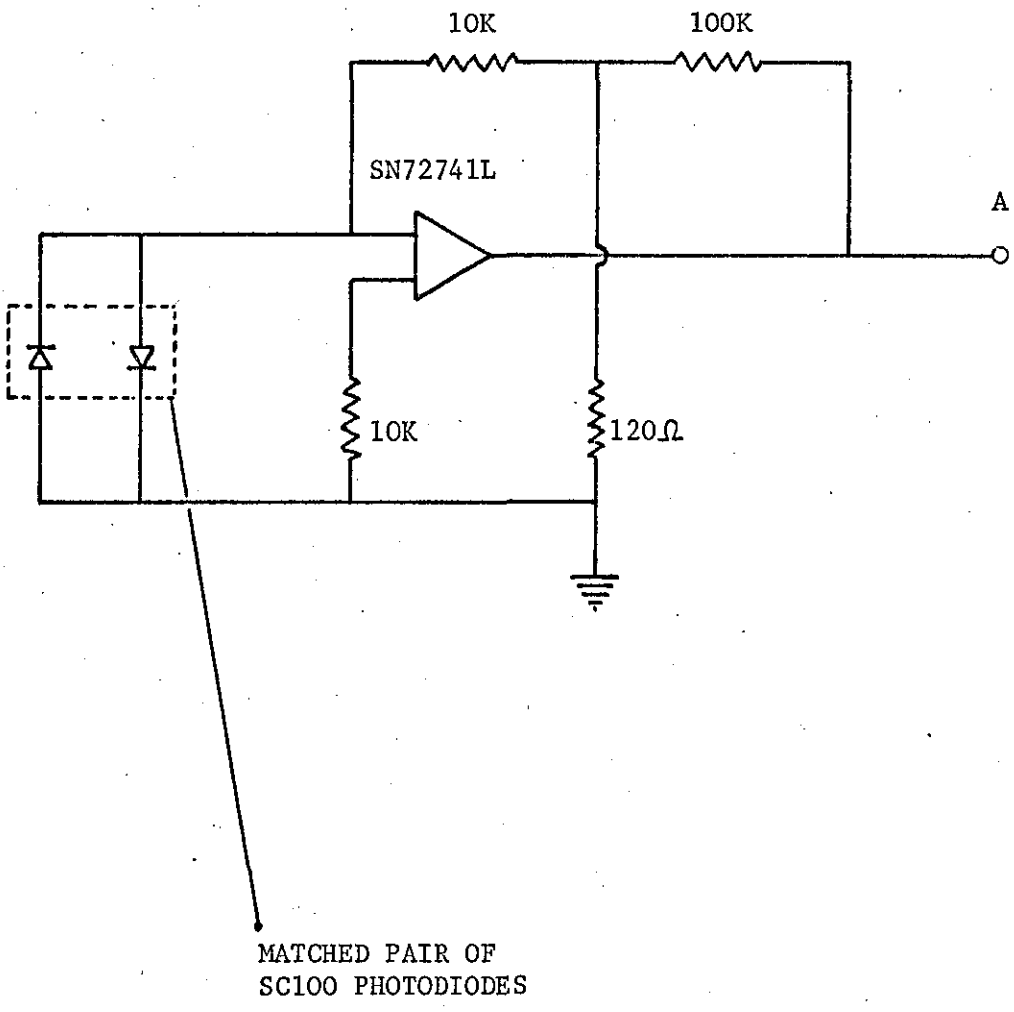
CIRCUIT BOARDS AND TRANSDUCERS:

TOP: ANGULAR VELOCITY BOARD

CENTRE: TRANSDUCERS

BOTTOM: ANGULAR DISPLACEMENT BOARD

FIG. 4 : CIRCUIT DIAGRAM OF ANGLE TRANSDUCER



In order to provide both electrical shielding and mechanical strength, the transducers were contained in light weight aluminium cases, which were electrically connected to signal ground.

The transducers were connected to the main circuitry by means of light-weight, flexible cable, consisting of two conductors and a braided shield. Power was transmitted to the transducer via one of the conductors and the shield. The signal was returned via the second conductor and was referenced to the shield.

2.3.2. Angular Velocity Circuitry

In order to provide on-line output of signals which are proportional to the angular velocity of the transducers, some additional circuitry was designed. Its principle of operation is based on calculating the derivative of a function by the method of finite differences. That is, the signal levels of each consecutive pair of samples of the angular displacement signal are compared. A signal which is proportional to their difference, $d\phi$, is then presented at the output of the angular velocity circuit. If dt is the sampling period, then the angular velocity, $v\phi$, is given by

$$v\phi = \frac{d\phi}{dt}$$

Thus, if $d\phi$ is in degrees, the output of the velocity circuit must be multiplied by a factor $^1/dt$ in order to give $v\phi$ in degrees per second. In practice since the sampling period is determined by the projector disc revolution rate of 150 revolutions per second, then:

$$^1/dt = 150$$

Thus the output of the angular velocity circuit must be amplified by a factor of 150.

Figure 5 shows a block diagram of the angular velocity circuit. The angular displacement signal is split at the input, being fed to a sample and hold element and to a line which by-passes the sample and hold element. A triggering pulse derived from the reference photo-cell of the projector provides the clock pulse for switching logic circuitry, which in turn controls the operating mode of the sample and hold elements. The timing sequence of the mode switching is arranged so that the input signal is sampled at the end of each angular displacement sampling period. The output from the sample and hold element and the unprocessed input signal are fed to an operational amplifier. Since the input signal is inverted by the sample and hold element, the output of the amplifier is proportional to the difference between the real time input signal and the input signal sampled at the end of the previous sampling period. This operational amplifier also provides the gain of 150 which is required to make the angular velocity output voltage equal to the angular displacement output voltage when the angular displacement in degrees, and the angular velocity, in degrees per second, are numerically equal.

The output from the operational amplifier is fed to another sample and hold element which holds the signal at this level for one sampling period. The switching logic circuit updates the sample and hold element in the middle of the angular displacement sampling period. In this way, the velocity output is held constant during the step discontinuity that occurs at the end of each angular displacem ent sampling period. The angular velocity output is thus a 'staircase' signal of the same step width as the angular displacement signal, but lagging it by one sampling period.

The detailed circuit diagram of the velocity circuitry is shown in

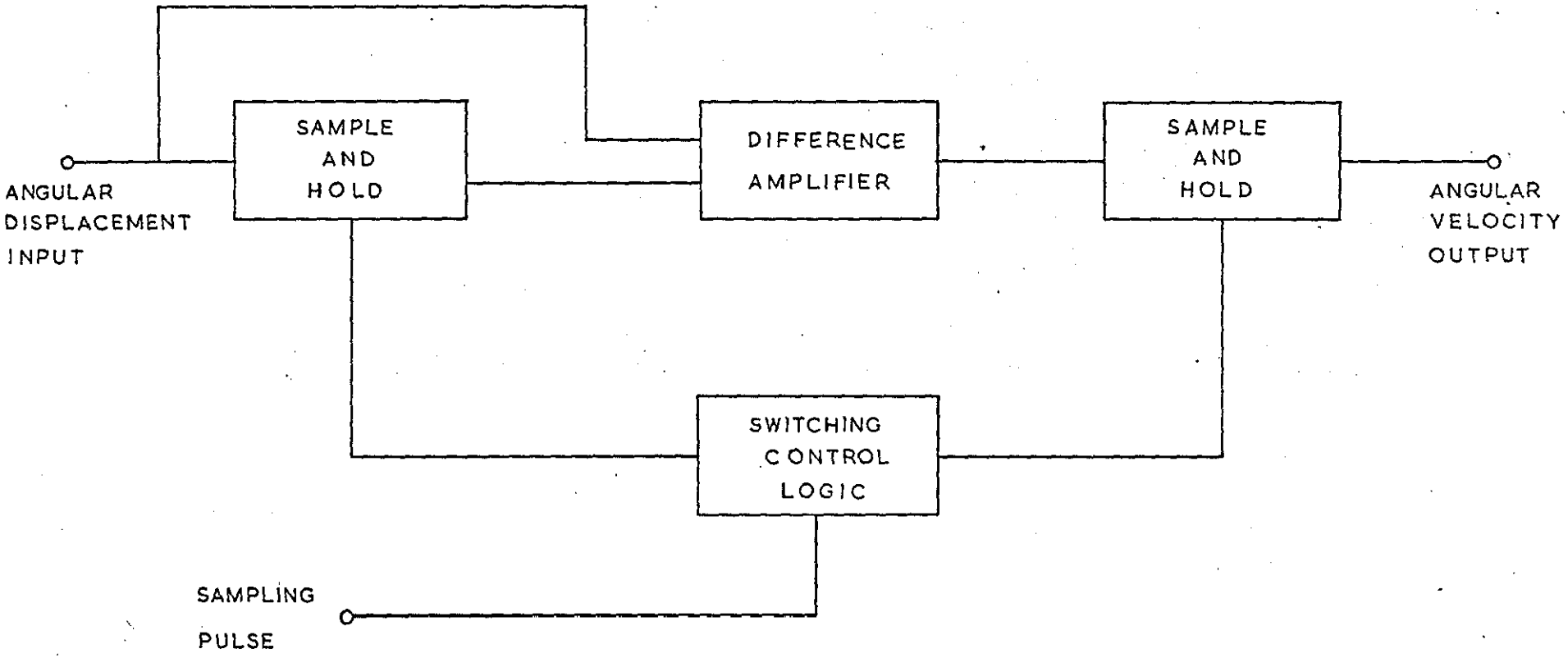


FIG. 5 : BLOCK DIAGRAM OF ANGULAR VELOCITY CIRCUITRY

Fig. 6. It was very important to ensure that the two inputs to the operational amplifier were fed through input resistors of precisely the same value, since any discrepancy would appear as a constant off-set at the output and hence add a constant error to the velocity signal.

It is possible to operate two such angular velocity circuits in series in order to obtain an angular acceleration output. The main difficulty in doing this, however, is that at each stage of differentiation there is a large increase in the noise level of the output signal. The reason for this may be understood if it is supposed that the angular displacement is held at some fixed value. Then both the angular velocity and angular acceleration outputs would be zero. But in each of the velocity circuits there is an overall gain factor of 150. Consequently any noise which is present on the angular displacement output is multiplied by 150 at each stage.

Since the measured noise level at the angular displacement output is in the region of 0.3 degrees, it follows that the noise level at the angular velocity output is equivalent to 45 degrees per second. This high level of noise is unacceptable for most practical applications. Of course, the angular acceleration output would have the absurd noise value of 6750 degrees per second per second.

While the apparatus as it exists produces a noise level at the angular velocity output which is too high, it will be possible to reduce the noise by simple modification of the projector. If the 35 watt projector lamp is replaced by a 300 watt lamp, then the signal to noise ratio would improve in the same proportion. The noise on the angular velocity signal would then be about 4 degrees per second.

Time did not permit this improvement to be carried out during the

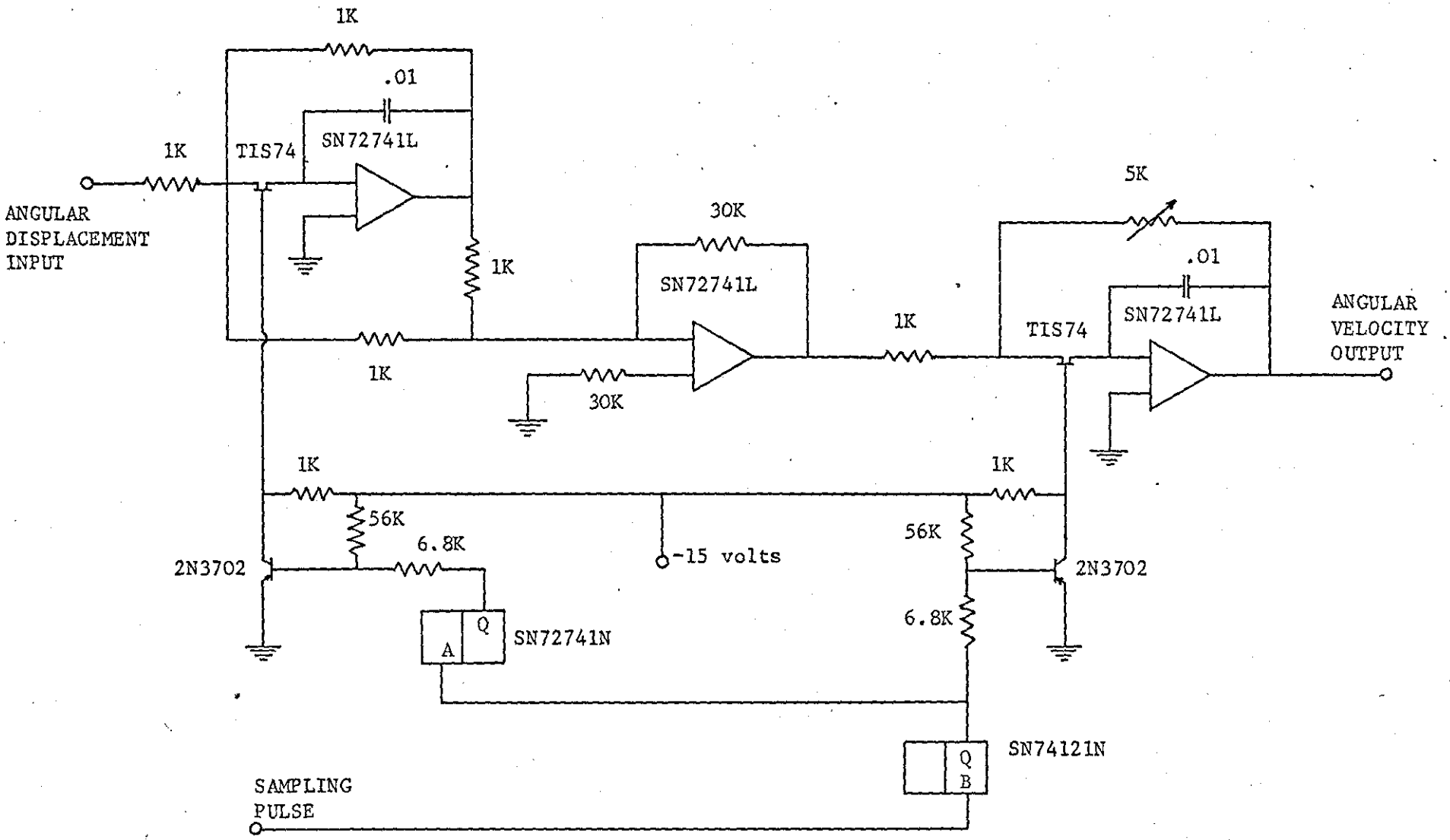


FIG. 6 : ANGULAR VELOCITY CIRCUITRY

course of the present work. Consequently, the experimental applications had to be limited to investigations concerned with angular displacements only.

2.4. Accuracy Analysis and Calibration

The factors affecting the accuracy of this equipment divide themselves naturally into three areas:- noise, electronic linearity, and geometric aberrations.

2.4 1. Noise

The main possible sources of noise appearing at the output of the apparatus are optical noise introduced at the transducer photo-cells, electromagnetic interference from the mains and radio stations, etc.; and mechanical vibration or irregularities in the rate of rotation of the polarizing disc.

The most useful way of assessing the effect of noise on the performance of the apparatus is to calculate the expected noise level for the worst case and also for the expected normal operating condition.

The worst case noise contribution from optical effects will occur when the transducer photo-cells are mismatched in optical sensitivity by the maximum of 10% allowed in their specified performance characteristics, and when the 100 Hz component of the room fluorescent lighting is of amplitude equal to the amplitude of the polarized beam signal. Since the light source in the projector is rated at 35 watts, the latter condition can only occur when the transducer is about equidistant from the 100 watt room lighting and the projector and inclined at about equal angles to both.

Under these conditions the ratio of signal to noise at the output of the transducer would be 10 : 1. The twin T filter in the feedback loop of the first amplifier in the main circuitry then provides a relative attenuation of the unwanted 100 Hz frequencies of 20 : 1, compared to the signal at the tuned frequency of 300 Hz. The worst case signal to noise ratio at the output of the first main amplifier is thus 200 : 1. The way in which this alters the time when the sinusoidal signal crosses zero, and hence the equivalent angular error at the output, may be determined by simple calculation.

If S is the instantaneous level of the signal at time t, then

$$S = K\left(200 \operatorname{Sin} wt + \operatorname{Sin} \frac{w}{3} t\right)$$

where K is some constant gain factor and w is the signal frequency (300 Hz) and w/3 is the noise frequency (100 Hz). The formula assumes that the noise component due to the room fluorescent lights is sinusoidal and of 100 Hz frequency. This has been checked by observing the signal from one photo-cell illuminated only by room lights, and was found to be the case.

The value of S at each zero crossing of the signal is zero, hence

$$200 \operatorname{Sin} wt + \operatorname{Sin} w/3t = 0$$

Making use of the identity,

$$\operatorname{Sin} 3x = 3 \operatorname{Sin} x - 4 \operatorname{Sin}^3 x$$

we have,

$$200\left(3 \operatorname{Sin} \frac{wt}{3} - 4 \operatorname{Sin}^3 \frac{wt}{3}\right) + \operatorname{Sin} \frac{wt}{3} = 0$$

i.e. $$601 \operatorname{Sin} \frac{wt}{3} = 800 \operatorname{Sin}^3 \frac{wt}{3}$$

i.e. $$\operatorname{Sin} \frac{wt}{3} = 0, \quad \text{or} \quad \operatorname{Sin} \frac{wt}{3} = \left(\frac{601}{800}\right)^{\frac{1}{2}}$$

Hence $$wt = 0 \quad \text{or} \quad \pm 180^{\circ}\ 15'$$

In the absence of noise the signal would cross the zero voltage level at increments of π radians, or 180 degrees. So for the above case the maximum error is $\pm$ 15' of arc, or 0.25 degrees.

In practice the level of optical interference is much lower than this since the light from the polarizing projector which is incident at the transducers is normally at least ten times greater in magnitude than the light from the room lights.

The noise contribution due to electromagnetic interference cannot be predicted by calculation and neither can the mechanical noise in the rotation of the disc. However, the combined effect of these two noise sources was judged by placing the transducers very near to the projector and well shielded from other light sources. This reduced optical interference to zero. By feeding the output to an oscilloscope whose time base was triggered by the mains frequency, it was possible to observe the amplitude of the 50 Hz mains frequency interference and also the remaining higher frequency mechanical noise components superimposed. The amplitude of the mains interference was equivalent to 0.08 degrees of arc, and that of the mechanical noise, less than 0.05 degrees of arc.

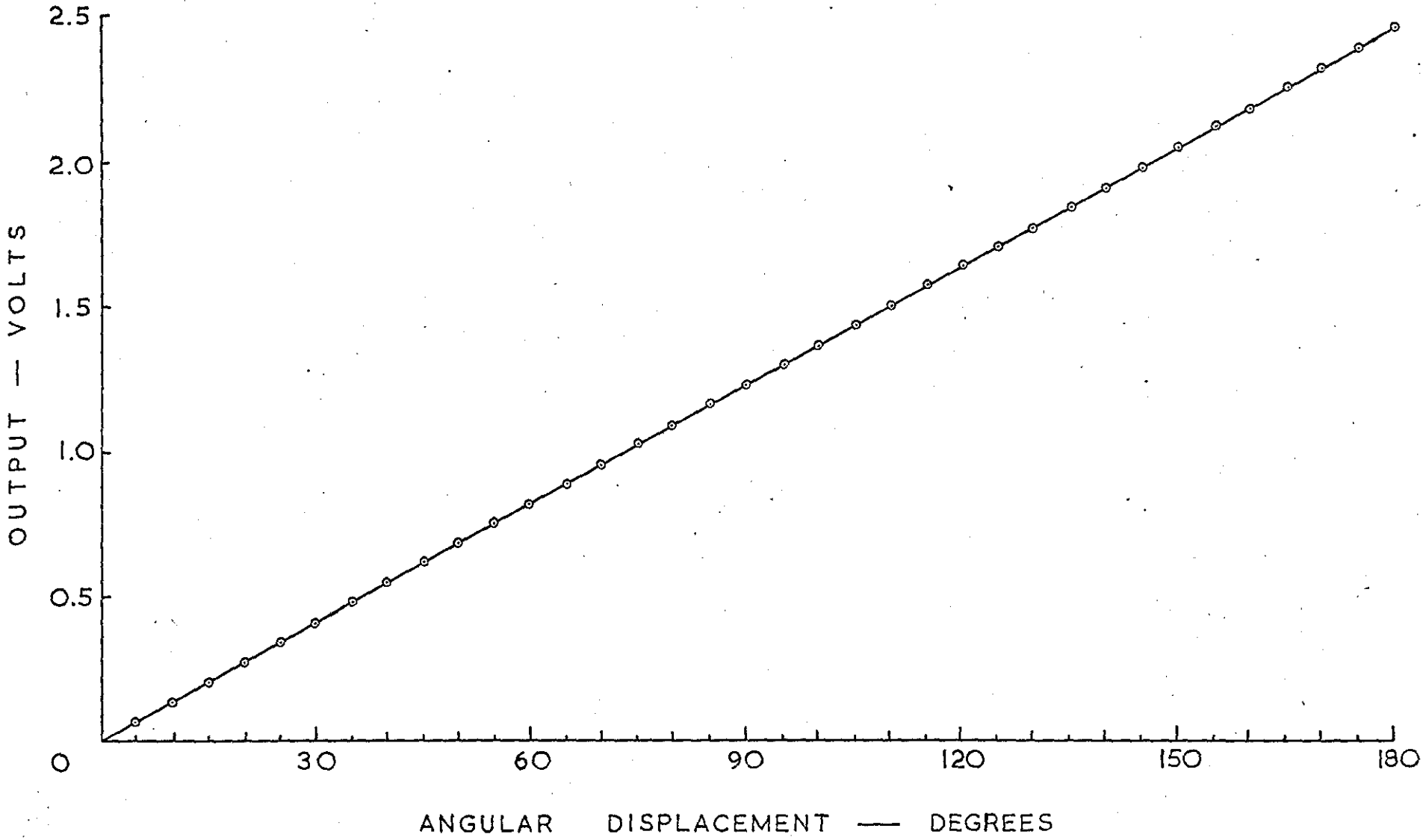
The maximum r.m.s. noise that may be expected is thus given by the square root of the sum of the squares of each noise component, i.e.

r.m.s. noise = 0.27 degrees of arc.

2.4.2. Linearity

The linearity of the output signal as a function of the angular position of the transducer is dependent on the uniform quality of a polarising filter over its total area; on the constancy of the angular velocity of the disc, and on the linearity of the ramping integrator in the main circuitry.

FIG. 7 : LINEARITY PLOT



The polarising filter was inspected optically. This was done by observing the light transmitted through it, and an analysing polaroid filter. Any small variations in the amount of light transmitted could be detected visually as the analysing filter was rotated slowly through the extinction angle. No optical flaws were detected in this way.

The constancy of disc rotation rate was checked by clamping the transducer very close to the projector and recording the output on a U.V. paper chart recorder over a period of one minute every five minutes for half an hour. No observable change in the output levels occurred.

Drift in the ramping integrators resulted in a maximum error of + .05 degrees of arc at the output. An overall linearity plot and calibration was made by attaching the transducer to a circular protractor and recording the output level at each five degree increment in transducer attitude. The resulting plot is shown in Figure 7 . Deviation from linearity was less than 60 seconds over the 180 degree range.

2.4.3. Geometric Factors Affecting Accuracy

For ease of reference in discussing geometrical factors which determine accuracy, the plane in which the polarising filters of the transducer are fixed will be called the primary transducer plane, and a line in that plane which joins the mid-point of each of the two filters will be called the primary transducer axis.

When the primary transducer plane is perpendicular to the line of sight from transducer to projector, then the output will be directly proportional to the angular displacement of the primary transducer axis within the primary transducer plane. If, however, the transducer is turned about any other axis than the line of sight, it is not immediately apparent how this will affect the output signal. In Fig. 8 a momen-

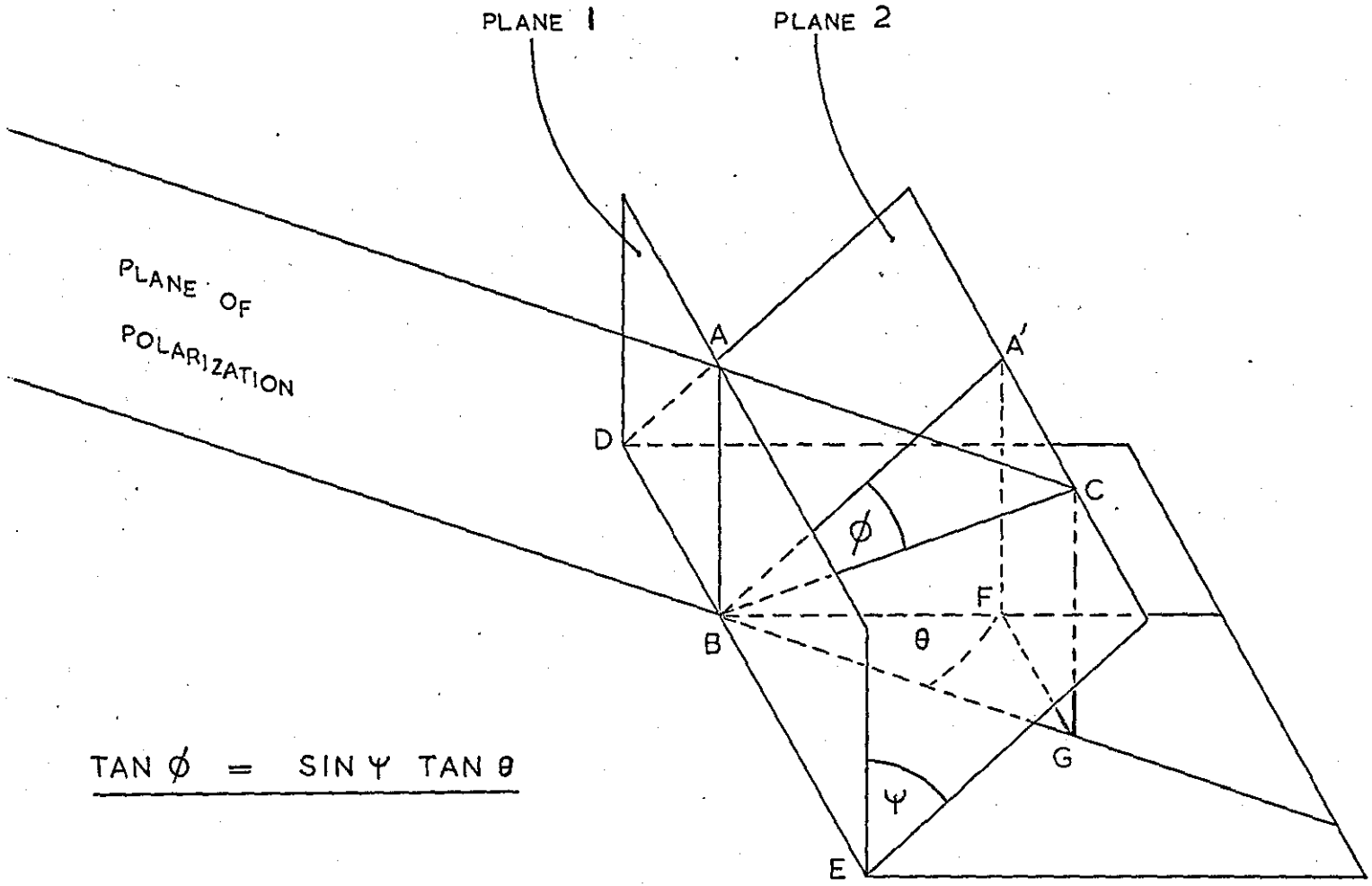


FIG. 8 : DIAGRAM ILLUSTRATING THE ERROR ANGLE ϕ DUE TO THE TWO ROTATIONS OF THE TRANSDUCER Ψ AND θ

tarily frozen projected light beam is indicated with its plane of polarisation vertical. If the line AB is regarded as the primary transducer axis it can be seen that, even if the primary transducer plane is rotated about AB by some angle θ to position indicated as plane 1 in the Figure, then the plane of polarisation still cuts the transducer through the line AB. Consequently, the linearity of the output is unaffected. Similar reasoning holds if the primary transducer plane starts in the position normal to the line of sight and is subsequently rotated about a horizontal axis normal to the plane of polarisation. Again, the linearity of the output is maintained. If, however, a combination of these two rotations takes place, then errors in the output will occur.

Returning to Fig. 8, with the primary transducer plane in the position indicated by plane 1, it is already rotated about axis AB by an angle θ. If, now, it is rotated about axis DE through an angle Ψ to the position indicated as plane 2, then the intersection of the plane of polarisation with the primary transducer plane no longer lies on the primary transducer axis A'B', but is displaced by an angle ϕ to the position of CB. The angle ϕ is thus the angular error at the output resulting from the two axis rotation of the transducer. This is the kind of error which will occur if, for example, the transducer were mounted on the lower arm in order to record angular movements in the sagittal plane, and the subject also made arm movements in a horizontal plane together with pronation-supernation twists of the arm. From Fig. 8 it is easy to calculate ϕ.

$$\text{Tan } \phi = A'C/A'B$$

But $A'C = FG$ (vertical projection)

and $\text{Sin } \Psi = BF/A'B$ and $\tan \theta = FG/BF$

$$\therefore \text{Tan } \phi = \text{Sin } \Psi \tan \theta$$

Thus if $\Psi = 20^{\circ}$ and $\theta = 20^{\circ}$

then $\phi = 7^{\circ}$

This is an error of much greater proportions than any of the other errors in the system. It is therefore most important to ensure that the projector is placed in such a configuration in relation to the movement of the subject that angular displacements of the transducer of either the Ψ or θ type, or both, should be restricted to an amount which keeps the error ϕ within the limits of accuracy required for a particular application.

The graph in Fig. 9 shows a family of curves of the angular displacement error ϕ as a function of θ at discrete values of Ψ. This may be used as an aid to estimate the maximum geometric errors which may occur for any proposed experimental design.

A more rigorous analysis which takes into account the effect of the rotation of the plane of polarisation indicates that additional errors may be attributed to this cause. However, an explicit functional relationship which defines the errors has not yet been found. Consequently the error function must be laboriously determined by numerical methods. A preliminary attempt to do this suggests that the magnitude of these errors will not exceed about 5 degrees for values of θ and Ψ up to 20 degrees.

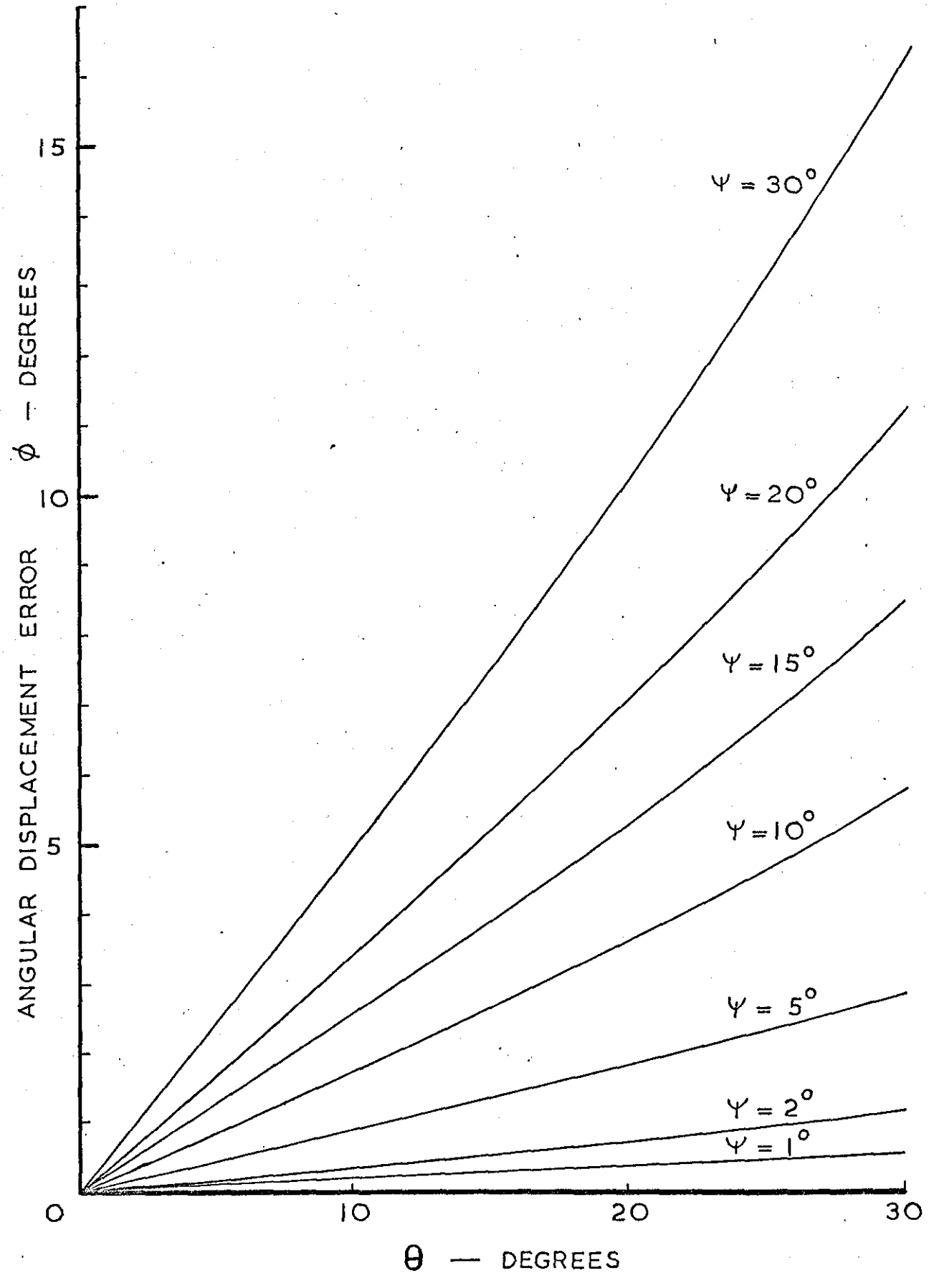


FIG. 9 : ERROR ANGLE ϕ AS A FUNCTION OF θ AT DISCRETE VALUES OF Ψ

3. EXPERIMENTAL APPLICATIONS

The purpose of carrying out the experiment described in the following sections was twofold. First, it was felt that a proper assessment of the apparatus could only be made in a real experimental situation. This is regarded as the most important function of these pilot experiments. The secondary purpose was to begin to study the characteristics of arm and trunk movements of a subject performing simple tasks seated at a work bench. So little is known about the details of the various movement patterns that go to make up a manual skill (other than movement time data of the work-study type) that the approach adopted was simply that of obtaining a descriptive record of some aspects of the movements. These could later be analysed in various ways to discover any significant trends.

3.1. Experiment I

This experiment was concerned with the amplitude of the abduction of the upper arm while lifting various weights from a table top on to a shelf placed above the table.

3.1.1. Procedure

The experimental arrangement is illustrated by Figure 10. The subject was seated at the table with his back to the projector. The seat height was adjusted so that the subject's elbow was between one and three cms. above the table top. The horizontal position of the seat was such that when the subject was holding the experimental weight at the edge of the table, his right upper arm was in a vertical position.

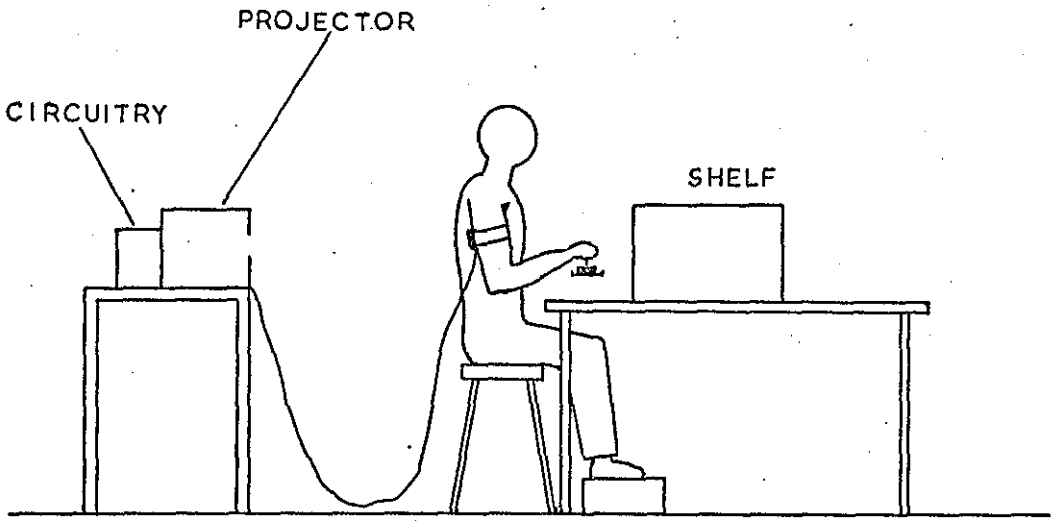


FIG. 10 : EXPERIMENTAL ARRANGEMENT FOR EXPERIMENT NO. I

The shelf was placed a horizontal distance of 30 cms. from the edge of the table, and 30 cms. above the table top. The weights were placed in a specially constructed carrier which was fitted with a handle as shown in Fig. 11. This ensured that the size and shape and handle configuration remained constant for the lighter and heavier weights.

Each experimental run consisted of lifting a particular weight with the right hand from the edge of the table to the shelf thirty times. The movements were performed in time with a metronome which was set to 1 beat per second, one cycle time (from table to shelf and back to table) taking a total of 2 seconds. This was in order to establish uniform times of movement from one subject to another, so that direct comparison of the recordings would be possible.

The weights used were 0; 200 gms., 400 gms., and 1 kgm. Even for the run with no weights, the subject was required to lift the weight carrier in order to preserve the constancy of the geometric configuration of the end points of each movement. The carrier itself weighed only 10 gms.

A photo-cell transducer was attached to the back of the right upper arm of each subject; this was done by buckling a rubber e.c.g. strap around the upper arm, then attaching the transducer to the strap using velcro. Such a method allowed both easy attachment and removal of the transducer. Also it was a simple matter to obtain a rough setting of the angular zero by altering the angular attitude at which the transducer was attached to the strap with the velcro.

The subjects were instructed to lift the weights in a natural manner without feeling constrained to move in any particular way. The runs were done with the 0, 200 gms , 400 gms., and 1 Kgm. weights in

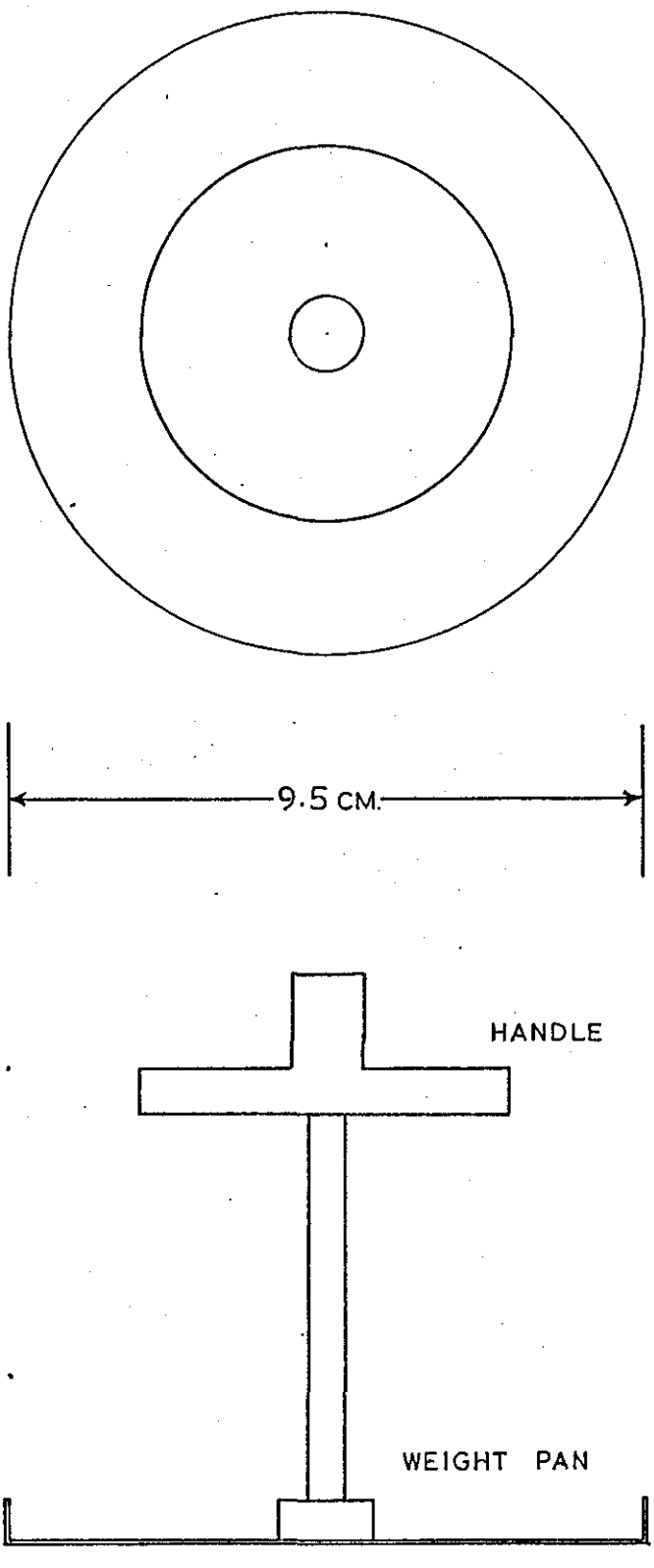


FIG. II : WEIGHT CARRIER : TO SCALE

that order, and with a 3 minute rest period between each run. A total of seven subjects were used. All of them were university students between 20 and 30 years old.

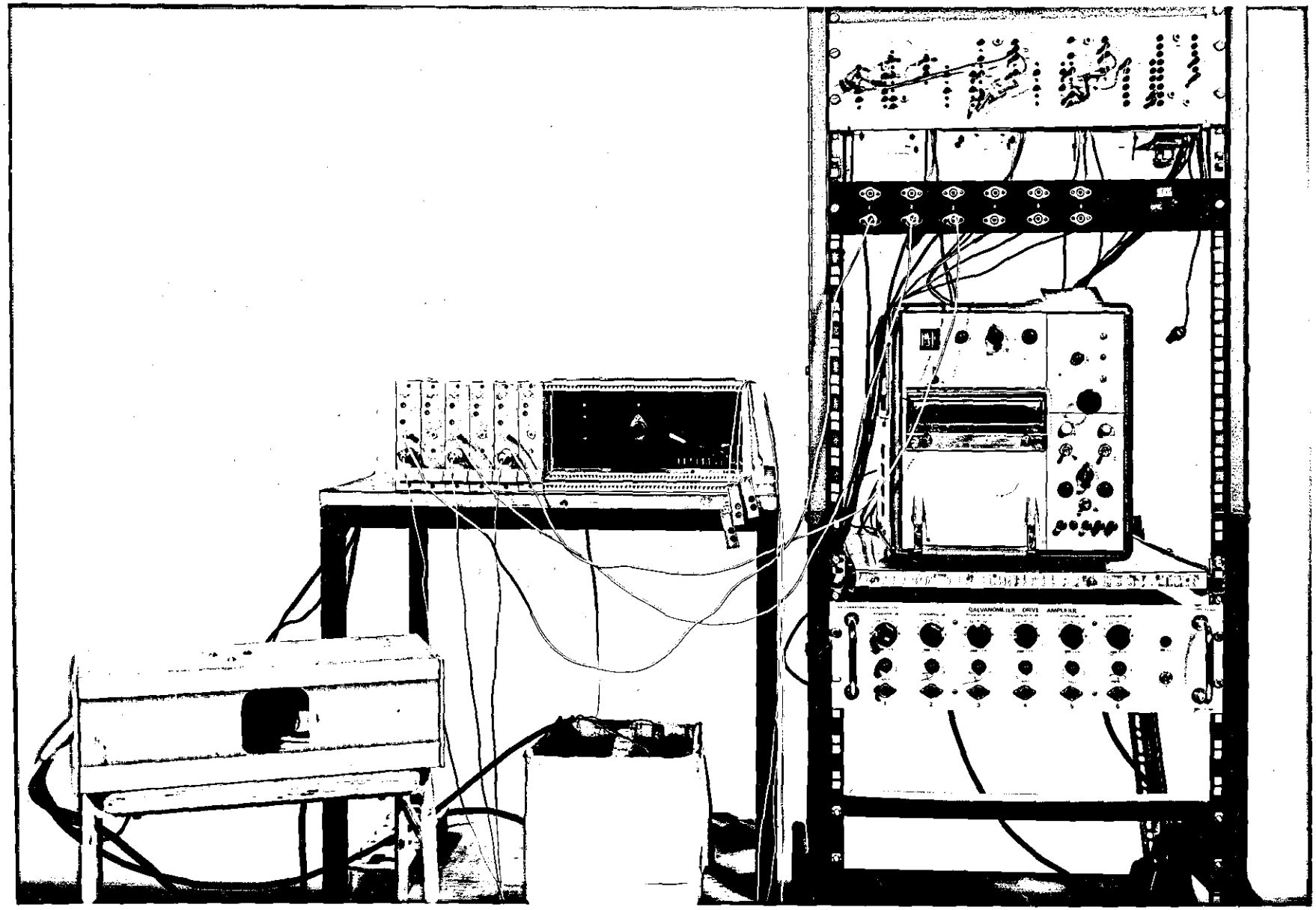
As the subjects made the movements, the amount of upper arm abduction from the vertical starting position was recorded on the U.V. recorder. Since the forward extension of the arm was the only rotation about an axis, orthogonal to the line of sight from the projector, there was little or no geometric error.

The photograph on page 34a shows the experimental apparatus, including projector, circuitry and U.V. recorder.

3.1.2. Results

Fig. 12 shows a sample of the recordings made during the experiment. The parameter which was measured was the amplitude of the upper arm abduction at the 1st, 10th, 20th and 30th lift of each run. These amplitudes are listed for each weight and each subject in Tables 2 to 8. Close examination of these tables shows that the amplitude of abduction bears no consistent relationship either to the weight being lifted, or to the number of times a particular weight was lifted in each run. Table 9 summarizes these results by giving the mean angle of abduction for each run. Again, there appear to be no trends in the results which would allow predictive models to be postulated.

EXPERIMENTAL APPARATUS: PROJECTOR, CIRCUITRY AND U.V. RECORDER



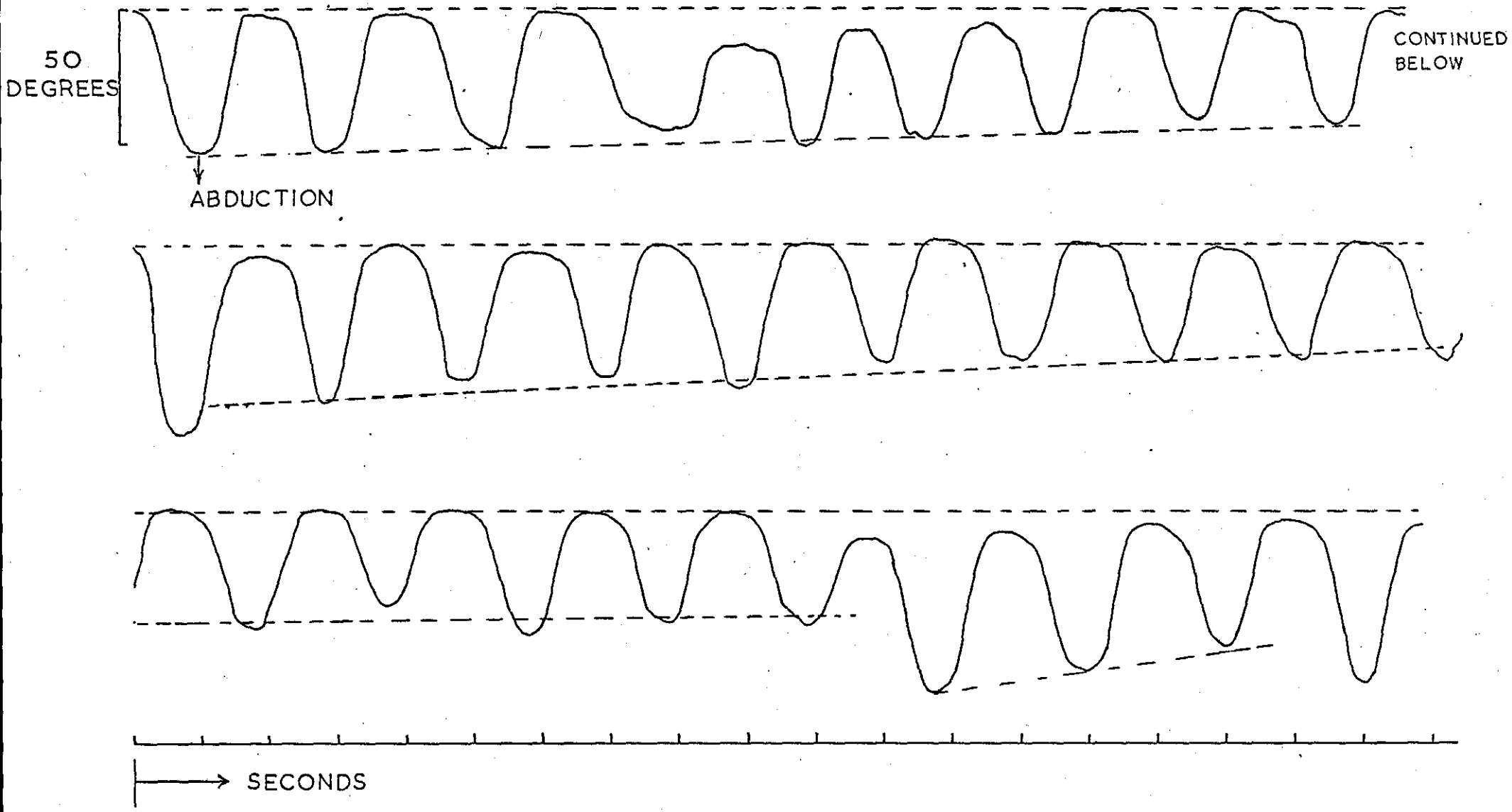


FIG. 12 : RECORDING OF UPPER ARM ABDUCTIONS FOR SUBJECT 7, LOADED WITH NO WEIGHT

TABLE 2

EXPERIMENT I : RESULTS FOR SUBJECT NO. 1.

WEIGHT gm.	LIFT NO.	ANGLES OF ABDUCTION, DEGREES FROM VERTICAL		ANGULAR DISPLACEMENT, DEGREES
		AT START OF LIFT	AT END OF LIFT	
0	1	16	44	28
	10	18	46	28
	20	16	48	32
	30	14	46	32
200	1	*		
	10			
	20			
	30			
400	1	24	48	24
	10	18	49	31
	20	19	49	30
	30	20	50	30
1000	1	22	46	24
	10	20	49	29
	20	15	49	34
	30	13	45	32

* Subject No.1 was used for a pilot experiment in which the 200 gm. weight was not included.

TABLE 3

EXPERIMENT I : RESULTS FOR SUBJECT NO. 2

WEIGHT gm.	LIFT NO.	ANGLES OF ABDUCTION, DEGREES FROM VERTICAL		ANGULAR DISPLACEMENT, DEGREES
		AT START OF LIFT	AT END OF LIFT	
0	1	22	43	21
	10	28	43	15
	20	30	48	18
	30	38	50	12
200	1	14	32	18
	10	18	34	16
	20	16	36	20
	30	20	37	17
400	1	18	33	15
	10	20	36	16
	20	20	37	17
	30	19	39	20
1000	1	18	36	18
	10	19	40	21
	20	18	41	23
	30	14	42	28

TABLE 4

EXPERIMENT I : RESULTS FOR SUBJECT NO. 3

WEIGHT gm.	LIFT NO.	ANGLES OF ABDUCTION DEGREES FROM VERTICAL		ANGULAR DISPLACEMENT, DEGREES
		AT START OF LIFT	AT END OF LIFT	
0	1	5	28	23
	10	2	30	28
	20	0	30	30
	30	0	24	24
200	1	0	29	29
	10	0	25	25
	20	0	30	30
	30	0	33	33
400	1	0	34	34
	10	0	34	34
	20	0	34	34
	30	0	34	34
1000	1	5	30	25
	10	6	36	30
	20	9	40	31
	30	10	41	31

TABLE 5

EXPERIMENT I : RESULTS FOR SUBJECT NO. 4

WEIGHT gm.	LIFT NO.	ANGLES OF ABDUCTION, DEGREES FROM VERTICAL		ANGULAR DISPLACEMENT, DEGREES
		AT START OF LIFT	AT END OF LIFT	
0	1	26	55	29
	10	30	57	27
	20	35	61	26
	30	35	61	25
200	1	17	47	30
	10	35	60	25
	20	35	62	27
	30	36	65	29
400	1	19	52	33
	10	38	64	26
	20	35	65	30
	30	40	66	26
1000	1	44	62	18
	10	44	68	24
	20	44	71	27
	30	44	72	28

TABLE 6

EXPERIMENT I : RESULTS FOR SUBJECT NO. 5

WEIGHT gm.	LIFT NO.	ANGLES OF ABDUCTION, DEGREES FROM VERTICAL		ANGULAR DISPLACEMENT, DEGREES
		AT START OF LIFT	AT END OF LIFT	
0	1	16	52	36
	10	5	51	46
	20	3	49	46
	30	3	50	47
200	1	20	59	39
	10	8	53	45
	20	7	49	42
	30	10	50	40
400	1	13	53	40
	10	10	55	45
	20	9	53	44
	30	9	54	45
1000	1	10	57	47
	10	12	58	42
	20	13	59	43
	30	18	57	39

TABLE 7

EXPERIMENT I : RESULTS FOR SUBJECT NO. 6

WEIGHT gm.	LIFT NO.	ANGLES OF ABDUCTION, DEGREES FROM VERTICAL		ANGULAR DISPLACEMENT, DEGREES
		AT START OF LIFT	AT END OF LIFT	
0	1	16	48	32
	10	14	46	32
	20	20	46	26
	30	21	47	26
200	1	13	46	33
	10	18	48	30
	20	22	50	28
	30	22	50	28
400	1	16	51	35
	10	18	50	30
	20	20	50	30
	30	22	49	27
1000	1	24	49	25
	10	19	49	30
	20	21	49	28
	30	22	49	27

TABLE 8

EXPERIMENT I : RESULTS FOR SUBJECT NO. 7

WEIGHT gm.	LIFT NO.	ANGLES OF ABDUCTION, DEGREES FROM VERTICAL		ANGULAR DISPLACEMENT, DEGREES
		AT START OF LIFT	AT END OF LIFT	
0	1	0	68	68
	10	26	68	42
	20	0	68	68
	30	26	68	42
200	1	0	58	58
	10	17	58	41
	20	22	59	37
	30	22	60	38
400	1	20	62	42
	10	22	64	42
	20	24	66	42
	30	25	68	43
1000	1	9	58	49
	10	10	58	48
	20	11	58	47
	30	12	58	46

TABLE 9

EXPERIMENT I : The body of the table contains the mean angles of upper arm abduction, in degrees, for each experimental condition.

WEIGHT gm.	ARM POSITION **	SUBJECT NUMBER						
		1	2	3	4	5	6	7
0	START	30	16	2	32	7	18	13
	END	46	46	28	59	51	48	68
200	START	17		0	31	11	19	15
	END	35		29	59	53	49	59
400	START	20	20	0	33	10	19	23
	END	36	49	34	63	54	50	65
1000	START	17	17	8	44	13	22	11
	END	40	47	37	68	58	49	58

** START and END refer to the mean angle of abduction of the upper arm at the start and the end of each lift, averaged over all of the lifts made with a particular weight.

3.2. Experiment II

This experiment was designed to study the nature of arm-trunk-head co-ordination when reaching to pick up objects placed on a table. Of particular interest was the question whether the trunk movements occurred because of the geometrical necessity to lean forward to reach an object, or whether there was some degree of trunk movement even when objects were placed well within arm's reach.

3.2.1. Procedure

As in Experiment I the subjects were seated at a table with the elbow between 1 cm. and 3 cms. above the table top. Transducers were mounted on the right upper arm and the head, again using rubber e.c.g. straps to which the transducers were attached with velcro. In order to attach a transducer on the back of the subject it was first necessary to mount a small, rigid cardboard box of dimension 16 cm. x 10 cm. x 10 cm. between the shoulder blades above the cervical spine. This was done by attaching the box to a 5 cm. wide nylon band which was passed over the right shoulder and under the left arm to be fastened together with velcro over the chest. This arrangement provided a mounting surface for the transducer in the sagittal plane through the spine and at a distance from the body such that the line of sight from the projector was not obscured by the shoulder blades. The experimental arrangement is illustrated in Fig. 13, and by the photograph on page 35a.

The subject's task was to pick up some 1 cm. diameter rubber grommets which were placed between 20 cms. and 95 cms. from the edge of the table in increments of 15 cms.

The instructions emphasized that the movement should be made using the right arm as the subject naturally would move when performing an

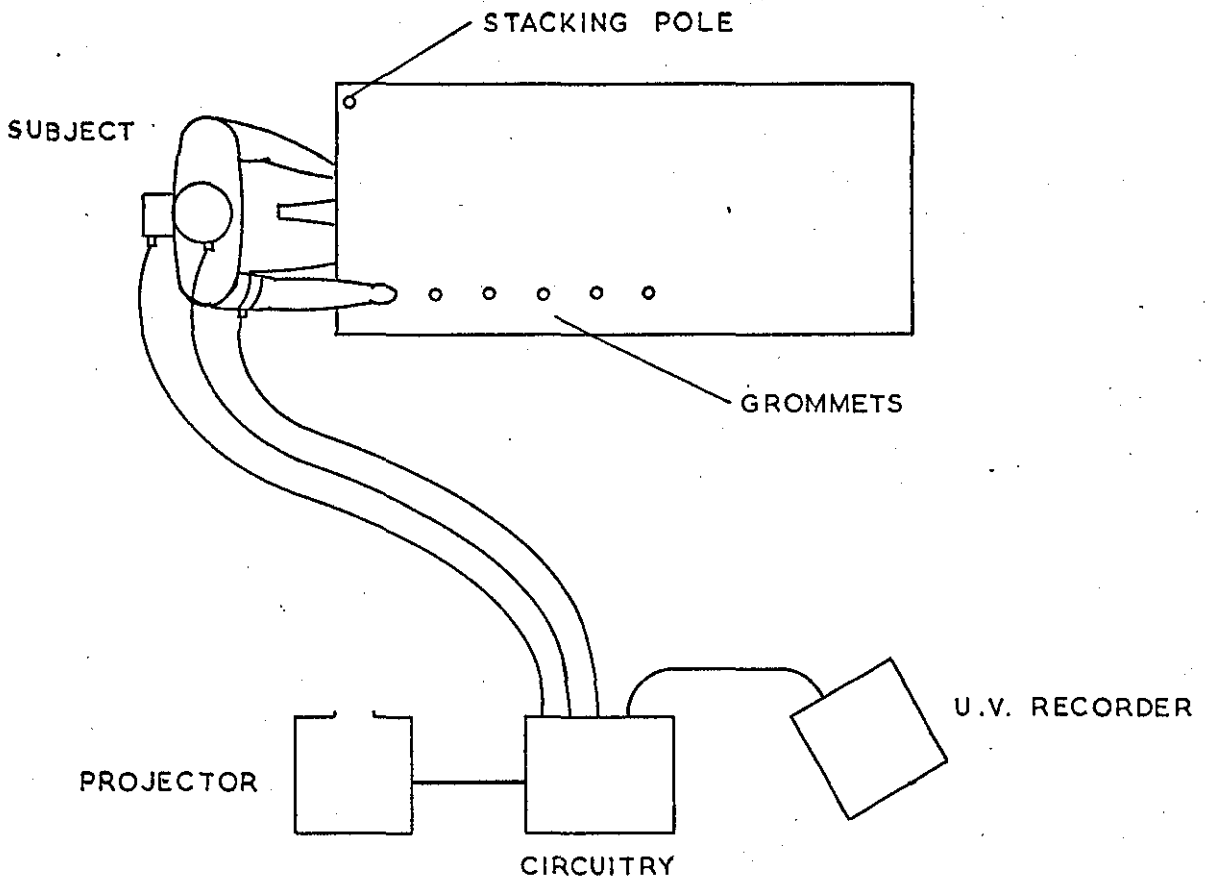


FIG. 13 EXPERIMENTAL ARRANGEMENT



EXPERIMENTAL ARRANGEMENT FOR EXPERIMENT II

SHOWING TRANSDUCERS MOUNTED ON THE SUBJECT

assembly task, for example. Each grommet was picked up in turn and placed at the edge of the table near to the subject. Then the grommet was threaded over a short vertical rod placed on the edge of the table to the left of the subject. This was in order to simulate a simple assembly task and break up any tendency to develop rhythmical forward and backward movements of the hand.

A total of eight subjects were used. Each subject performed two experimental runs, picking up the grommets from the nearest to the farthest, in turn, and two runs starting with the farthest grommets.

At the beginning and end of each run, the subjects were required to take up a reference pose in order to record the angular baselines for the head, trunk and upper arm. This was done with the aid of four reference marks which were made on the subject at the start of the experiment. An axis for the head was defined by marking the position of the centre of the depression in front of the right ear above the tragion, and marking the lowest point of the orbit of the right eye (i.e. Frankfurt horizontal). During the reference pose the subject was required to keep his head in such a position that these two marks fell on a horizontal line. The axis of the upper arm was defined by marking the position of the centre of the lower edge of the acromion process at the shoulder and marking the position of radiale as the arm was in a vertical position at the subject's side. These two marks were kept in a vertical line during the reference pose.

Static anthropometric data were taken using a standard anthropometer. The distance between the two marks on the upper arm was measured, together with the total distance from the underside of the acromion process to the distal end of the first proximal phalanx of the third digit of the right hand. Also the height of the acromion landmark above the table top

during the experimental task was measured as accurately as possible.

3.2.2. Results

The static anthropometric data for each subject are listed in Table 10. It can be seen that the length of the upper arm, as measured from the underside of the acromion process to the radiale, ranged from 310 mm for the smallest subject to 356 mm for the largest. Similarly, the length of the lower arm as measured from the radiale to the distal end of the first proximal phalanx ranged from 336 mm to 420 mm.

It has not been physically convenient to include the U.V. recordings of all the experimental runs, but Figure 14 shows a typical tracing of a run by subject No. 1. A particularly interesting characteristic of all of the recordings which were taken was the linearity of the greater part of the angular excursions of both the upper arm and the trunk. This means that except at the start and finish of each movement the angular velocity at which the movements were executed was virtually constant. All the relevant measurements taken from the recordings are listed in Tables 11 to 18. These include the amplitude of the angular displacement of the head, trunk, and upper arm for each grommet position. Also, the movement times for the arm and trunk and the time lag between the start of each arm movement and the start of the corresponding trunk movement are recorded. The graph in Fig. 15 shows this mean time lag as a percentage of total movement time, plotted against trunk inclination for all eight subjects.

The time at which the movements began was decided by applying a uniform method of measurement to each movement. This entailed first drawing the baseline for the movement tangent to the recorded trace. Since the greater part of each displacement record was linear with time,

it was decided simply to project this line down to the baseline. The point of intersection so formed was taken as the starting point of the movement. While this procedure is somewhat arbitrary, it does provide a consistent means of deciding when each movement begins. In addition, the points arrived at in this way appeared to be the most reasonable starting points for the movements when assessed subjectively.

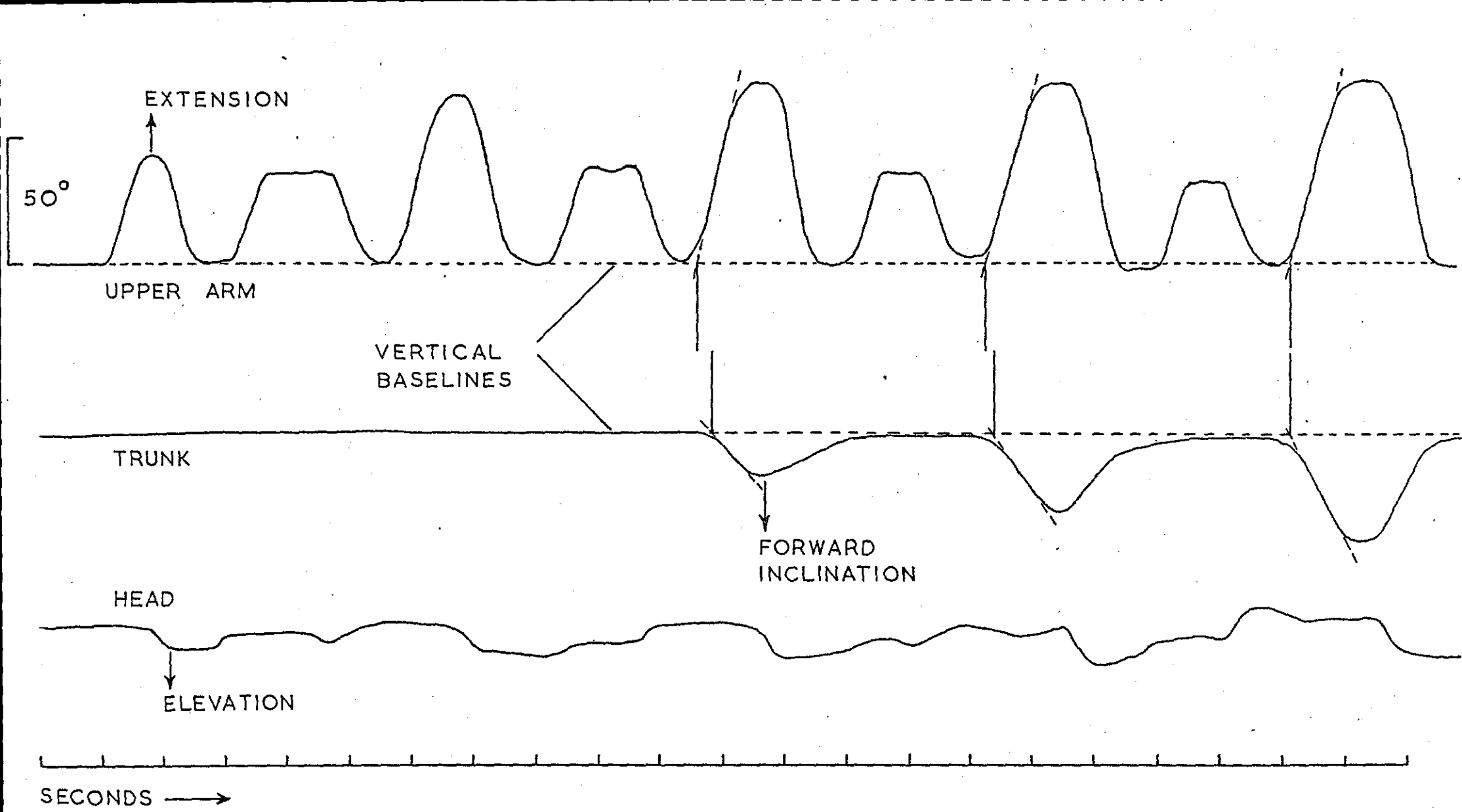


FIG.14 ANGULAR DISPLACEMENT VS. TIME RECORDINGS FOR HEAD, TRUNK AND UPPER ARM

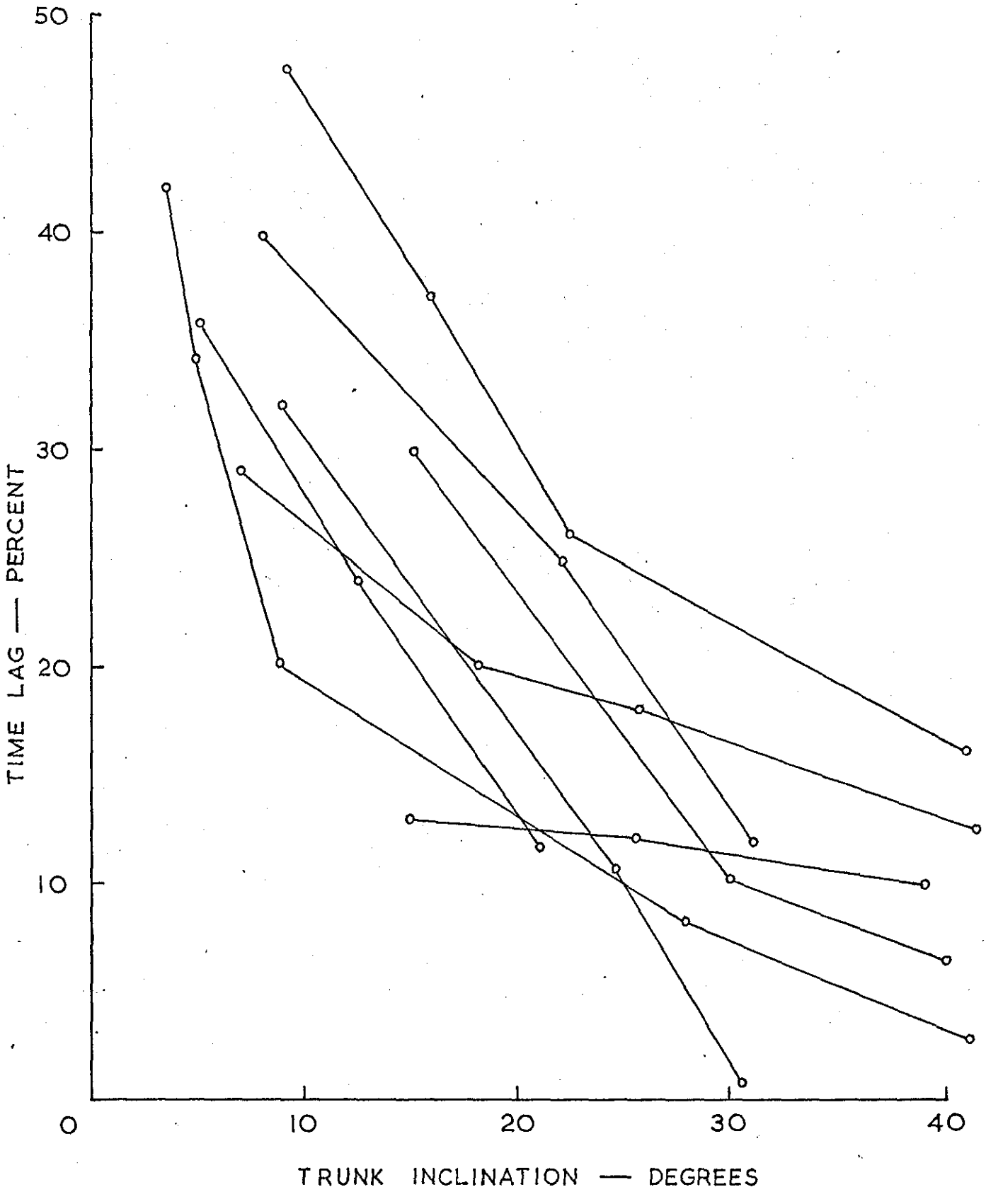


FIG. 15 Percentage of total movement time by which the initiation of trunk movement lags the initiation of arm movement plotted against trunk inclination, for eight subjects.

TABLE 10

EXPERIMENT II : ANTHROPOMETRIC DATA

SUBJECT NUMBER	ANTHROPOMETRIC MEASUREMENTS IN m.m.*		
	A	B	C
1	340	420	380
2	336	393	311
3	351	407	380
4	342	398	325
5	335	370	275
6	334	386	320
7	310	336	285
8	318	351	271

* NOTES:

A = Distance from the underside of the acromion process to the radiale at the elbow.

B = Distance from the radiale to the distal end of the first proximal phalanx of the third digit of the right hand.

C = Height of the underside of the acromion process to the top of the table.

TABLE 11

EXPERIMENT II : RESULTS FOR SUBJECT NO. 1

GROMMET DISTANCE[1] cm.	DISPLACEMENT FROM VERTICAL - DEGREES		HEAD ELEVATION[2] DEGREES	MOVEMENT TIME SECONDS		
	UPPER ARM	TRUNK		TOTAL	LAG[3]	% LAG[4]
20	24	0	7	.48		
35	45	0	8	.76		
50	70	0	12	1.03		
65	75	15	16	1.05	.32	30.0
80	75	30	17	1.12	.14	12.5
95	76	40	18	1.20	.08	6.5

NOTES:

1 Grommet Distance from edge of table.

2. Amplitude of head elevation from resting posture. For this subject the attitude of the head in resting posture was 42 degrees below horizontal.

3 Time lag between start of arm movement and start of trunk movement.

4 Time lag as a percentage of total movement time.

TABLE 12

EXPERIMENT II : RESULTS FOR SUBJECT NO. 2

GROMMET DISTANCE[1] cm.	DISPLACEMENT FROM VERTICAL - DEGREES		HEAD ELEVATION[2] DEGREES	MOVEMENT TIME SECONDS		
	UPPER ARM	TRUNK		TOTAL	LAG[3]	% LAG[4]
20	32	0	5	.70		
35	43	5	7	.75	.20	26.7
50	45	15	10	.75	.10	13.3
65	53	26	8	.82	.10	12.2
80	60	39	9	1.00	.10	10.0

NOTES:

1. Grommet distance from edge of table
2. Amplitude of head elevation from resting posture. For this subject the attitude of the head in resting posture was 31 degrees below horizontal.
3. Time lag between start of arm movement and start of trunk movement.
4. Time lag as a percentage of total movement time.

TABLE 13

EXPERIMENT II : RESULTS FOR SUBJECT NO. 3

GROMMET DISTANCE[1] cm.	DISPLACEMENT FROM VERTICAL - DEGREES		HEAD ELEVATION[2]	MOVEMENT TIME SECONDS		
	UPPER ARM	TRUNK	DEGREES	TOTAL	LAG[3]	% LAG[4]
20	23	0	6	.52		
35	42	0	9	.65		
50	54	3	13	.70	.40	57.2
65	65	16	16	.80	.30	37.5
80	68	22	16	1.15	.30	26.5
95	70	41	18	1.15	.18	15.7

NOTES:

1. Grommet distance from edge of table
2. Amplitude of head elevation from resting posture. For this subject the attitude of the head in resting posture was 18 degrees below horizontal.
3. Time lag between start of arm movement and start of trunk movement.
4. Time lag as a percentage of total movement time.

TABLE 14

EXPERIMENT II : RESULTS FOR SUBJECT NO. 4

GROMMET DISTANCE [1] cm.	DISPLACEMENT FROM VERTICAL - DEGREES		HEAD ELEVATION [2]	MOVEMENT TIME SECONDS		
	UPPER ARM	TRUNK	DEGREES	TOTAL	LAG [3]	% LAG [4]
20	22	0	9	.63		
35	38	0	11	.68		
50	47	5	16	.70	.25	35.7
65	60	12	14	.80	.20	25.0
80	64	21	18	1.10	.15	13.7

NOTES:

1. Grommet distance from edge of table
2. Amplitude of head elevation from resting posture. For this subject the attitude of the head in resting posture was 24 degrees below horizontal.
3. Time lag between start of arm movement and start of trunk movement.
4. Time lag as a percentage of total movement time.

TABLE 15

EXPERIMENT II : RESULTS FOR SUBJECT NO. 5

GROMMET [1] DISTANCE CM.	DISPLACEMENT FROM VERTICAL – DEGREES		HEAD [2] ELEVATION	MOVEMENT TIME SECONDS		
	UPPER ARM	TRUNK	DEGREES	TOTAL	LAG [3]	% LAG [4]
20	31	0	6	.8		
35	53	0	11	.8		
50	55	8	31	1.0	.40	40.0
65	55	22	31	1.0	.25	25.0
80	65	31	31	1.0	.12	12.0

NOTES:

1. Grommet distance from edge of table.
2. Amplitude of head elevation from resting posture. For this subject the attitude of the head in resting posture was 22 degrees below horizontal
3. Time lag between start of arm movement and start of trunk movement.
4. Time lag as a percentage of total movement time

TABLE 16

EXPERIMENT II : RESULTS FOR SUBJECT NO. 6

GROMMET DISTANCE [1] cm.	DISPLACEMENT FROM VERTICAL - DEGREES		HEAD ELEVATION [2]	MOVEMENT TIME SECONDS		
	UPPER ARM	TRUNK	DEGREES	TOTAL	LAG [3]	% LAG [4]
20	16	3	19	.72	.32	44.5
35	36	5	20	.93	.30	32.3
50	46	9	16	1.00	.20	20.0
65	55	28	14	1.00	.08	8.0
80	60	48	16	1.75	.00	0.0

NOTES:

1. Grommet distance from edge of table.
2. Amplitude of head elevation from resting posture. For this subject the attitude of the head in resting posture was 35 degrees below horizontal.
3. Time lag between start of arm movement and start of trunk movement.
4. Time lag as a percentage of total movement time.

TABLE 17

EXPERIMENT II : RESULTS FOR SUBJECT NO. 7

GROMMET[1] DISTANCE cm.	DISPLACEMENT FROM VERTICAL - DEGREES		HEAD[2] ELEVATION	MOVEMENT TIME SECONDS		
	UPPER ARM	TRUNK	DEGREES	TOTAL	LAG[3]	% LAG[4]
20	34	0	9	.81		
35	55	0	10	.85		
50	60	7	9	1.00	.29	29.0
65	61	18	8	1.05	.21	20.0
80	65	26	10	1.35	.25	18.5
90	63	48	14	1.65	.21	12.7

NOTES:

1. Grommet distance from edge of table.
2. Amplitude of head elevation from resting posture. For this subject the attitude of the head in resting posture was 18 degrees below horizontal.
3. Time lag between start of arm movement and start of trunk movement.
4. Time lag as a percentage of total movement time.

TABLE 18

EXPERIMENT II : RESULTS FOR SUBJECT NO. 8

GROMMET DISTANCE [1] cm.	DISPLACEMENT FROM VERTICAL - DEGREES		HEAD ELEVATION [2]	MOVEMENT TIME SECONDS		
	UPPER ARM	TRUNK	DEGREES	TOTAL	LAG [3]	% LAG [4]
20	30	0	7	.75		
35	48	0	10	.82		
50	50	9	30	.85	.27	31.8
65	55	25	31	1.10	.11	10.0
80	61	31	31	1.10	.00	0.0

NOTES:

1. Grommet distance from edge of table.
2. Amplitude of head elevation from resting posture. For this subject the attitude of the head in resting posture was 21 degrees below horizontal.
3. Time lag between start of arm movement and start of trunk movement.
4. Time lag as a percentage of total movement time.

4. DISCUSSION

The work covered by this thesis divides itself naturally into two areas for purposes of discussion. These are the experimental applications and the instrumentation which has been developed and used for the experimental work.

4.1. Experimental Applications

4.1.1. Experiment I

It appears from an examination of the results listed in Tables 2 to 9 that there is no clear relationship between the amplitude of upper arm abduction and the weight lifted. Nor do any trends emerge which may be related to fatigue or learning factors. The amplitude of arm abduction of individual subjects exhibited variations of a seemingly 'random' type. That is the deviations from the mean angle of abduction were scattered evenly between the start and finish of a run of 30 lifts. Four of the subjects showed a more interesting effect. They began some of their runs with large angles of abduction for each lift and then progressively decreased the amplitude over about 8 to 12 lifts. At this point, they suddenly reverted to the large abduction and again progressively reduced it over the next few lifts. This process was repeated between two and three times during some of the runs of the subjects concerned. Fig. 12 shows a sample recording for subject No. 1 which illustrates this effect.

The results of this experiment highlight one of the main problems which is likely to be encountered in measuring movement characteristics. This is the difficulty of finding the appropriate conceptual models to describe the observed phenomena. In this particular case the lack of any obvious trends in the results not only makes it impossible to build a predictive model for arm abduction. It creates difficulty in deciding

what new questions to ask and therefore how best to design future experiments.

The only hypothesis which seems reasonable is to suggest that within certain wide limits the upper arm abduction represents a degree of freedom of arm movements in excess of the number of degrees of freedom required in order to make the lifting movements. This would then imply that the amount of abduction can vary according to the preferences of the subject. Future questions would then revolve around what factors determine these preferences. It may be that changing the amount of abduction from one lift to another helps to spread the muscular load and hence reduce the rate at which fatigue occurs. Or it may be that since fine control of abduction is not required in performing the task, the muscular control system simply allows more or less random processes to take over in this respect. It is possible that the subjects who exhibited apparent random changes in arm abduction are best described in this way and the subjects who showed progressive changes in abduction did so in order to spread the muscular load.

An experiment which includes e.m.g. recordings of all the major muscle groups of the upper arm and shoulder, together with recordings of the movement may help to resolve some of these questions.

4.1.2. Experiment II

The results of this experiment showed much more definite trends than did the previous one. The graphs of Figure 15 show an inverse relationship between the amplitude of trunk inclination and the time lag between initiation of the arm and the trunk movements. The amplitudes of the arm and trunk movements are also much more consistent from one subject to another. The reason for this is almost certainly that the geometry

of the arm and trunk positions when picking up a grommet from a particular position is fairly uniquely determined by the grommet position. In other words, it is a geometric necessity for the subject to move to a particular limb-trunk configuration. The way in which the head moves is less well determined. Although all of the subjects elevated the head by a few degrees during the reaching movement, the timing and overall shape of the amplitude-time recordings varied considerably from one subject to another. As with the upper arm abduction in Experiment I, it may be supposed that this is due to the availability of an extra degree of freedom over and above what is the minimum necessary. This would arise from the ability to alter the attitude of the eyes independently of the attitude of the head.

While the geometric configuration of the arm and trunk at the point where the grommet is picked up may be an absolute constraint, the time pattern of the movements leading up to this configuration are not obviously constrained to follow any particular path. The question then arises as to why is there a fairly consistent relationship between time lag and amplitude of trunk inclination. The most plausible hypothesis for this phenomenon comes from concepts of movement time based on an information processing model.

It seems reasonable to assume that the subjects do not start to lean forward with the trunk until they perceive that this is necessary in order to reach the object to be grasped. From this it follows that a subjective perceptual criterion of some kind is employed in order to determine whether it is necessary to lean forward. The simplest form which such a criterion may take is suggested by the theories of psychophysical scaling such as that due to Weber in which a just noticeable change, ds, in some physical quantity is related to the absolute value, s,

of the quantity by the relation

$$ds/s = \text{a constant}$$

This formulation may provide a basis for the perceptual criterion being sought. For if θ is the minimum amount of trunk inclination which is needed in order to reach the desired point on the table surface, and Ψ_m is the maximum amount of angular extension of the upper arm consistent with keeping the hand in contact with the table at the desired point, then we may write:-

$$\frac{\theta}{a\Psi_m - \Psi_c} = \text{criterion, K} \quad \ldots \quad (1)$$

Where a is a constant and Ψ_c is some intermediate value of the upper arm extension at the point where the subject perceives that he will be unable to reach the desired position by arm extension alone. The time it takes from the initiation of the arm movement to reach the criterion point may be calculated quite readily if it is assumed that the value of Ψ for upper arm extension increases at a constant angular velocity $V\Psi$. Although this is not the case at the very start of the movement, an analysis of the recordings shows that the rate of increase is fairly constant after the first tenth of the total excursion Ψ_m.

The time t_c taken to reach the criterion point may thus be given by

$$t_c = \Psi_{c/V\Psi}$$

Also the total time t_T for the movement will be

$$t_T = \Psi_{m/V\Psi}$$

Therefore time to reach criterion as a percentage T of the total movement time is

$$T = \frac{t_c}{t_T} \times 100 = \frac{\Psi_c}{\Psi_m} \times 100 \quad \ldots \quad (2)$$

But from (1), $\psi_c = a\psi_m - \theta/K$

Hence $T = (a - \theta/K\,\psi_m)\ 100$ . . . . (3)

If we make one further assumption, that the time to reach criterion is equivalent to the time lag between the initiation of arm and trunk movements, then the above formula (3) for T is a fair mathematical description of the dependence of the time lag on the amplitude of trunk inclination.

4.2. Discussion of the Instrumentation

Perhaps the best way of assessing the overall performance of the instrumentation is to compare its performance characteristics with the ideal list of requirements listed in Section 2.1.

a) The instrumentation fully meets the requirement for producing on-line recordings. Since the primary outputs are voltage levels, the particular form of the permanent record is open to choice. It may be, as used in these experiments, a U.V. chart recorder or a pen recorder. In some cases it may be convenient to record the outputs on multi-channel analogue magnetic tape. This could then be used to drive an off-line graph plotting device.

b) The recordings are not continuous in time but are the result of repetitive sampling of the angular position ofthe transducer. So although the equipment does not completely fulfil this requirement the sampling rate of 150 per second was found to be quite adequate for recording the movements which were studied. It would be relatively easy to modify the design of the projector so that the

disc revolution rate was increased by a factor of 3 or 4 in order to resolve more rapid movements to the required level of accuracy.

c) The output signals could be used directly to drive a visual display of the angular parameters on a cathode ray tube. For purposes of computational analysis the signals may be fed directly to a digital computer, provided that the computer has an analogue to digital convertor at its input.

d) The upper limit of the bandwidth of the instrumentation is set by the revolution rate of the polaroid disc in the projector. Consequently, frequencies up to half the disc revolution rate can be resolved. The frequency response is flat up to one fifth of the disc revolution rate, that is up to 30 Hz. This would seem to be adequate for most movement studies. Again, if higher bandwidth is needed, the disc revolution rate can be increased.

e) The apparatus is only capable of measuring angular displacement and velocity. Techniques of a different type will be needed for recording linear movements. The instrumentation used for the present work, however, does meet the requirement for making recordings from many limb segments simultaneously. While only three transducers were built for this project, there is no practical limit to the total number that may be employed.

The angular velocity and acceleration outputs were of little or no value due to the noise content of the signals. As indicated in Section 2.3.2., this problem may be substantially overcome in the case of the angular velocity outputs by using a 300 watt projector lamp. Even with this modification it would not be possible to obtain usable acceleration outputs.

f) The small size and light weight of the transducers leave the subjects relatively free from physical encumbrance when making movements. The only limitation on movements is imposed by the lightweight cables which connect the transducers to the main circuitry. This limitation may only become a problem when movements involving complete rotations of the whole body are studied, as for example, in measuring movements made in some areas of athletics.

g) Although the instrumentation is not easily portable in its present prototype form, it could readily be fitted into three metal cases: one for the projector, one for the main circuitry, and one for the power supplies. If recordings were made on a portable analogue tape recorder, then the apparatus could be quite conveniently transported by two people.

One problem which came to light as a result of the experimental applications was that of the interaction of the signal noise and the geometric errors. In order to keep the signal noise below the equivalent of 0.3 degrees of arc, it was necessary to place the projector at a distance of about 2 metres from the subject. This meant that during the movements in Experiment II the transducer on the upper arm followed a path which subtended an angle of about 20 degrees at the projector. That is, the transducer deviated from perpendicularity from the line of sight to the projector by up to 20 degrees. Since the angular deviation of this transducer from the vertical was up to 10 degrees, the total error at the output was 5 degrees (from the graph in Fig. 9). Once again, a more powerful light source will allow the distance from the subject to the projector to be increased, and hence the geometric error to be decreased.

Despite some of the limitations mentioned here, the opto-electronic apparatus proved to be easy to use in practice. Furthermore, the results which it yielded in the experimental applications have shown that it is a very useful research tool. The relationship between trunk inclination and time lag between arm and trunk movements is an effect which would not have been observed easily by any other technique. It would appear that there is great scope for the application of this technique in many areas of study concerned with human movement.

4.3. Suggestions for further work

As already mentioned, the substitution of the 35 watt projector lamp by a more powerful one will significantly improve the signal-to-noise ratio of the apparatus. This will make possible the use of the angular velocity circuitry, and will enable the distance from subject to projector to be increased, thus reducing the geometric errors.

It may prove feasible to use gallium arsenide electro-luminescent diodes as light sources in the projector. In this case the Ga As diodes could be pulsed at high frequency. The amplifier in the transducer might then be tuned to this frequency in order to obtain much better rejection of the unwanted low frequency noise components. The use of Ga As diodes would also make it possible to use two projectors mounted at right angles to each other with their light sources being pulsed alternately. The signals received by the transducers could then be multiplexed into two channels corresponding to angular movement about the two projector axes. It should also be possible to apply cross correction factors between the data from the two channels in order to correct for the geometric errors.

It may prove possible to build an opto-electronic system which provides outputs proportional to the cartesian co-ordinates of given landmarks on the limbs. Small Ga As diodes could be used as the landmarks, and a suitable infra-red camera could provide output voltages proportional to the landmark co-ordinates. The author proposes to investigate the feasibility of such a system in detail at a future date. If it proves possible to build this type of apparatus, then it could be used in conjunction with the apparatus described in this thesis in order to provide a complete three dimensional movement analysis capability.

The outputs from both the linear and angular measuring instruments could be recorded on analogue magnetic tape, and the recordings subsequently converted to digital form. They may then be fed to a digital computer so that important parameters of the movement under study could be computed automatically and then presented in some convenient graphical or tabular form.

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