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A FEASIBILITY STUDY
OF
LIMB VOLUME MEASURING SYSTEMS

by

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PREFACE

This study was initiated by the Cardiovascular Laboratory, NASA Lyndon B. Johnson Space Center, Houston, Texas, under Contract NAS 9-12749. The work was performed by the Wenner-Gren Research Laboratory, The University of Kentucky. Dr. G. W. Hoffler of the Cardiovascular Laboratory, NASA Lyndon B. Johnson Space Center served as technical monitor.

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I. INTRODUCTION

Cardiovascular deconditioning, as evidenced by diminished orthostatic tolerance, is the most consistently observed and most profound of the effects induced by a zero gravity environment upon the human cardiovascular system. The study and evaluation of cardiovascular deconditioning by lower body negative pressure (LBNP) experiments during space flight impose unique requirements on the limb volume measuring system (LVMS) used. The LVMS must operate in both earth gravity and zero gravity in the presence of dirt, saltwater, high humidity, variable temperature and variable pressure. The size and operation of the LVMS must be compatible with those of the LBNP tank. Acceptable operation of the LVMS permits a maximum error of 0.3% of the volume change. Methods of measurement which meet the above requirements must also be evaluated on the basis of:

1. Sensitivity
2. Accuracy
3. Interaction with Subject
4. Simplicity of Operation
5. Size
6. Calibration requirements
7. Range and adjustability
8. Cost
9. Operational availability

The purpose of this feasibility study is to:

1. Evaluate current and potential methods for measuring limb volume

2. Perform indepth studies of those methods which show promise of meeting the functional requirements within the operational restrictions of the LBNP experiments.

3. Design, fabricate, test and analyze the LVMS system(s) which shows the highest probability of success.

II. CURRENT METHODS OF PLETHYSMOGRAPHY

Plethysmography originated in the mid-seventeenth century with the work of Francis Glisson and Jan Swammerdam [14]. Modern plethysmography, however, is considered to have originated with the work of Hewlett and Van Zwaluwenburg [14] which was concerned with blood flow rates determined from volume changes in animal and human organs. The use of plethysmography to measure blood flow and volume changes in the extremities of the human body is now common practice. Although plethysmographic techniques are used for a variety of applications, this report is restricted to those techniques applicable to lower limb volume measurements. These techniques may be divided into three basic types: photo-electric, fluid displacement and electrical.

A. Photo-Electric Plethysmographs

The photo-electric plethysmograph detects changes in the transparency and reflectivity of a body region as a function of blood flow [8, 14]. While transparency and reflectivity measurements are made on smaller appendages, such as ear lobes and fingers, only reflectivity measurements are applicable to the limbs.

Present systems contain the light source and photo detector side-by side in a small unit. These are commercially available and are designed to be clipped to a small segment (finger tip, etc.) or attached with elastic straps or adhesives directly over a major artery. While this technique is less susceptible to muscle movement than others, it is difficult to extrapolate the discreet measurements to reflect total volume of the limb. The basic technique may, however, be used in a system more applicable to the requirements of a LVMS.

B. Fluid Displacement Plethysmographs

Basically, this technique employs a rigid compartment which encloses the organ or limb under investigation. The compartment is sealed such that it becomes air-or-water-tight, except for passage to the measuring or monitoring device. An increase in the volume of the limb or organ should thus displace an exactly equal volume of water or air (at constant temperature and pressure). The displaced fluid can then be measured and related directly to the volume change of the organ.

Since fluid displacement plethysmographs measure directly the volume change and because they are simpler than other types, they are generally considered the most reliable for quantitative measurements of changes in limb volume [4]. This type of plethysmograph, however, does have basic deficiences, the most prominent of which are (1) temperature change of the mediums must be taken into account and (2) a fluid seal must be maintained. If the chamber is sealed to the limb, the seal must not compress or stretch the tissue; if the seal is in the form of a sleeve which encloses the limb, it also must neither compress the tissue nor restrain any volume increase in the limb.

Early versions of the displacement plethysmograph [4, 6, 7, 17] utilized mechanical means of detecting volume displacement while modern systems provide improved reliability and convenience through the use of electrical transducers [2, 10, 15, 19, 23].

The open water plethysmograph [26] shown in Fig. 1 is representative of modern displacement systems. This plethysmograph has two chambers which are completely independent. Rubber sleeves are used for

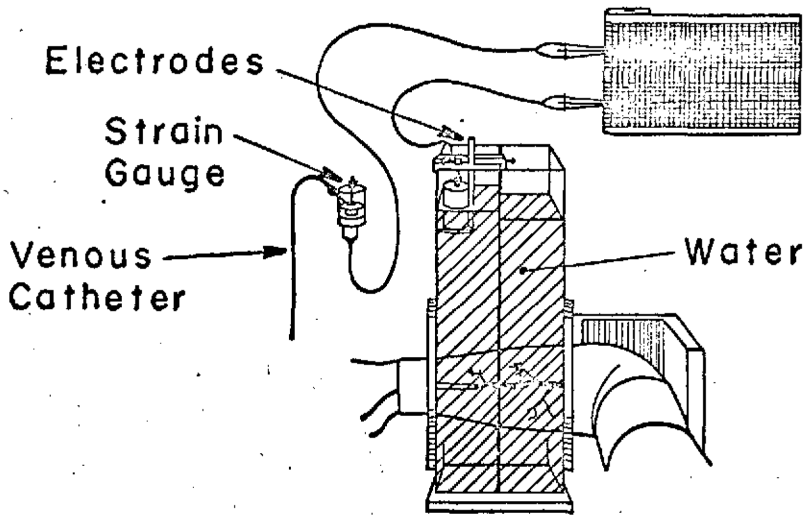


Fig. 1 TWO-COMPARTMENT, FREE SURFACE PLETHYSMOGRAPH

sealing and skin contact. Volume change is measured in the distal chamber while the proximal chamber is used to prevent venous congestion. Venous pressure is measured with a small catheter inserted into a forearm vein. This system gives an accurate pressure-volume curve from which local venous volume at local venous pressure can be accurately predicted.

The simple and direct measurement provided by the fluid-displacement plethysmograph has consistently been more reliable than that provided by alternate systems. However, it still has problems of immobility, bulkiness and, in the gas systems, the problems of compressibility and high thermal expansion of the gas must be considered. In all displacement plethysmographs, sealing against leakage is a problem. While these problems exist, care and compromise have allowed extensive application of this type of system.

C. Electrical Plethysmographs

The most commonly used electrical device is the Whitney gauge [24] which measures the circumference of the limb by the change in resistance of a mercury thread. The mercury is contained in a small bore, thick wall rubber tube. Electrical contact with the mercury is maintained by tapered copper pins which close the ends of the tube. This assembly provides a flexible, highly extensible strain gauge which, when used as one arm of a Wheatstone bridge, is very sensitive to small changes in length.

Since bench calibration is not necessarily applicable to the same gauge mounted on a limb, absolute measurements of limb circumference are questionable; however, relative changes can be measured with a high degree of sensitivity and repeatability. Temperature compensation is required to obtain maximum repeatability. According to Whitney this gauge is as accurate as the air and water plethysmographs. The possible outgassing of mercury at reduced ambient pressure in a closed environment poses a distinct hazard, however.

A more recent electrical plethysmographic technique is the electrical impedance method in which low-level current is applied in the radio frequency range to the body segment through electrodes placed on either side or around the segment. Electronic instrumentation of impedance plethysmography is usually designed to measure changes in the resistive component of impedance occurring with volume change [21]. Such measurements provide a useful qualitative index of volume changes. Quantitative information concerning volume changes is based on a knowledge of the specific resistivity, segment length and the measured resistive impedance. These attempts, while encouraging, have failed to establish the quantitative reliability of the technique [4]. Major problems inherent with electrical impedance plethysmography include inadequate calibration, electrode instability and inconstancy of specific resistivity [9].

A third electrical approach to limb volume measurement is offered by the electro-capacitance technique which utilizes the variation of capacitance with the orientation of the plates. While several investigators have reported various configurations [3, 5, 12, 13, 25] of the capacitance plethysmograph, the system reported by Mannex and Gowen [20] appears to offer the most reliable operation. This capacitance transducer consists of a circumferential semi-rigid band as one plate of a capacitor separated from the other plate (the skin) by a layer of polyurethane foam. With changes in leg volume, the skin to band distance is altered and the resultant change in capacitance is detected at the demodulator located on the band. Appropriate shielding techniques are utilized to reduce proximity and fringing effects. The transducer contains a series of volume calibration plates for relating the output change to leg volume changes.

The Mannex-Gowen system avoids some of the problems of the "standard" Whitney gauge, however, sensitivity to changes in pressure, temperature and humidity present operational complications.

Of all the current methods of plethysmography considered, only the capacitance gauge is directly applicable to the LBNP experiments; however, the photo-electric, fluid displacement and strain gauge methods offer various advantages which warrant their consideration.

III. COMPARISON AND EVALUATION OF POTENTIAL PLETHYSMOGRAPHIC TECHNIQUES

The relative change in volume of a body segment can be readily detected in a great variety of ways. The requirements of sensitivity and accuracy, plus the special requirements of LBNP experiments, immediately eliminate many of these techniques from consideration. The techniques considered in this report include new concepts as well as modification of current methods that offer particular advantages such as simplicity or accuracy. The capacitance gauge is not considered in this evaluation since it has previously undergone extensive development and analysis for use with LBNP experiemnts [20]. The methods considered may be grouped in four categories as follows:

1. Fluid Displacement
   a. Water displacement
2. Pneumatic
   a. Pneumatic capacitance (Fluidic)
3. Optical
   a. Moving Image
   b. Contourometric
   c. Reflective Scanner
4. Electromechanical
   a. Radial Displacement Transducer (LVDT)
   b. Odometric (Rolling contact)

A. Fluid Displacement

The system considered consists of a water-filled closed chamber (hermetically sealed) which fits around the limb and is separated from the limb by a silastic rubber envelope. The chamber is in two parts (Fig. 2) and hinged to facilitate mounting. Although this concept showed promise of providing accurate and sensitive measurements under laboratory

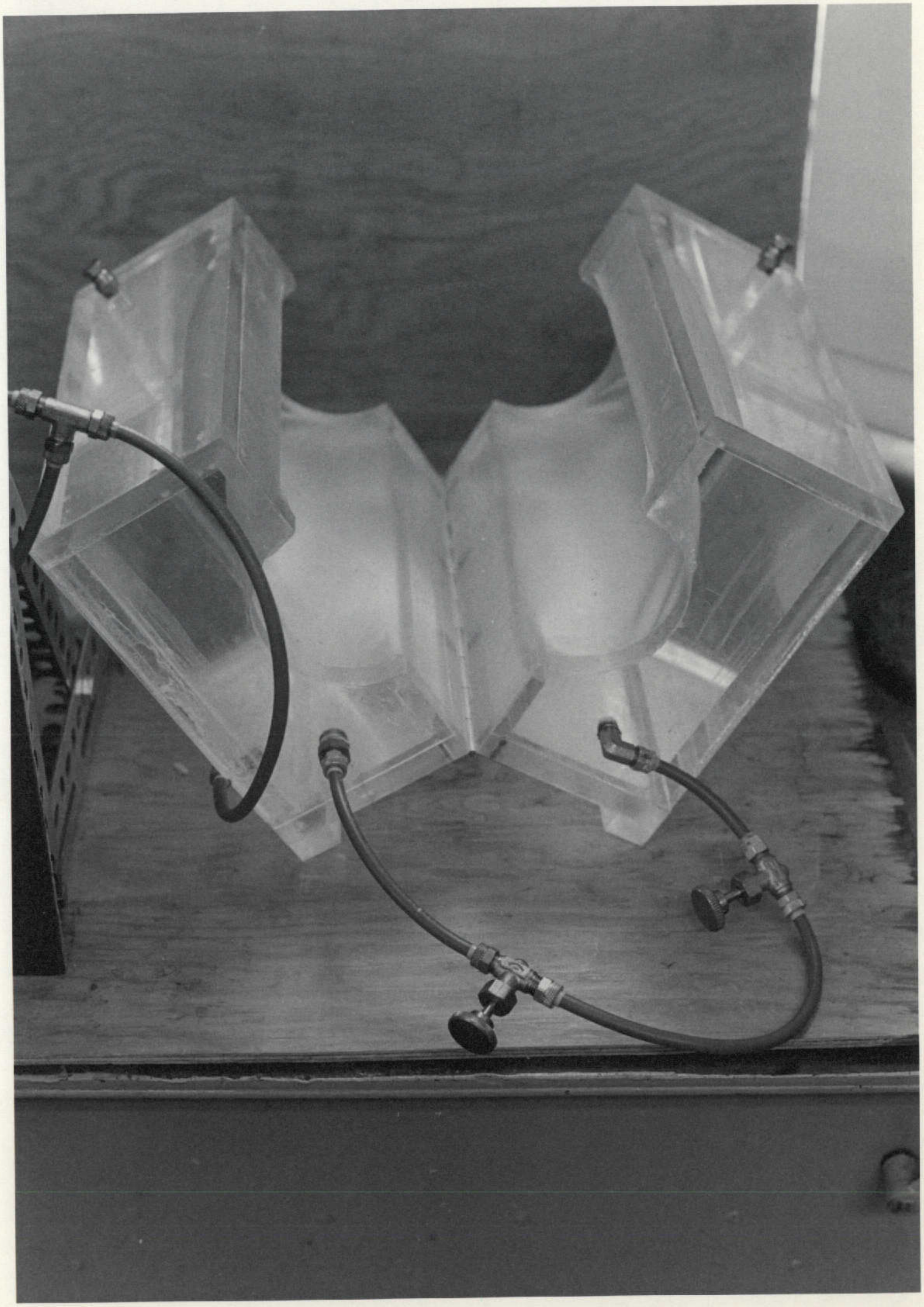


Fig. 2 HERMETICALLY SEALED, LIQUID DISPLACEMENT PLETHYSMOGRAPH

conditions, sealing problems coupled with limited adjustability and gravity dependent hydraulic forces discouraged further development.

B. Pneumatic

1. Pneumatic Capacitance

In this method the limb is surrounded by a rigid enclosure. The annular gap (chamber) bounded by the limb and the rigid enclosure can be used as a tunable capacitor in a fluidic oscillator circuit. The volume of the annular gap, which will change directly with the leg volume, can be related to the frequency of oscillation of a properly contrived fluidic circuit. This system, illustrated schematically in Fig. 3, consists of a Schmitt trigger, an OR/NOR gate and the pneumatic capacitor.

When air flows from supply pressure P_s, the output of the Schmitt Trigger which leads to the input of the OR/NOR gate is active. This causes the output of the OR/NOR gate to switch to the right which allows the capacitor to charge. When the pressure P_s of the capacitor exceeds the bias pressure of the Schmitt Trigger, the output of the Schmitt Trigger switches. Consequently, the output of the OR/NOR gate switches, allowing the capacitor to discharge. When the capacitor pressure drops below the bias pressure, the outputs switch back. Thus, the system oscillates and its frequency depends on the volume of the capacitor. As the capacitance decreases (increasing volume of limb) the time constant decreases resulting in a faster rise time and consequently a higher frequency.

The analysis of the system operation is based on the electrical analog of Fig. 4. The equations describing the charging and discharging are

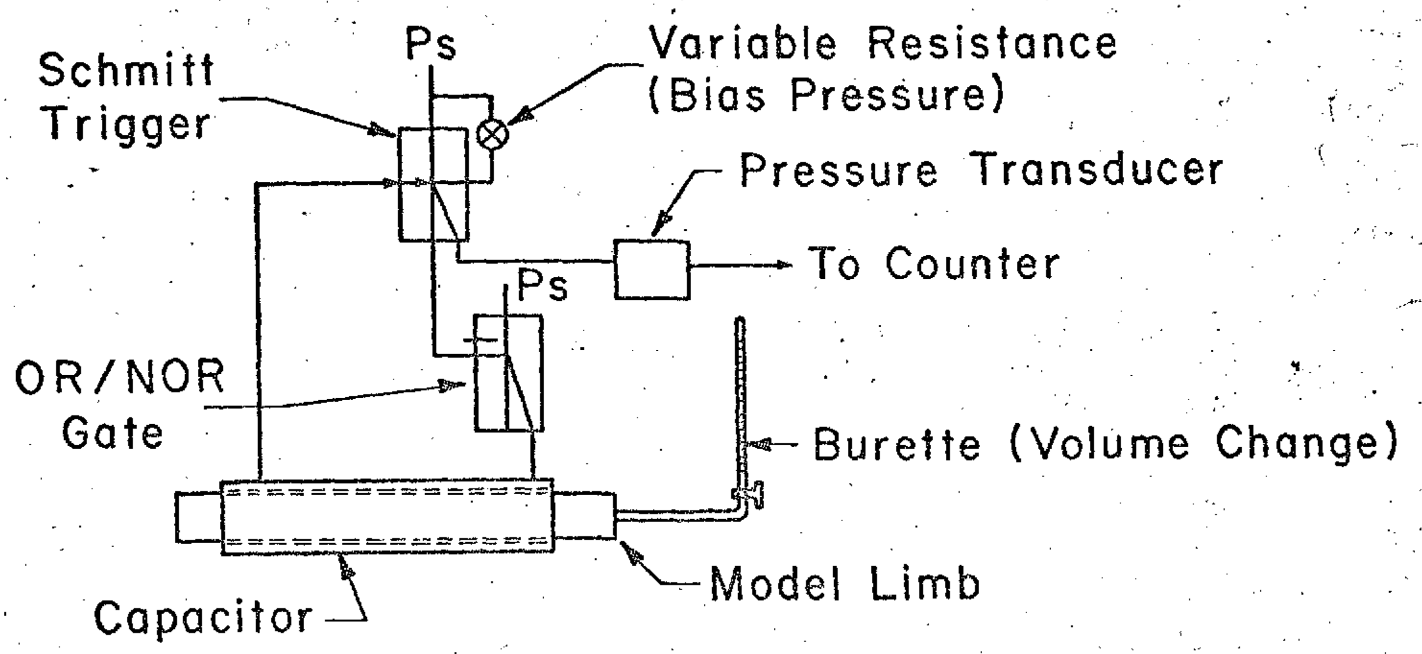


Fig. 3 Fluidic Circuit, Pneumatic Capacitance Plethysmograph

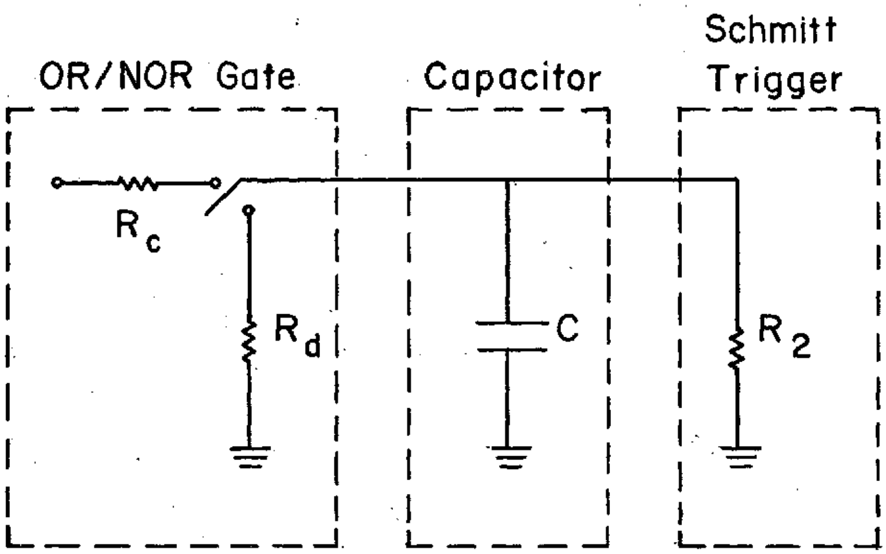


Fig. 4 ELECTRICAL ANALOG OF PNEUMATIC CAPACITOR SYSTEM

$$\frac{R_c R_2}{R_c + R_2} \quad C \dot{P}_c + P_c = \frac{R_2 P_e}{R_c + R_2} \tag{1}$$

and

$$\frac{R_d R_2}{R_d + R_2} \quad C \dot{P}_c + P_c = 0 \tag{2}$$

respectively. The pressure is gauge pressure so that the initial conditions for (1) and (2) are $P_c\ (0) = 0$ and $P_c\ (0) = R_2 P_e / (R_2 + R_c)$ respectively.

The respective time constants are:

$$\tau_c = \frac{R_c R_2}{R_c + R_2} C \qquad \text{for charging}$$

$$\tau_d = \frac{R_d R_2}{R_c + R_2} C \qquad \text{for discharging} \tag{3}$$

Assuming that the switching threshold pressures for the Schmitt trigger are P_{t1} and P_{t2} the period of oscillation T is given by

$$T = \tau_c \ln \left[\alpha \cdot \left(\frac{P_{t2}}{P_{t1}} \right)^{\beta} \right] \tag{4}$$

where

$$\alpha = \frac{R_2 P_e - (R_2 + R_c) P_{t1}}{R_c P_e - (R_2 + R_c) P_{t2}}$$

$$\beta = \frac{R_d (R_2 + R_c)}{R_c (R_2 + R_c)}$$

Since α, β and P_{t2}/P_{t1} are constant, it can be seen that the period T is linearly related to τ_c; using eq. (3)

$$\tau_c = \gamma \cdot V$$

where $$\gamma = \frac{R_c \, R_2}{(R_c + R_2) \, n \, R \, T} \quad (5)$$

hence $$T = \gamma \cdot \ln \left[\alpha \cdot \left(\frac{P_{t2}}{P_{t1}} \right)^{\beta} \right] \cdot V \quad (6)$$

The theoretical frequency, found from 1/T, is compared in Fig. 5 to the experimental results of a typical test. While the experimental data are highly consistent, the sensitivity of the device is far below that predicted by theory. The sensitivity decreases with increasing volume of the chamber which definitely rules out the use of the LBNP tank as the capacitor chamber.

Further modifications of the fluidic circuit provided no significant increase in the system sensitivity to volume changes. While this system was shown to work in principal, it does not meet the requirements of the LBNP experiments nor that of general LVMS applications.

C. Optical Systems

1. Moving Image

In this method a light beam impinges upon the leg and the reflected beam is intercepted by a photosensitive pickup. With the position of the light source and sensor fixed, the point at which the reflected beam strikes the sensor will vary in proportion to movement of the leg surface. If the output of the sensor varies with position of the reflected beam, this output can be used as a measure of movement of the leg surface.

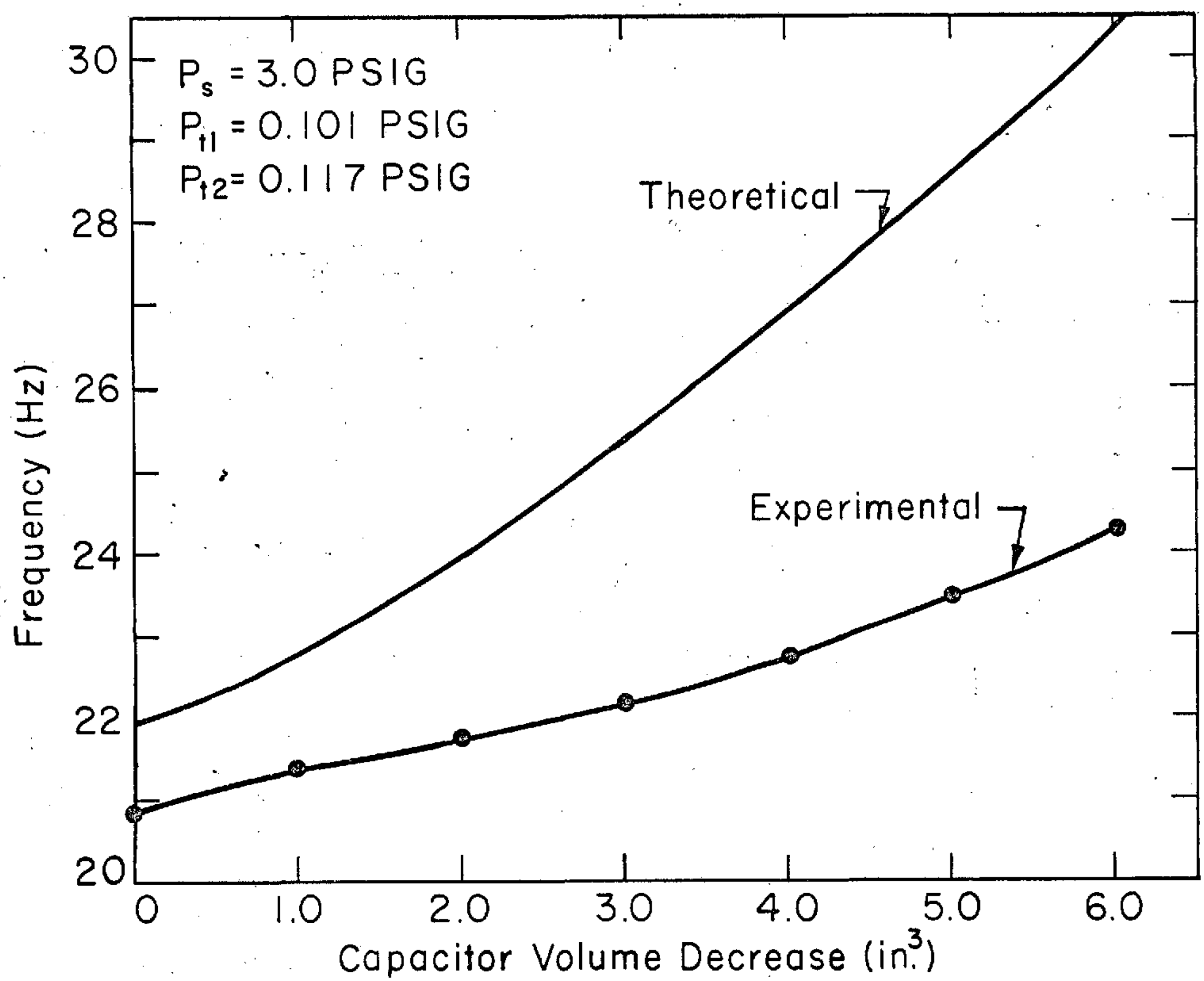


Fig. 5 COMPARISON OF THEORETICAL AND EXPERIMENTAL RESPONSE OF THE PNEUMATIC PLETHYSMOGRAPH

The sensor can be made sensitive to position of the reflected beam by use of a transmission grating, a grid or by using an array of miniature photo diodes.

If a well-defined beam of light is used, this technique gives very good results. Using a laser beam (2 MW laser) as the light source and a television camera as the sensor, the motion of the reflected beam was monitored on a television receiver. With a rectangular grid superimposed on the screen of the receiver, the system was easily calibrated in terms of displacement of a test surface. Tests with a disc rotated off-center showed the system to be both sensitive and accurate.

A practical system using the moving image technique requires a rotating system or multiple source-receiver units; in either case, size restrictions pose a substantial design problem. Further development of this approach was therefore postponed until other optical techniques could be evaluated.

2. Contourometric

The use of Moire' patterns or projected grids are known to provide sensitive measures of relative motion or size [1, 18, 22]. Use of this technique requires the comparison of photographs to quantify the variations in size, shape or position. Automatic data acquisition can conceivably be accomplished with optical scanners or a grid of sensitive photodiodes; however, the complexity of such systems and anticipated expense of development has restricted this approach to conceptual considerations.

3. Reflective Scanner

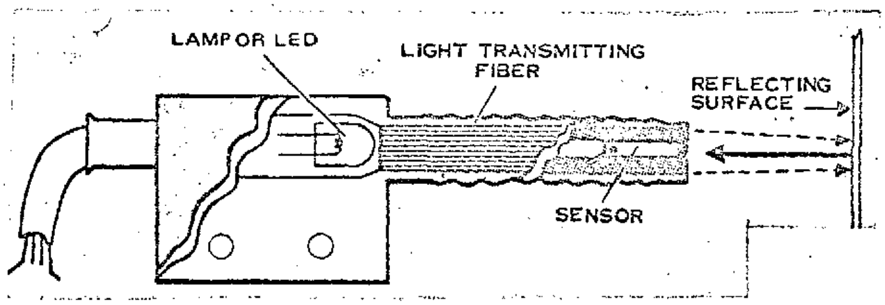
The reflective scanner is a modification of the photoelectric technique in that it consists of a light source (light emitting diode, LED) and a photosensitive receiver (phototransistor) mounted side by side. Light reflected from a test surface is sensed by the phototransistor whose output is then a very sensitive function of the distance from the test surface. A typical device of this type and a plot of the phototransistor output as a function of distance from a test surface is illustrated in Fig. 6. The most appropriate light source for plethysmographic applications appears to be a near-infrared (1.0 μ) LED since, at this wavelength, skin reflectance (about 50%) is not strongly dependent on either ethnic origin or degree of tan [16].

This type of transducer offers two mehtods of monitoring small motions of a surface;

Mode 1. The direct output of the phototransister is calibrated as a function of distance from the test surface i.e., the scanner remains in a fixed radial location and the output varies with motion of the surface.

Mode 2. The scanner is maintained at a fixed distance from the surface by using a feedback loop to vary the scanner's radial position to maintain a constant output. The scanner's motion, monitored by a displacement transducer, will be directly proportioned to the motion of the test surface.

The latter mode of operation is particularly attractive since it should be independent of the surface reflectance and the unit could be made selfcalibrating and self-adjusting without physical contact with the limb.



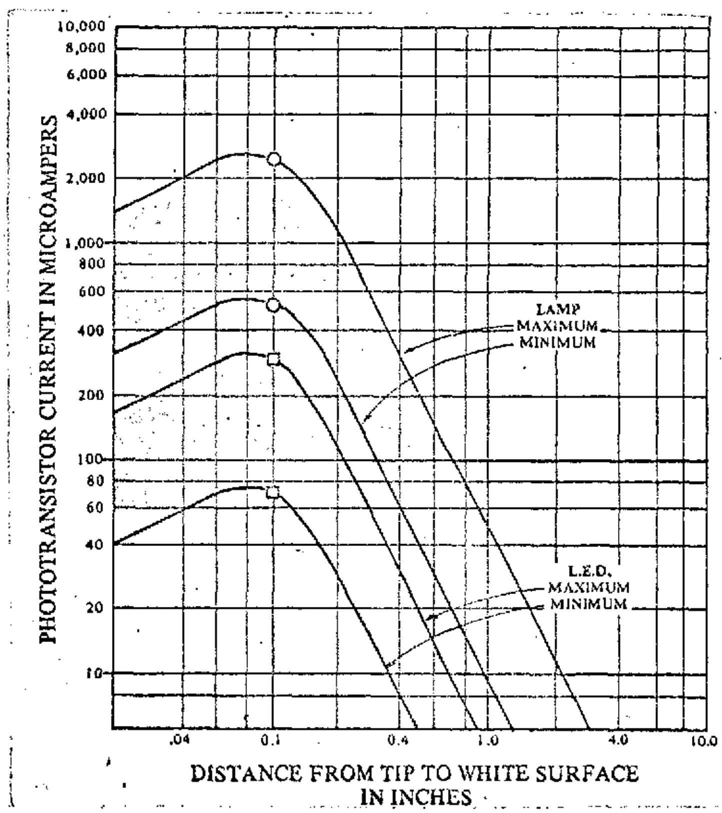


Fig. 6. Commercial reflective transducer characteristics (Skan-A-Matic Corp.)

A chord length across a general cross section can be measured by combining the output of two transducers which are located on opposite sides of the section. In the case of the second mode of operation in which each scanner maintains a constant distance from the surface, the chord length d is given simply by

$$d = S - (X_1 + X_2)$$

where S is the distance between the transducers and X is the distance from the test surface to the transducer. The distance X is essentially constant for a particular transducer and S is obtained by suitably summing the outputs of the two displacement transducers.

The reflective scanner technique was evaluated by using the direct output (Mode 1) and the calibration curve of Fig. 6 to obtain the diameter of a circular disc. The disc was rotated off-center with the two scanners mounted opposite each other on a line through the center of rotation. With measurements taken every 10 degrees of rotation, the percentage error ranged from 0.012% to 1.2% based on cross sectional area.*

Improved results should be obtained from coaxial scanners in which the infrared light is emitted from a cylindrical source surrounding the phototransistor. The second mode of operation remains to be evaluated and will require suitable feedback circuits and drive units for practical operation.

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*The validity of deducing the cross sectional area of a non-circular cylinder from the measurement of circumference or from the measurement of a finite number of radii is examined in Appendix A.

D. <u>Electromechanical</u>

1. LVDT Displacement Transducer

The linear variable differential transformer (LVDT) provides a sensitive measure of displacement of a local area. The integrated output of several LVDT's can be used to provide an accurate measure of the motion of an area of arbitrary size and shape. This technique applied to plethysmography was evaluated by arranging a series of the transducers in a circular geometry as illustrated in Fig. 7. The transducers used have a stroke of 0.200 inches and an adapter was required to provide the adjustability necessary to accomodate a variety of limb sizes. The adapter, illustrated in Fig. 8, is designed to slide in and out of a fixed frame and is held in position by an "O" ring friction seal. A probe is attached to the armature of the LVTD as shown and is lightly loaded by a spring. The LVTD's are all connected in series in such a way that the combined output is -22 to +22 volts d. c. over the maximum stroke range. The voltages are thus summed algebraically and result in a measurement of the average displacement of limb surface.

In operation, the limb is inserted in the frame and the adapters are pressed inward until the tip touches the limb. When they are released, the return spring retracts the adapter 0.20 in. leaving the sensor in contact with the limb at its outer stroke position.

Tests of this assembly verified the sensitivity to be very good (better than 0.0004 inches displacement); however, accuracy suffered from variable indentation of the skin under the probe tips thus indicating questionable applicability of this concept to plethysmography.

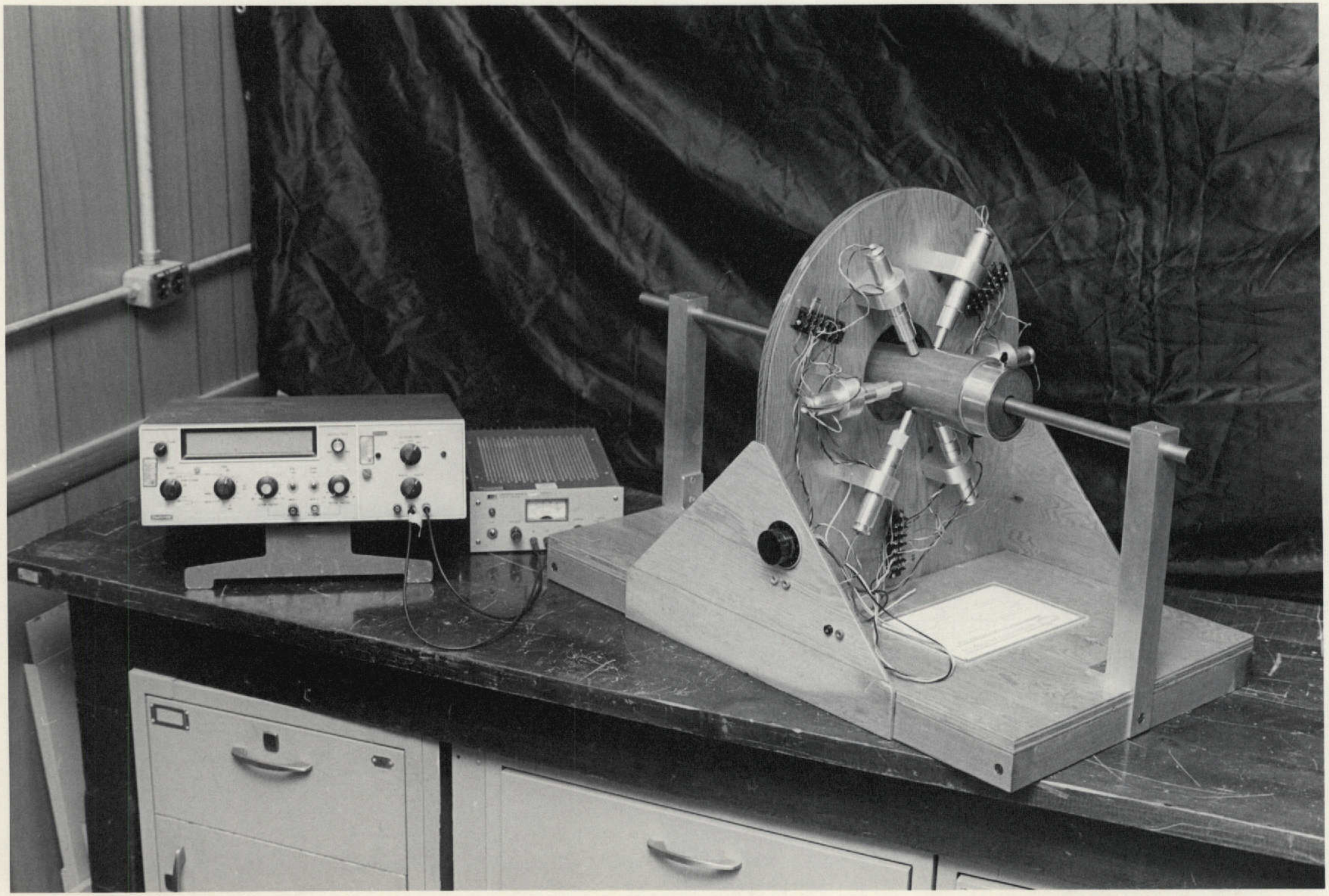

Fig. 7 LVDT PLETHYSMOGRAPH

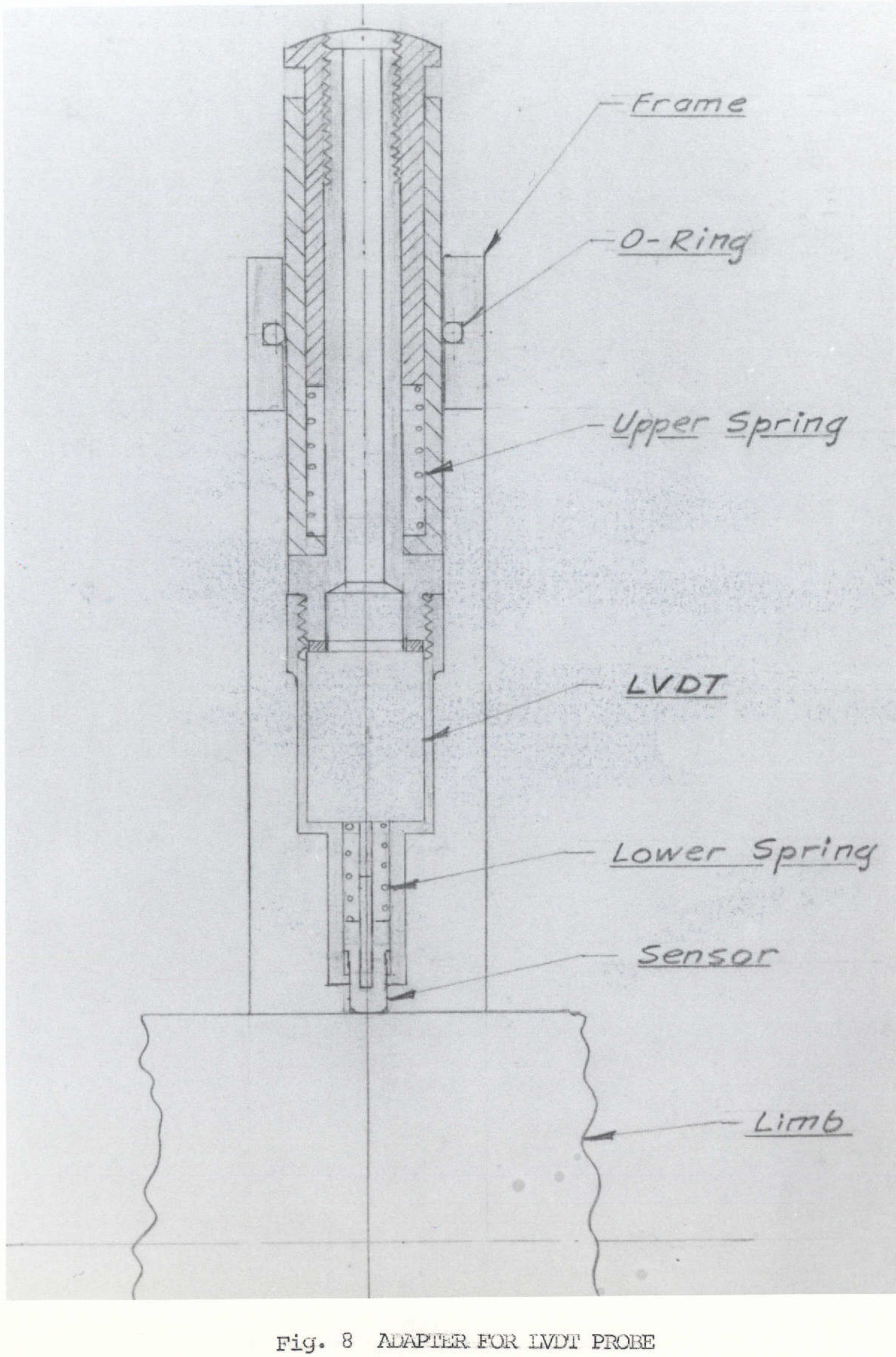

Fig. 8 ADAPTER FOR LVDT PROBE

2. Odometric (rolling contact)

Consideration of the problems associated with the LVDT unit led to the concept of rolling contact to measure limb circumference. This device utilizes a small disc or wheel that is revolved continuously around the limb. The wheel is mounted on a counter balanced arm which is spring loaded to keep the wheel in contact with the limb. The early versions of the odometric unit measured the limb circumference by magnetic tape which was driven by the wheel. Timing marks on the tape were sensed by a magnetic pickup mounted on the arm. Improved sensitivity and repeatability was obtained by replacing the tape system with an incremental shaft encoder mounted directly on the wheel.

The wheel-encoder assembly is mounted on a rotating drum surrounding the limb. The photograph of Fig. 9 illustrates the first bench model of this system. The power input and data output were through slip rings mounted on the rotating drum. Tests of this assembly indicated the need for a larger rotating drum (to accomodate a greater variety of leg sizes) and an alternate means of data transmission to avoid electrical noise generated by the slip rings. With the drum rotating at the rate of 12 rpm the error per revolution was on the order of $\pm$ 0.05 cm when the slip rings were in good condition.

Redesign of the odometric unit increased the inside diameter of the rotating ring from six inches to 8.5 inches and increased the sampling rate (rpm) to 30/min. An optical coupling technique was developed to avoid slip ring noise in the data channels; improved slip rings were made to provide power input to the rotating elements.

The principle of operation of the redesigned unit is basically the same as that of the original model. With reference to the elements shown

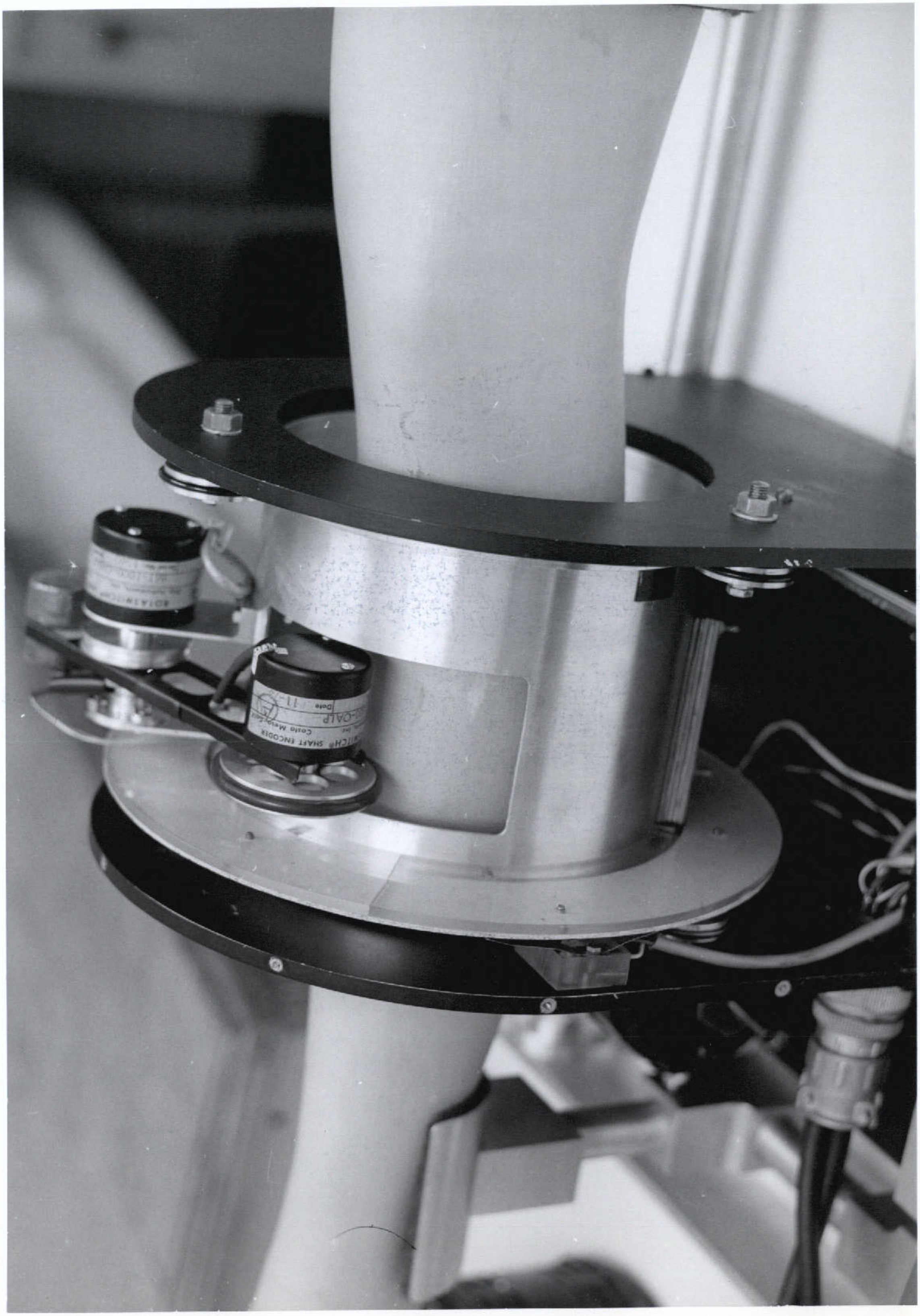

Fig. 9 EARLY MODEL OF THE ODOMETRIC PLETHYSMOGRAPH

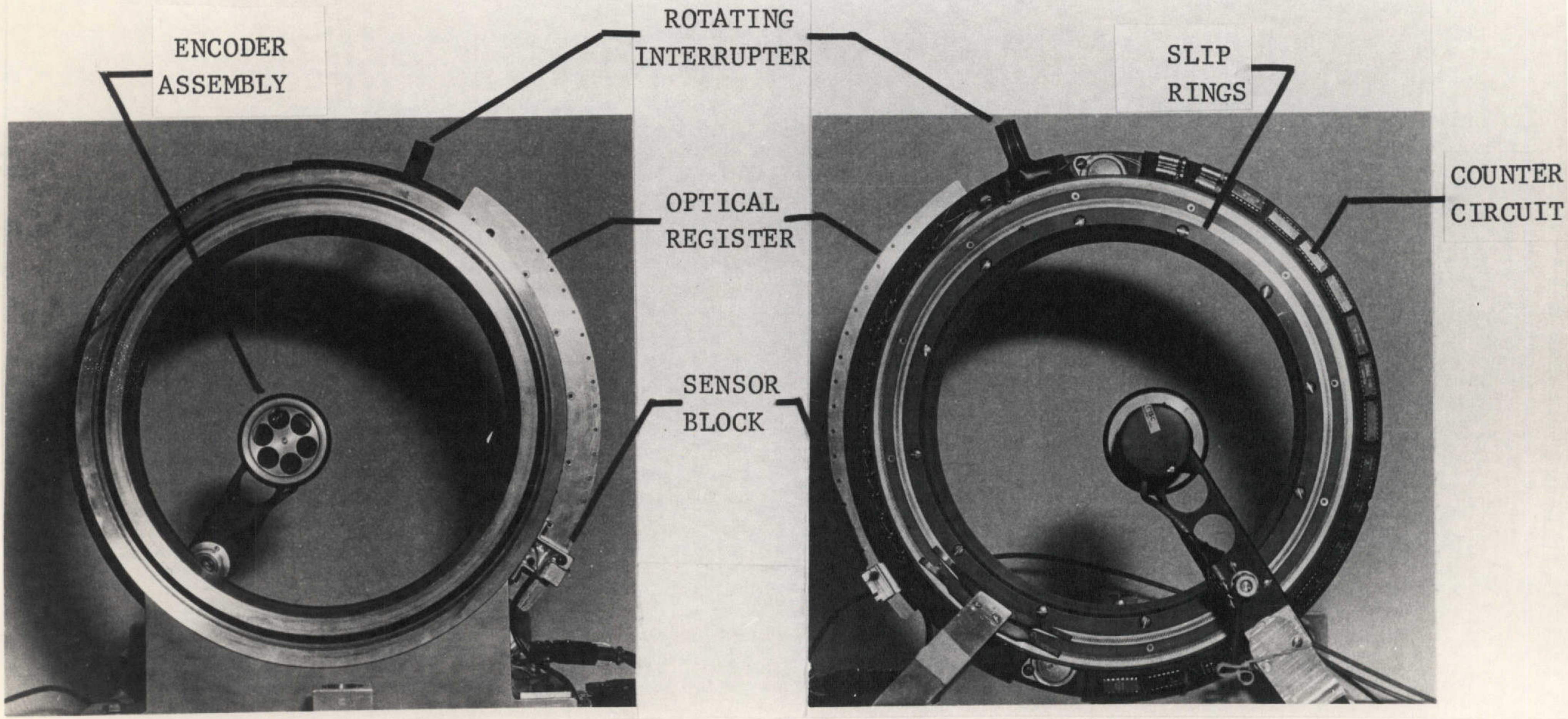

Fig. 10 ODOMETRIC PLETHYSMOGRAPH WITH OPTICAL DATA TRANSMISSION SYSTEM

in Fig. 10, the shaft encoder creates 1000 equally spaced, rectangular pulses per shaft revolution as the unit is rotated about the limb to be measured. Transistions (leading and trailing edges) are counted by a four digit BCD counter such that pulses occur 2000 times per shaft revolution. Encoder transistions are counted through one revolution about the limb. The count is terminated and transferred as a 16 bit word to an optical register on the outer edge of the rotating device. The counter is cleared to zero as this transfer occurs. A rotating optical interrupter is triggered by a stationary member at the same point in each revolution about the limb. This signal is used to terminate the count, transfer the 16 bit word and reset the counter to zero for the beginning of a new sample.

Each data word is stored in the optical register for one revolution while a new word is being generated in the BCD counter. It is during this storage revolution that the data word is optically scanned and transmitted to stationary electronics for display and processing.

The scanning process is synchronized by a signal generated in stationary optical interrupter which is triggered by holes located above each LED in the optical register. As the optical register rotates through a sensor block the data word is loaded (least significant bit first) into a 16 bit shift register. After all sixteen bits have been loaded the word is transferred to a latch for storage and display in a 4 digit BCD register. During this storage cycle the data word is processed by a multiplying (3 BCD digit) digital-to-analog converter. The last three least significant digits are processed into an analog signal for strip chart recording. Conversion of count to centimeters circumference is an additional function of the multiplying D/A converter. Conversion requires only 1.5 μsec and occurs once each time a new word is generated and transmitted to the four digit BCD register.

The analog signal lags that of a reference Whitney gauge by approximately 4 sec or two revolutions of the rotating ring (one revolution for counting and one for data transfer to the stationary display-processing unit).

Tests of the new unit (using a metal cylinder) showed the error per sample was reduced to ± one count, or, ± 0.00886 cm/sample. Baseline data on a human limb (at 30 rpm) indicated a maximum variation of ± 2 counts/sample (± 0.018 cm/sample). Typical analog output of the unit is shown on the strip chart record of Fig. 11 where it is compared to the output of a Whitney gauge which was placed just distal to the odometric unit.

The complete system, consisting of the odometric unit, signal display-processing unit and control unit, is shown in Fig. 12. The circuit diagrams, with associated wiring coordinates, for the system is contained in Appendix B.

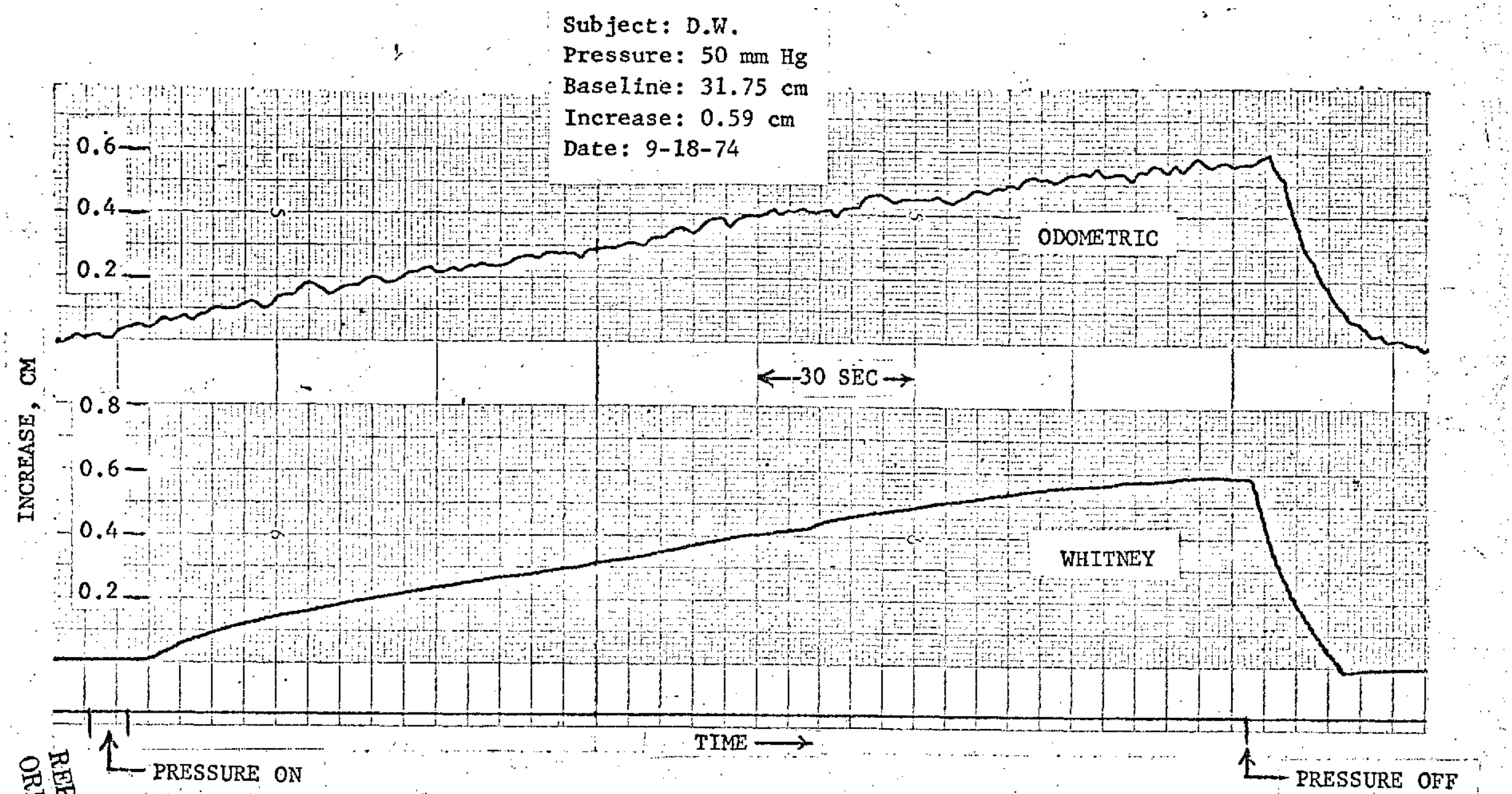

Fig. 11 STRIPCHART RECORD OF ODOMETRIC ANALOG OUTPUT COMPARED TO THAT OF DISTAL WHITNEY GAUGE

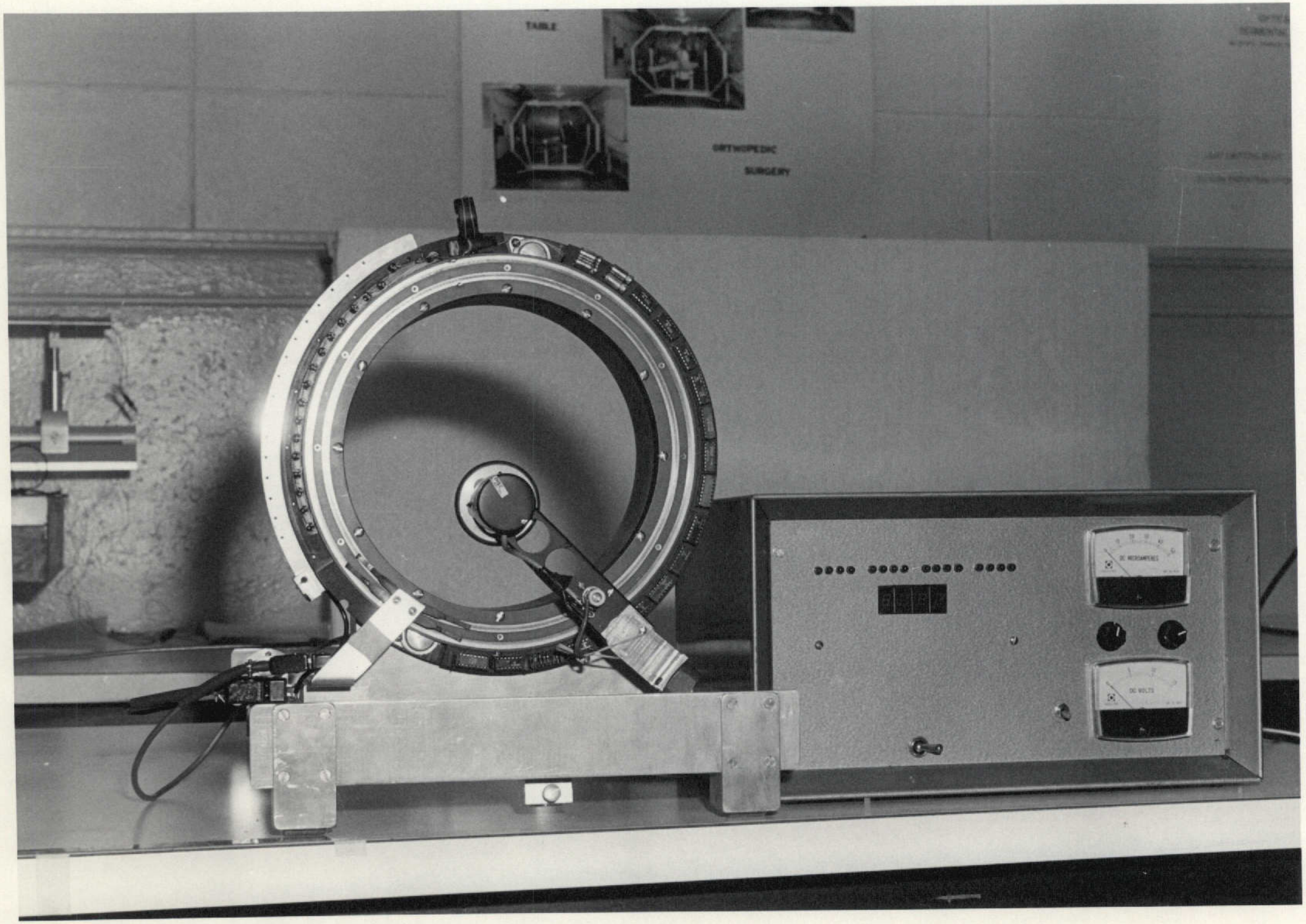

Fig. 12 ODOMETRIC SYSTEM ILLUSTRATING DISPLAY-PROCESSING-CONTROL UNIT

IV. SUMMARY

Evaluation of the various techniques by which limb volume can be measured indicates that the odometric (electromechanical) method and the reflective scanner (optical) have a high probability of meeting the specifications of the LBNP experiments. Both of these methods provide segmental measurements from which the cross sectional area of the limb can be determined (See Appendix A).

The odometric unit has been shown to provide accurate measurements and has the advantage that the circumferential measurements are absolute. The rolling contact has minimal physiological interference and, if the skin does not stretch under the indentation, this contact does not affect the physical measurement. This unit supplies both digital and analog output and does not require repeated calibration. This concept has the disadvantages that 1) relative motion of the limb is sensed by the encoder assembly and 2) the data is sampled at 2 second intervals rather than continuously. A faster sampling rate results in a tendency for the wheel to bounce which induces extraneous counts. These drawbacks are balanced by the accuracy of the unit, its insensitivity to variations of environmental conditions and its simplicity of operation.

The reflective scanner technique has not been developed to the point of providing a working plethysmograph, however, feasibility studies using painted surfaces have given encouraging results. The only major drawback to the use of reflective scanners is that each unit monitors the motion of a small area on the surface. This is a drawback only with respect to the complexity and cost of using multiple units. The effect of varying orientation of the surface is expected to be minimized with the use of the coaxial units; however, this is yet to be evaluated.

The advantages of a simple optical system which 1) produces no physiological interference, 2) is selfadjusting and 3) is insensitive to small movements of the limb (other than volume change) are sufficiently attractive to justify continued study and development of this concept.

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APPENDIX A

Evaluation of Method of Obtaining Cross Sectional Area of Non-Symmetrical Areas from Measurement of Circumference or from a Finite Number of Radii.

CROSS SECTIONAL AREA FROM RADIAL MEASUREMENTS

Some of the schemes for determining volume which have been developed for this work involve the measurement of a finite number of radii of an area of nearly circular cross section. In the application of these methods, it is important to know how many such radii must be measured and to what accuracy each measurement must be made in order to achieve a given accuracy in the final result.

Consider a closed cross-section of area A. Let an estimate of the area be denoted by A_e. Then the error associated with the estimate will be

$$\epsilon_A = \frac{A_e - A}{A} \qquad \text{(A-1)}$$

Let n radii be measured from the edge of the area to a fixed interior point of the cross section. For simplicity, we assume the radii are equally spaced at the angle $2\pi/n$. One estimate of the area (more complicated formulas can be used) is given by

$$A_e = \frac{\pi}{n} \sum_{i=1}^{n} r_i^2 \qquad \text{(A-2)}$$

Let us now define

$$A_i = \frac{\pi}{n} r_i^2 \qquad \text{(A-3)}$$

so that

$$A_e = \sum_{i=1}^{n} A_i \tag{A-4}$$

If the basic measure is the radius, then the error associated with A_i is

$$\delta A_i = A_i \, 2 \, \frac{\delta r_i}{r_i} \tag{A-5}$$

and that with A_e is

$$\delta A_e = \sum_{i=1}^{n} \delta A_i \tag{A-6}$$

Now, if a representative error in r_i is taken to be a constant

$$\epsilon_r = \frac{\delta r_i}{r_i} \tag{A-7}$$

and the assumption is made that each radius measurement is independent of each other radius measurement, we have from equations A-6 and A-7,

$$\delta A_e = 2\epsilon_r \sum_{i=1}^{n} A_i = 2\epsilon_r A_e$$

or by comparison with equation A-1,

$$\epsilon_A = 2\epsilon_r \tag{A-8}$$

so that the error in an area determination can be as bad as twice the error in a single radius measurement.

The above analysis yields the so-called maximum indeterminate error. Such an analysis does not give a realistic estimate of the error, however, since it assumes that all of the errors in A_i would be equal to the maximum value and all could be in the same direction. A better approach is to assume that the errors in A_i are normally distributed, so that instead of equation A-6 we have,

$$\delta A_e = \left[\sum_{i=1}^{n} (\delta A_i)^2 \right]^{\frac{1}{2}} \tag{A-9}$$

Again, if we use equation A-5 and take equation A-7 as a representative constant error in the radius measurement, we have

$$\delta A_e = 2\epsilon_r \left[\sum_{i=1}^{n} [A_i]^2 \right]^{\frac{1}{2}} \tag{A-10}$$

or, using equations A-1, A-2, and A-3

$$\epsilon_A = 2\epsilon_r \frac{\left[\sum_{i=1}^{n} (r_i)^4 \right]^{\frac{1}{2}}}{\sum_{i=1}^{n} (r_i)^2} \tag{A-11}$$

The important features of this result can be deduced by assuming that the object whose area is being measured is a circle of radius r. Then

$$\sum_{i=1}^{n} r_i^4 = n\, r^4 \text{ and } \sum_{i=1}^{n} r_i^2 = n\, r^2$$

so that

$$\epsilon_A = \frac{2}{\sqrt{n}} \epsilon_r \tag{A-12}$$

Although the error is greater than this if the area is non-circular, the reciprocal dependence on $\sqrt{n}$ will be unchanged. As an example, suppose the mean radius of the cross-section whose area is to be found is 50 mm, that a measurement system capable of determining the radius to 1 mm is available and that 25 independent radius measurements are made. Then $\epsilon_r = 0.02$ and $\epsilon_A = 0.008$.

Determination of Cross-Sectional Area from Circumference Measurements

Consider an expanding polygon composed of several sided as shown in Figure A-1.

Let p = perimeter of the inside boundary

A = area enclosed within the inside boundary

ΔA = area added, or area between inside and outside boundaries

Δr = distance between inside and outside boundaries

Further, let Δp = increase in perimeter between inside and outside boundaries. The assumption must be made at this point that there will be a circular contour of the boundary at the corners, also shown in Figure A-1. Now, if all these areas at the corners are brought together, they will form a circle, as shown, the radius of which will be Δr and the perimeter, Δp.

This circle will now give the relationship between Δp and ΔA that is required.

$$\Delta A = p\ \Delta r + \pi \Delta r^2 \qquad \text{(A-13)}$$

But, $\Delta p = 2\pi\ \Delta r$

Hence,

$$\Delta A = p\ \frac{\Delta p}{2\pi} + \frac{\Delta p^2}{4\pi^2} \qquad \text{(A-14)}$$

$$\Delta A = \Delta p\ \left(\frac{p}{2\pi} + \frac{\Delta p}{4\pi} \right) \qquad \text{(A-15)}$$

$$\Delta A = \Delta p\ \left(\frac{2p + \Delta p}{4\pi} \right) \qquad \text{(A-16)}$$

If Δp is small compared to 2p, then

$$\Delta A = \Delta p\ \frac{p}{2\pi} \qquad \text{(A-17)}$$

It further is noted that if the number of sides of the polygon is increased indefinitely, then the polygon approaches a closed curve, and the same relationship still holds.

For a circle

$$A = \frac{\pi}{4}\ d^2 \qquad \text{(A-18)}$$

where d = diameter of the circle

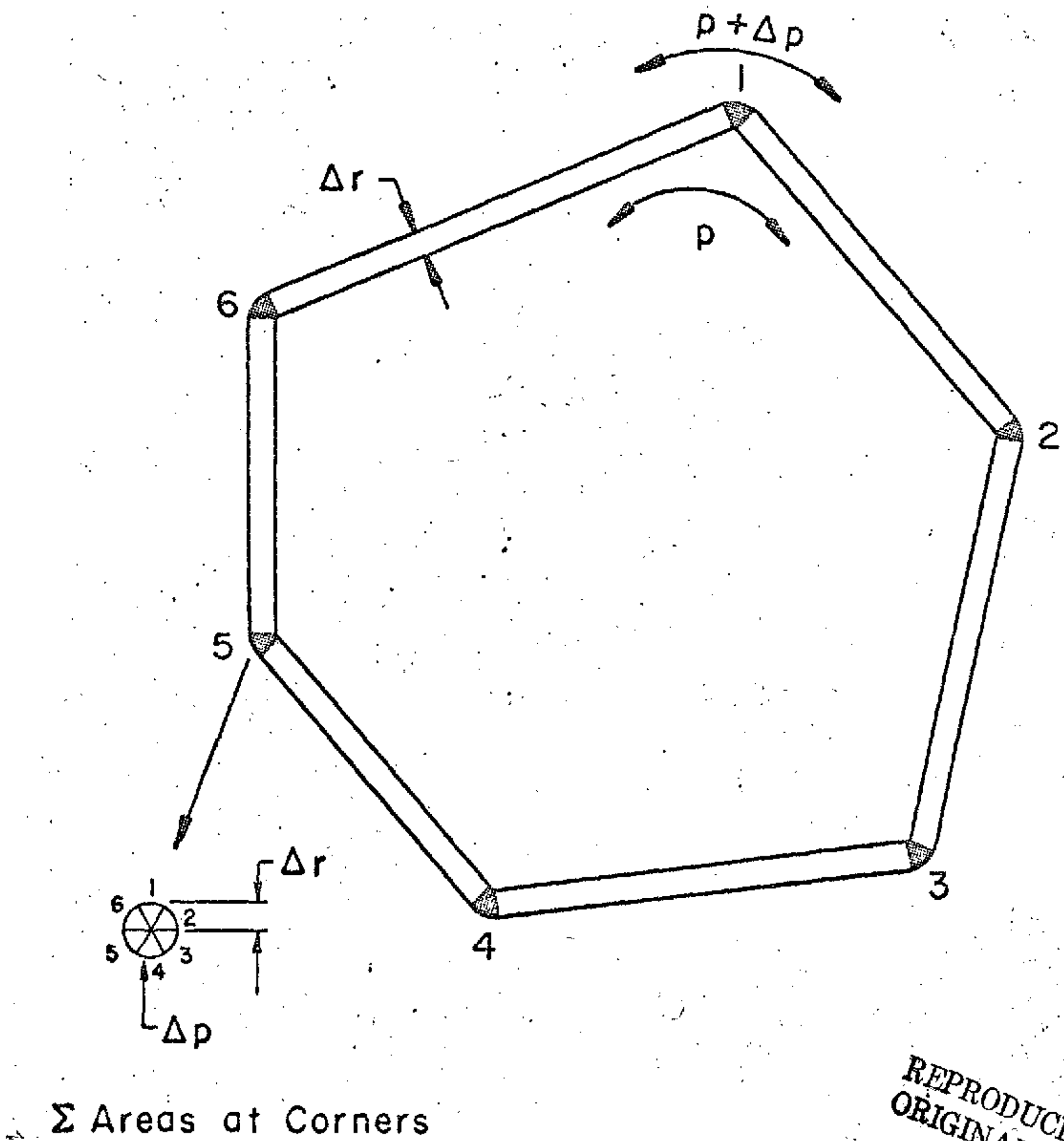


Fig. A-1 Expanding Polygon

Also, $p = \pi d$

Hence, $p^2 = \pi^2 d^2$

and

$$d^2 = \frac{p^2}{\pi^2} \qquad \text{(A-19)}$$

$$\therefore A = \frac{\pi}{4} \frac{p^2}{\pi^2} = \frac{p^2}{4\pi} \qquad \text{(A-20)}$$

$$\frac{dA}{dp} = \frac{p}{2\pi} \qquad \text{(A-21)}$$

and

$$dA = \frac{dp}{2\pi} p \qquad \text{(A-22)}$$

Thus, the formula developed for the expanding polygon or irregularily shaped curve is the same as that for a circle as Δp approaches zero. This means that for an irregularily closed curve the change in area would be the same as that for a circle whose circumference is equal to the perimeter of the closed curve, for incremental changes of perimeter.

Now, if the timing marks, either magnetic or optical, are recorded against time, and if the time for each complete circumference of the limb is noted on this same record, then there will be sufficient information is make a plot of cross-sectional area vs. time.

It should be pointed out that only two assumptions were made in this derivation:

1) That the change in perimeter is small in comparison to twice the original perimeter, and

2) That there is a uniform change between the inside and outside boundaries, or, in other words, Δr remains constant.

The first of these assumptions seem valid since the change of the limb perimeter will be very small compared with twice the original perimeter. The second, however, will require some evaluation, since it is not certain that the limb will increase uniformly.

To evaluate the effect of non-circular shapes which increase non-uniformily a mathematical model was constructed using an ellipse as a basis. The major and minor axes of this ellipse were 5.0 inches and 4.0 inches, selected to approximate a typical limb cross-section. A program was written to evaluate the area and perimeter. Then the major axis was incremented by 0.010 inches in 10 steps while at the same time the minor axis was incremented only 0.9 of the major axis, or 0.009 inches. Calculations were made to evaluate the area by the method illustrated in Figure A-1, and by the theoretical method. The results showed a percent error of only 0.0579 percent, which indicates that even though the change in a radial direction might not be completely uniform, the error is still quite within an acceptable range. For a uniform increase the error was less than 0.009 percent. Experimental work will be needed to verify these results.

APPENDIX B

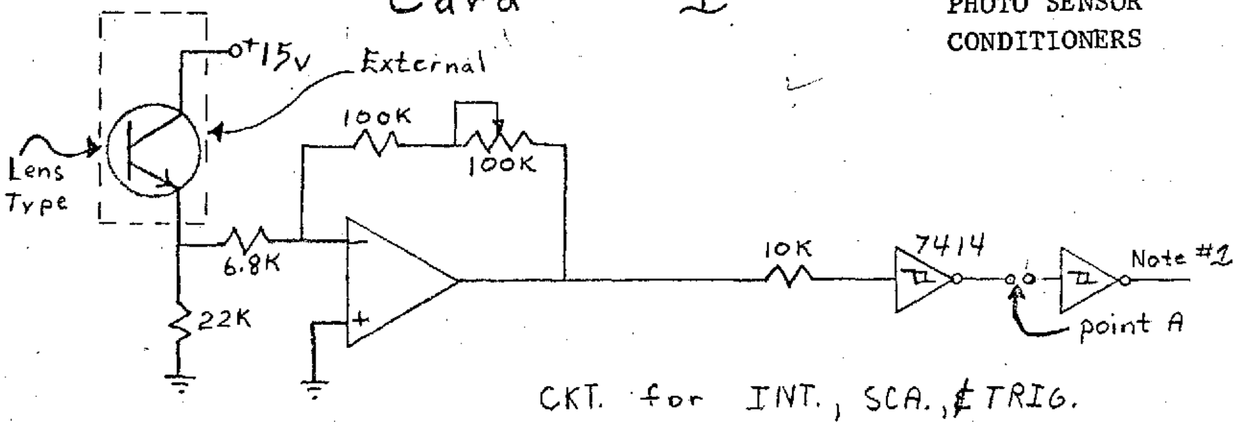
Circuit Diagram and Wiring Coordinates

for the

Optically Isolated Odometric Plethysmograph

Card #1

PHOTO SENSOR CONDITIONERS



CKT. for INT., SCA., & TRIG.

Card Connections

A2 - +15

B2 - Com

C2 - -15

D2 - +16.8

E2 - INT. In

F2 - INT. Out

H2 - SCA. In.

J2 - SCA. Out

K2 - TRIG. In

L2 - TRIG. Out

M2 - +5v

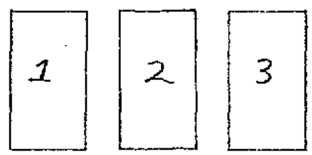
Component Location

1C - 741

2C - Resistors

3C - 7414

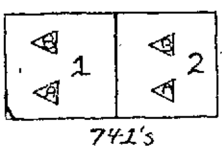
1B - Resistors



TRIM POTS

(Shown from wire wrap side)

Op Amp Socket



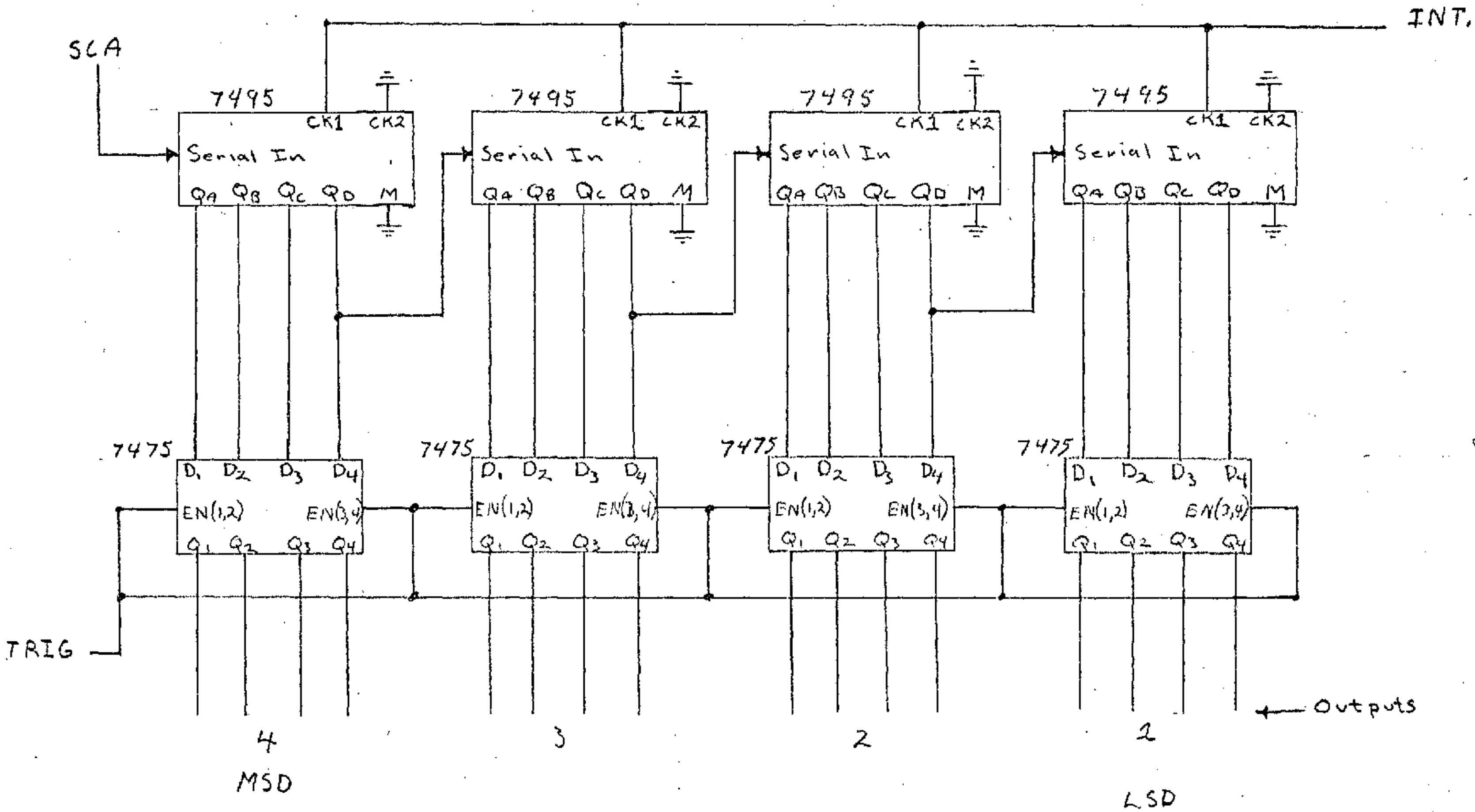
INT. - 1A

SCA. - 1B

TRIG - 2A

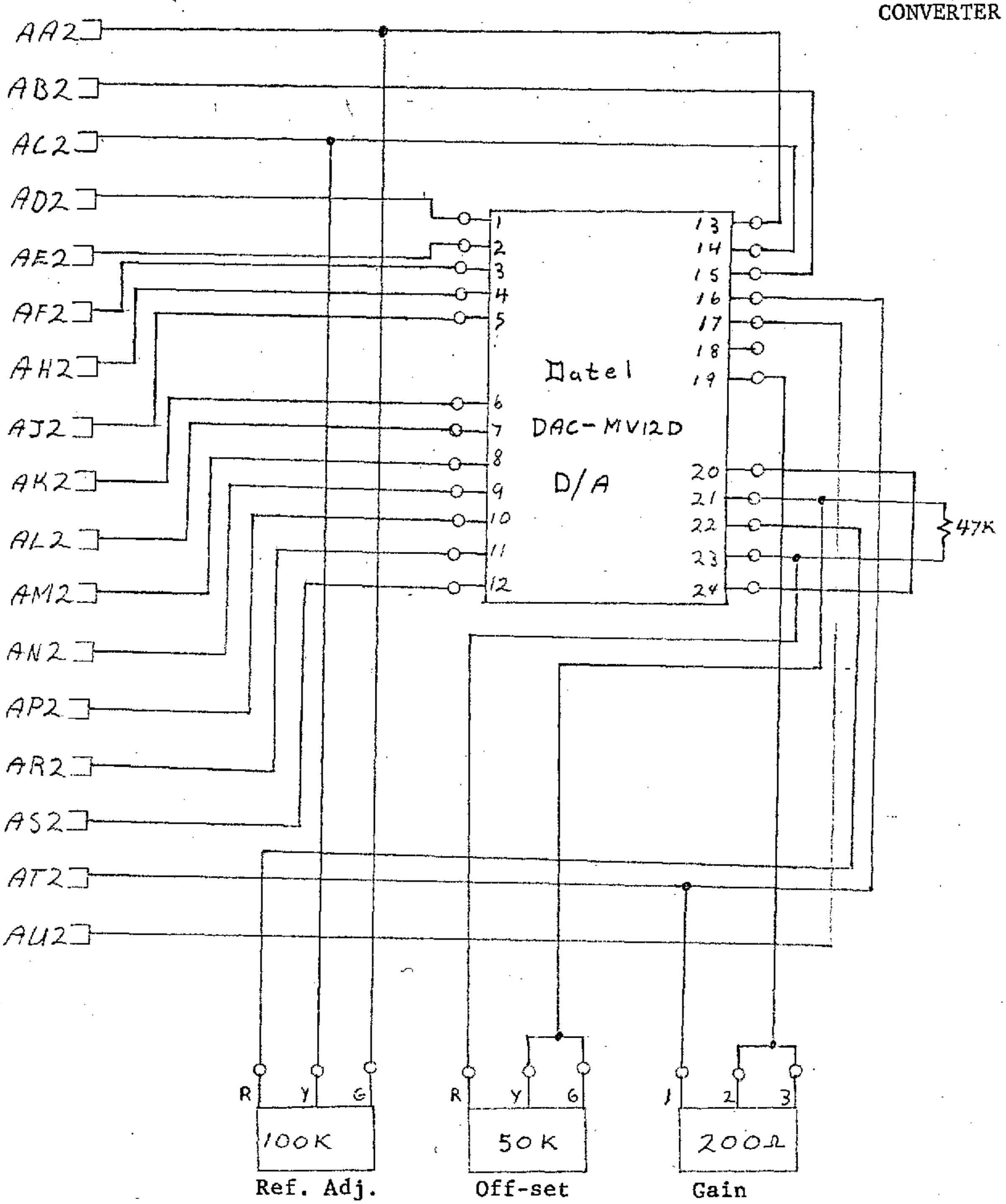
Note #1. SCA and TRIG. circuits terminate at point A. INT. is inverted twice.

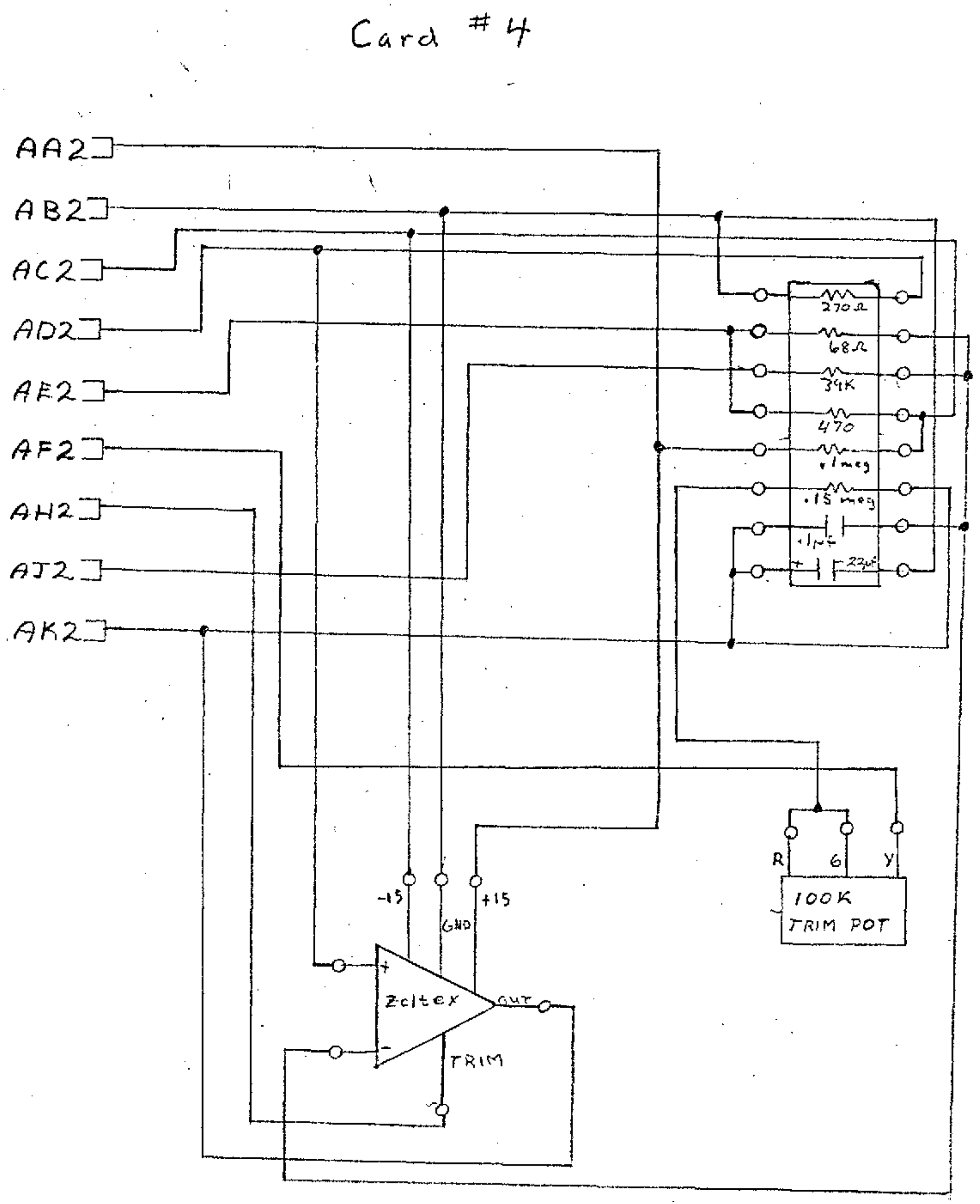
16 BIT SHIFT-REGISTER
AND LATCH



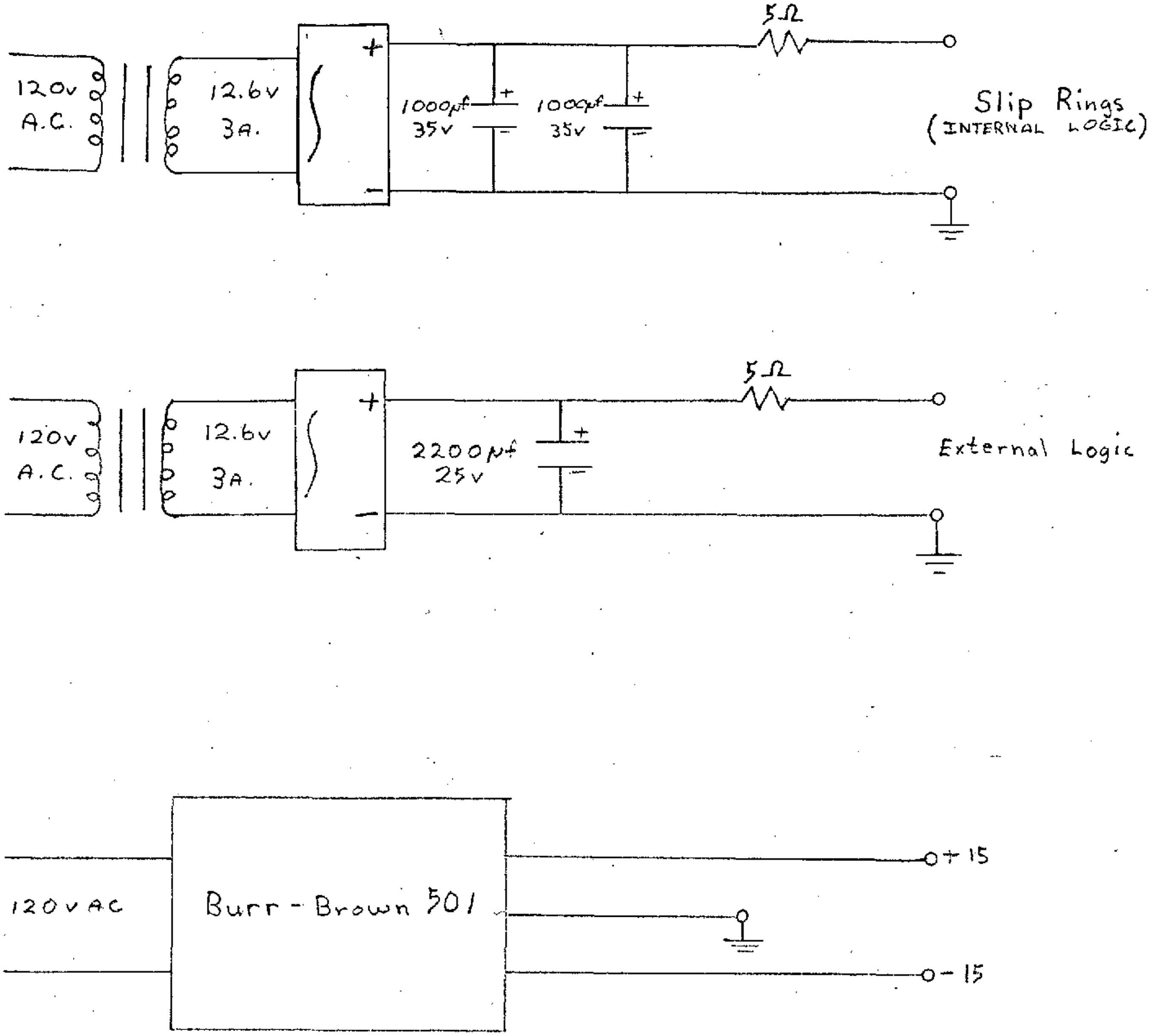
Card #2

Card # 3


AA2
AB2
AC2
AD2
AE2
AF2
AH2
AJ2
AK2
AL2
AM2
AN2
AP2
AR2
AS2
AT2
AU2
Datel
DAC-MV12D
D/A
47K
R
Y
G
100K
R
Y
G
50K
1
2
3
200Ω
Ref. Adj.
Off-set
Gain



STRAIN GAGE AMPLYFIER



Power Supply Circuits

GROUND MAP	V_{cc} MAP
1,8	1,16
2,7	2,14
4,7	4,14
5,7	5,14
6,10	6,5
7,10	7,5
8,10	8,5
9,10	9,5
10,12	10,5
11,12	11,5
12,12	12,5
13,12	13,5
14,7	14,14
15,7	15,14
16,7	16,14

1,1;1,10
1,1;2,3
1,4;C.S.
1,4;2,5
1,7;3,4
1,9;GND
1,10;1,1
1,12;2,4
1,15;3,5

2,2;ENC
2,3;1,1
2,3;1,10
2,4;1,12
2,5;1,4
2,6;6,14

3,3;4,5
3,4;1,7
3,5;1,15
3,10;3,11
3,11;V_{cc}
3,12;GND

4,5;3,3
4,9;V_{cc}

5,3;16,12
5,3;10,4
5,3;10,13
5,6;9,2
5,9;V_{cc}
5,10;C.S.
5,11;C.S.

6,1;6,12
6,2;7,2
6,8;13,6
6,6;GND
6,9;13,3
6,11;13,7
6,11;7,14
6,12;13,2
6,14;2,6

7,1;7,12
7,2;6,2
7,2;8,2
7,6;GND
7,8;12,6
7,9;12,3
7,11,;12,7
7,11;8,14
7,12;12,2
7,14;6,11

8,1;8,12
8,2;7,2
8,2;9,2
8,6;GND
8,8;11,6
8,9;11,3
8,11;11,7
8,12;8,1
8,12;11,2
8,14;7,11

9,1;9,12
9,2;8,2
9,2;5,6
9,6;GND
9,8;10,6
9,9;10,3
9,11;10,7
9,12;10,2
9,14;8,11