OCULAR CONTROL OF THE RANCHO ELECTRIC ARM

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Summary

A pressing problem in the control of prosthetic and orthotic devices is the development of control sites that are task related, easily accessible, and applicable to most subjects. A transducer using infrared reflection techniques to monitor eye motion has been developed to permit use of the eyes as a control site. This ocular transducer provides two proportional, bi-directional control signals with the sources and detectors located so they do not interfere with normal lines of vision.

A minicomputer is used to provide hierorachical control of the electric arm. The following functions provided by the computer are described:

a. Coordinate transformation - the required rate of motion for each arm joint is computed from the input control signals defining desired direction and speed of hand movement. This processing done using either the cartesion or spherical coordinate system.

b. Motor control - The proper sequence of pulses to drive each motor of the splint structure at its required speed is computed. This permits compensation for the nonlinearities present in the electric arm.

Introduction

In the past two years significant efforts have been made in the design of powered orthoses for upper extremities. These arm aids often consist of several linkages and many actuators making their control quite complex.

The critical problem to be discussed here is the development of a control system which will make it easy for the user to utilize the capabilities of the arm aid. The following are diserable properties of the control system:

1. Volitional control of the wrist of the arm aid over as wide a range of motion as possible.
2. Variable speeds to permit fast gross motion and slower speeds for fine positioning.
3. Direct control of wrist motion along natural trajectories using automatic coordination of individual joint motion.

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4. Automatic features, such as keeping the hand level while drinking, available when the user desires.
5. The motion required to obtain control signals should be as naturally related to the task as possible to reduce the level of concentration and mental effort required.

While these properties determine the performance requirements of the control system, there are several additional factors which are of vital importance in determining patient acceptance of the complete system. These are:

1. Cosmesis - A disabled person has a desire to look as natural as possible. All equipment used should be designed to be as inconspicous as possible.
2. Cost- Effectiveness - The additional function afforded the patient must be commensurate with the cost.
3. Reliability - The equipment should be designed to work for years without maintenance. If the equipment requires frequent maintenance it will tend to be discarded by the patient
4. Ease of Application - It should be easy to put the equipment on the patient each time he wants to use it.
5. Simple Activation and Deactivation - It should be easy for the patient to turn the control system on and off with simple control signals. This will permit the patient to relax the muscles used to obtain control signals.

These requirements greatly increase the engineering effort required in the design of the arm aid, the control system, and the transducers used to obtain the required control signals. The objective of the research described here is the development of a complete arm aid system which has the specified control properties and also meets the additional requirements for patient acceptance.

Approach

Effective application of externally powered orthotic arms requires that the user be able to easily control the device to accomplish a variety of tasks. This ease of control is fundamentally related to the availability of control sites as well as the provision for obtaining coordinated motion. The system under development is designed to be of assistance to high-level quadriplegics which places severe constraints on the location of control sites. A block diagram of the complete system is shown in Figure 1. This diagram shows the major components of the system and indicates the major paths of information transfer.

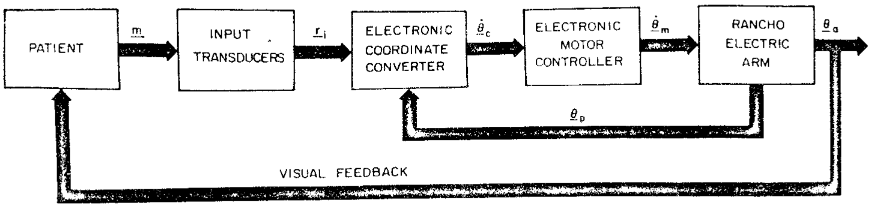

Fig. 1. Block diagram of system

Control sites capable of providing signals, $\underline{r}_i$, which can be smoothly controlled over a wide dynamic range are essential to obtain the speed control desired. A transducer which monitors eye motion by means of infrared reflection techniques is being developed to provide two of these signals since smooth control of eye motion is avilable in even the most severely paralyzed patients. Additional control sites are chosen to utilize residual function.

To simplify the control task an electronic coordinate converter is employed to compute the rate of motion for each joint of the arm aid when the desired direction and rate of speed of the hand is specified. The conscious effort required for control of the hand is minimized since the user can use the control transducers to specify speed and direction of motion of the hand rather than specifying anatomical joint motion. In order to achieve the desired motion, variable motor speed control is needed. Since the arm aid used was the Rancho electric arm /1/, which has permanent magnet dc motors, it was necessary to develop a circuit to generate a variable frequency pulse train to obtain the necessary range of motor speeds.

Ocular Transducer

Previous tests using EOG methods for monitioring eye motion for control purposes indicated that such control was feasible /2, 3, 4/. However, because the use of electrodes did not seem compatible with the requirements of patient acceptance, this method of monitoring eye motion was discarded in favor of a method using infrared reflection techniques. This new transducer shown in Figure 2, uses infrared sources and detectors placed so that they do not interfere with normal lines of vision. Vertical motion is sensed by the source and two detectors above the right arm and horizontal motion is sensed by the sources and detectors on the sides of the glasses. Fairchild FPM-200 photo-diodes are used for the detectors. A Monsanto ME-3 source is used for the vertical channel and two General Electric SSL-315 sources are used in the horizontal channel. By modulating the sources it was possible to design the transducer to operate over a wide range of ambient light conditions. A block diagram of the ocular transducer is shown in Figure 3.

The control currently available from the ocular transducer is illustrated by the eye "writing" shown in Figure 4. This writing was obtain by attaching the vertical and horizontal outputs of the ocular transducer to the vertical and horizontal inputs of a storage oscilloscope.

A study of infrared hazards to the eye indicate that the power levels used for the sources produces infrared radiation well below the threshold of damage to the eye /5/.

It is important that the patient be able to turn off the control system quickly when wants to look around or talk to someone. Two approaches to this problem are currently being invetigated. The first method uses the occurrence of two blinks within a 175 to 350 milliseconds period to disconnect the transducer. The other method uses the presence of a zero signal in both channels for a specified period, as the indication. Of course, similar methods can be used to reconnect the transducer.

Electronic Coordinate Converter

Many techniques can be used to perform the calculations necessary to convert the input signals specifying direction and speed into signals specifying individual joint rates. Since these calculations effectively transform signals from a spatial coordinate system into the coordinate system of the arm, the device performing the calculations will be called a coordinate converter. Earlier research used a mechanical coordinate convertor based on spherical coordinates for the spatial coordinate system /2, 3, 4/. Zebo /6/ has used a mechanical coordinate converter based on Cartesian coordinates. Because of slow operating speeds and lack of flexibility, these mechanical coordinate converters have given way to electronic coordinate converters. Many approaches to coordi-

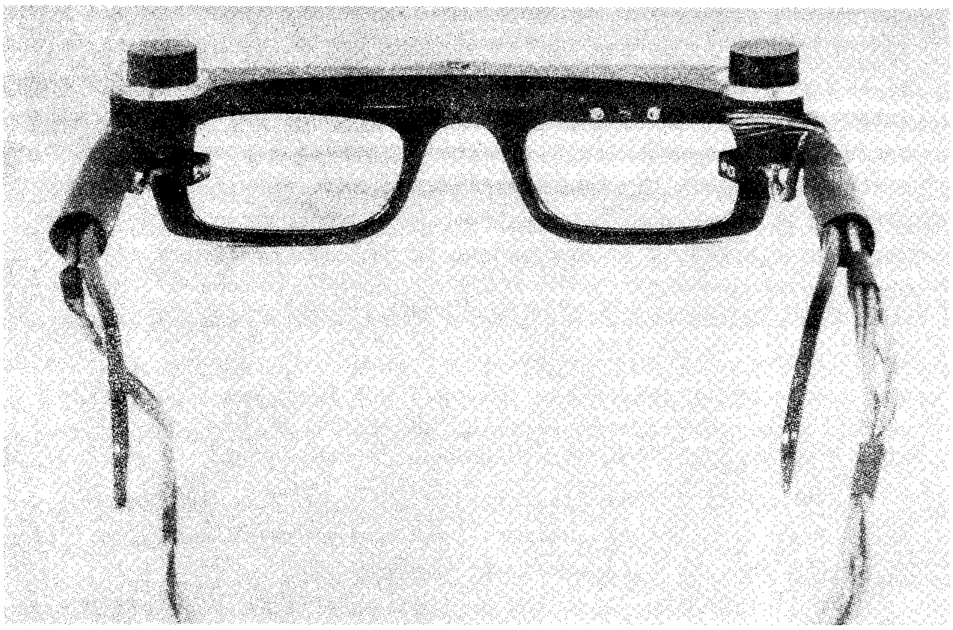

Fig. 2. Infrared ocular transducer

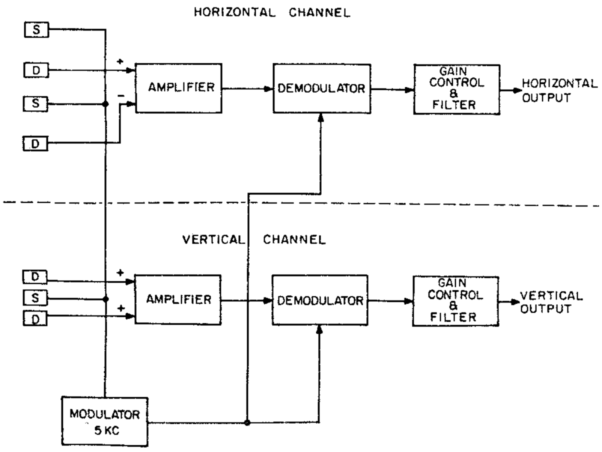

Fig. 3. Block diagram of ocular transducer electronics

nate conversion have appeared in the literature. Whitney /7, 8/ has proposed a coordinate system based upon the direction the hand is pointing. Lawrence and Lin /9/ have proposed a statistical method for determining the elbow positions of an arm aid. Gavrilović and Marić /10/ have developed equations for keeping the hand direction colinear with wrist velocity. Singh /11/ developed the coordinate transformation equations for spherical coordinates with the center of the coordinate system at the shoulder. This was later extained by Greeb /12/ to allow the center of the spherical coordinate system to be displaced from the shoulder. Greeb also developed the equations for a Cartesian coordinate system. If the center of the spherical system is located at the mouth then a single signal can be used to bring the hand to the mouth. Thus, the spherical coordinate system would seem to be good for eating. However, the Cartesian system may be better for lapboard activities when motion parallel to the board is desired.

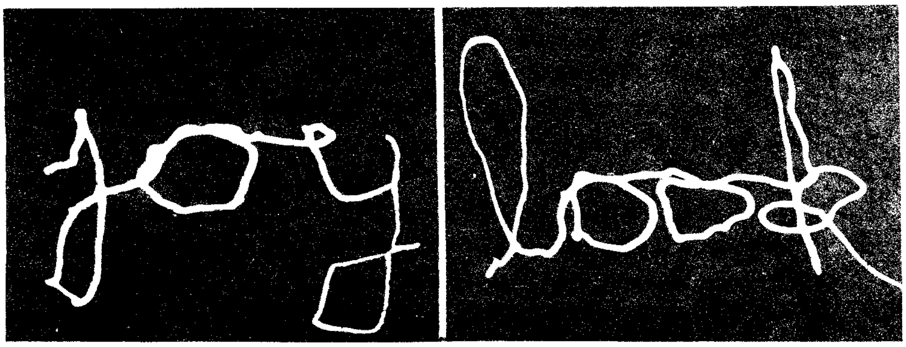

Fig. 4. Eye "writing" using infrared ocular transducer

Any implementation of a coordinate converter must make specific choices to resolve 3 situations which arise. The first is a result of the two-bar linkage having four degrees-of-freedom when only three degrees-of-freedom are required to define a point in space. This extra degree-of-freedom makes the solution of the coordinate transformation equation non-unique. Each resolution of this ambiguity leads to a different control strategy. Some strategies proposed are:

1. Minimization of instantaneous weighted system kinetic energy /7/

2. Hold one joint, such as humeral rotation, fixed /12/
3. Use statistical procedures to determine whether to use high or low elbow position /9/

None of these strategies has yet received enough testing to determine which would be preferred by the user.

The second situation arises when one of the joints of the arm aid reaches a limit. In this case, the joint cannot move further so coordinated motion is destroyed if motion toward that limit is required. Some of the possible resolutions of this proble are:

1. Permit uncoordinated motion by stopping the joint at the limit but letting the other joints continue moving. This procedure can be unnerving to the user as it often appears to him that he has lost control.
2. Stop the arm aid when any joint reaches a limit and ignore all input commands which require motion against the limit. This often severely limits the range of motion of the arm. Also, since the inputs are endpoint commands and not joint commands, it is often difficult for the patient to determine a command that will permit motion away from the limit. The lack of a response to input commands which are illegal because they require motion into a limit is very discomforting to the user.
3. Control the arm to move in a direction which most closely approximates the desired direction. This would greatly complicate the control algorithm although it may be necessary to give the patient an adequate feel of control.

While the first two strategies have been used in preliminary tests, none has been used extensively enough to evaluate its effectiveness.

The third situation arises because of the singularities which must arise in the solution of the coordinate transformation equations because of mechanical structure of the arm aid. Some strategies which can be used to avoid the singularities are:

1. Adjust the limits of the arm aid so it cannot be driven to a point where a singularity exists.
2. Modify the arm position data when close to a singularity so that the position data used by the equations do not result in a singular solution. Since the actual arm angles are then a few degrees from the angles used in the co-

ordinate conversion process, a degradation in coordinated motion results. However in general the change in performance is not noticeable to the user.

3. Adopt a different control algorithm in the vicinity of a singularity. Because of the unique position of the arm near a singularity a simple strategy such as temporarily going directly to joint angle control may be adequate.

In the system currently being tested, as shown in the block diagram of Figure 1, the coordinate converter computes the desired joint rates $\underline{\theta}_c$, specified by the command signals, $\underline{r}_i$, and information on the current position of the arm, $\underline{\theta}_p$, as measured by potentiometers. Both Cartesian and spherical coordinate systems are being used by the coordinate converter for evaluation. At present, the extra degree-of-freedom problem is being resolved by letting the patient directly control humeral rotation so its rate is not computed by the coordinate converter.

The equations developed by Greeb /12/ are those currently being used in the electronic coordinate converter. The origin of the reference coordinate system is located in the mouth, and oriented such that +X is forward, +Y is to the right and +Z is down. the constant vector, S_o, where

$$S_o = \begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix}$$

defines the location of the shoulder with respect to the origin.

The location of the wrist in space is defined by four joint angles as shown in Figure 5. The reference position is the arm extended to the front parallel with the X axis. From this reference position a positive rotation of ψ_1 moves the wrist to the right; a positive rotation of θ_1 raises the wrist and a positive rotation of ϕ_1 rotates the arm clockwise when viewed from the shoulder. Positive rotation of θ_2 produces elbow flexion bringing the wrist closer to the shoulder. The components of the wrist position can be expressed as:

$$\begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = \begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix} + \begin{bmatrix} C\psi_1 C\theta_1 L_1 + (C\psi_1 C\theta_1 C\theta_2 - C\psi_1 S\theta_1 C\phi_1 S\theta_2 - S\psi_1 S\phi_1 S\theta_2) L_2 \\ S\psi_1 C\theta_1 L_1 + (S\psi_1 C\theta_1 C\theta_2 - S\psi_1 S\theta_1 C\phi_1 S\theta_2 + C\psi_1 S\phi_1 S\theta_2) L_2 \\ -S\theta_1 L_1 - (S\theta_1 C\theta_2 + C\theta_1 C\phi_1 S\theta_2) L_2 \end{bmatrix} \qquad (1)$$

where L_1 = Length of upper arm
L_2 = Length of lower arm
and C and S are used to designate the Cosine and Sine, respectively.

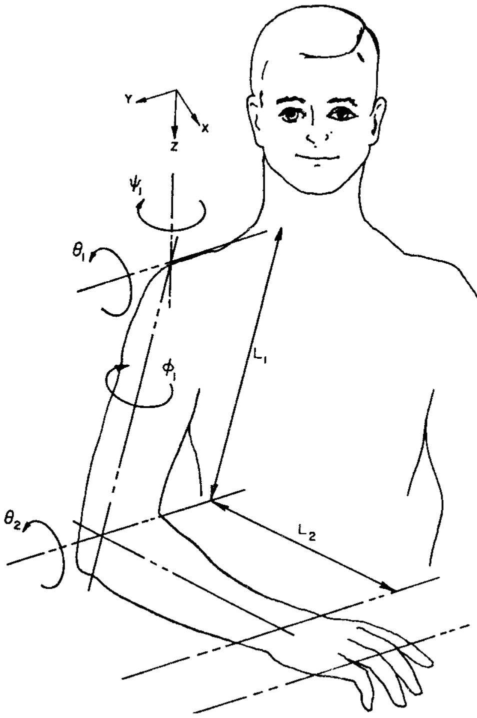

Fig. 5. Angles defining wrist position in space

In order to simplify the equations, the upper and lower arm will be assumed to be of the same length: $L = L_1 = L_2$. This is actually an advantage since it permits control of the palm of the hand rather than the wrist, although we will still call it the wrist. The rate equations for the wrist can be written:

$$\begin{bmatrix} \dot{X}_w \\ \dot{Y}_w \\ \dot{Z}_w \end{bmatrix} = LA \begin{bmatrix} \dot{\psi}_1 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \qquad (2)$$

where it is assumed ϕ_1 is held constant. Thus, ϕ_1 is not used in the coordinate conversion process but rather is placed under direct control of the patient. The components of A can be written as follows:

$$a_{11} = S\psi_1[S\theta_1 C\phi_1 S\theta_2 - C\theta_1(1+C\theta_2)] - C\psi_1 S\phi_1 S\theta_2$$
$$a_{12} = -C\psi_1[S\theta_1(1+C\theta_2) + C\theta_1 C\phi_1 S\theta_2]$$
$$a_{13} = -[C\psi_1(C\theta_1 S\theta_2 + S\theta_1 C\phi_1 C\theta_2) + S\psi_1 S\phi_1 C\theta_2]$$
$$a_{21} = C\psi_1[C\theta_1(1+C\theta_2) - S\theta_1 C\phi_1 S\theta_2] - S\psi_1 S\phi_1 S\theta_2$$
$$a_{22} = -S\psi_1[S\theta_1(1+C\theta_2) + C\theta_1 C\phi_1 S\theta_2]$$
$$a_{23} = -[S\psi_1(C\theta_1 S\theta_2 + S\theta_1 C\phi_1 C\theta_2) - C\psi_1 S\phi_1 C\theta_2]$$
$$a_{31} = 0$$
$$a_{32} = S\theta_1 C\phi_1 S\theta_2 - C\theta_1(1+C\theta_2)$$
$$a_{33} = S\theta_1 S\theta_2 - C\theta_1 C\phi_1 C\theta_2$$

The desired joint speeds can then be computed from Equation /2/ to obtain:

$$\begin{bmatrix} \dot{\psi}_1 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \frac{1}{L} A^{-1} \begin{bmatrix} \dot{X}_w \\ \dot{Y}_w \\ \dot{Z}_w \end{bmatrix} \tag{3}$$

As we would expect, the equations reveal that the joint rates are not dependent on position of the origin of the coordinate system relative to the shoulder.

For the spherical coordinate system, the origin will be assumed to be the mouth. The position of the wrist will be defined by the radial distance, R, the azimuth angle, θ, and the elevation angle, ϕ. The input commands will be $\dot{R}$, $\dot{\theta}$, and $\dot{\phi}$, and defined such that positive $\dot{R}$ moves the hand away from the mouth, a positive $\dot{\theta}$, moves the wrist to the right and a positive $\dot{\phi}$ raises the wrist. The rate equations can be written:

$$G \begin{bmatrix} \dot{R} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix} = H \begin{bmatrix} \dot{\psi}_1 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \tag{4}$$

Before defining the elements of G and H, we first define:

$$\begin{aligned}
r &= \sqrt{X_0^2 + Y_0^2} \\
\alpha &= \mathrm{Tan}^{-1}\frac{Y_O}{X_O} \\
T &= L(C\theta_1 + C\theta_1C\theta_2 - S\theta_1C\phi_1S\theta_2) - rC(\alpha+\psi_1) \\
B &= LS\phi_1S\theta_2 + rS(\alpha+\psi_1) \\
z_w &= Z_O - L(S\theta_1 + S\theta_1C\theta_2 + C\theta_1C\phi_1S\theta_2) \\
R &= \quad T^2 + B^2 + z_w^2
\end{aligned} \tag{5}$$

Then the elements of G may be written:

$$\begin{aligned}
g_{11} &= \frac{T^2 + B^2}{R} \\
g_{12} &= 0 \\
g_{13} &= z_w \quad T^2 + B^2 \\
g_{21} &= 0 \\
g_{22} &= T^2 + B^2 \\
g_{31} &= R \\
g_{32} &= g_{33} = 0
\end{aligned} \tag{6}$$

and the elements of H may be written:

$$\begin{aligned}
h_{11} &= rTS(\alpha+\psi_1) + rBC(\alpha+\psi_1) \\
h_{12} &= -LT(S\theta_1 + S\theta_1C\theta_2 + C\theta_1C\phi_1S\theta_2) \\
h_{13} &= -LT(C\theta_1S\theta_2 + S\theta_1C\phi_1C\theta_2) - LBS\phi_1C\theta_2 \\
h_{21} &= T^2 + B^2 - rBS(\alpha+\psi_1) + rTC(\alpha+\psi_1) \\
h_{22} &= LB(S\theta_1 + S\theta_1C\theta_2 + C\theta_1C\phi_1S\theta_2) \\
h_{23} &= LB(C\theta_1S\theta_2 + S\theta_1C\phi_1C\theta_2) + LTS\phi_1C\theta_2 \\
h_{31} &= h_{11}
\end{aligned} \tag{7}$$

$$h_{32} = -LT(S\theta_1+S\theta_1C\theta_2+C\theta_1C\phi_1S\theta_2)+Lz_w(S\theta_1C\phi_1S\theta_2-C\theta_1-C\theta_1C\theta_2)$$

$$h_{33} = -LT(C\theta_1S\theta_2+S\theta_1C\phi_1C\theta_2)+LBS\phi_1C\theta_2+Lz_w(S\theta_1S\theta_2-C\theta_1C\phi_1C\theta_2)$$

The desired joint speeds can then be computed from Equation 4 :

$$\begin{bmatrix} \dot{\psi}_1 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = H^{-1}G \begin{bmatrix} \dot{R} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix} \tag{8}$$

It can be seen that the coefficients of G and H are somewhat more complex to calculate than those of A. Also, since the spherical coordinate system uses the mouth-to-shoulder offset , S_o, these measurements of the patient must be available in addition to arm length.

The prototype electronic coordinate converter was inplemented using a Data General Nova 1200 minicomputer with a 4K core. A flow diagram of the program is shown in Figure 6. A front panel switch is used to determine whether the Cartesian or spherical coordinate system is used. This switch can be changed during program operation and allows the patient to make a quick comparasion between the Cartesian and spherical coordinate systems for any task.

A complete pass through the program takes about 20 milliseconds using fixed point computations and about 60 milliseconds using simple high speed floating point calculations.

Electronic Motor Controller

Since the permanent magnet motors of the Rancho electric arm do not have good speed control using a variable voltage, and proportional control of motors using linear amplifiers results in high power dissipation in the drive circuitry, a variable frequency pulse drive is being used. The computer is programmed to produce a series of pulses with the duty cycle required to obtain the desired speed. The pulse train controls a solid state electronic switch which connects the motor to the battery with the appropriate polarity during each pulse. Since the pulse sequence for each joint is determined by the computer, it is easy to experiment with different strategies of pulse frequency or pulse width modulation.

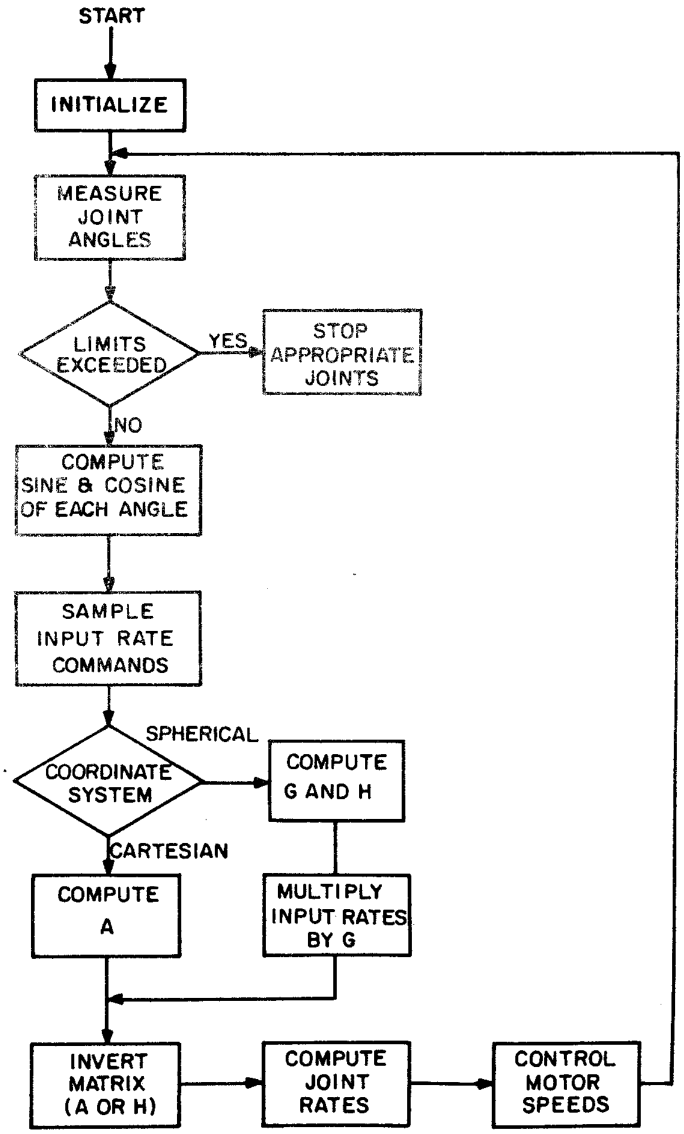

Fig. 6. Flow diagram of computer program

Patient Testing

The prototype system being used for preliminary patient tests is shown in Figure 7. The patient is shown operating the Rancho electric arm by use of the ocular transducer. The minicomputer used to perform the coordinate transformations and control the arm aid motors is shown in the background.

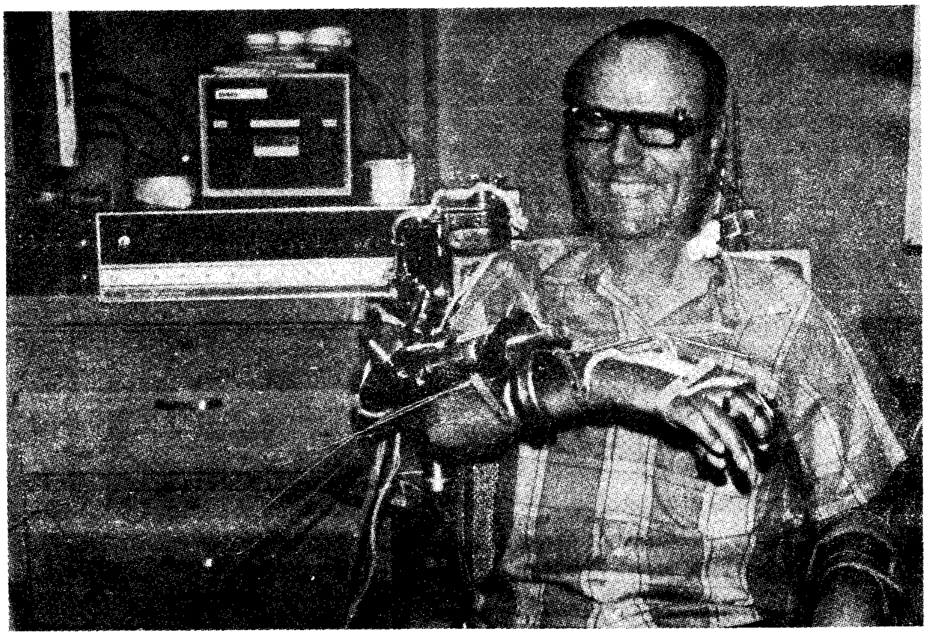

Fig. 7. Patient using ocular control system

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