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EXTRAVEHICULAR ATTITUDE CONTROL
BY USE OF HEAD MOTIONS

by

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S.M. Thesis

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I sing the Body Electric.

-- Walt Whitman

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Submitted to the Department of Aeronautics and Astronautics on May 1st, 1970, in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

On the basis of a survey conducted on existing techniques for astronaut extravehicular attitude control in space, experiments were performed to determine the usefulness of bioelectric currents generated in muscle tissue as a control signal source.

Muscle sites were identified on the neck and bio-currents (electromyographic signals or EMG's) were detected using surface electrodes. Raw signals were generated by turning the head right or left with respect to the body; subsequent conditioning was performed using a hybrid computer. Motion cues (yaw) were provided by a rotating chair which a subject attempted to control by moving his head. Performance levels based upon integrated squared error were compared for two separate plant dynamics between electromyographic and conventional pencil-stick control.

Examination of the data revealed that control of yaw attitude using EMG's was a practical means of providing hands-off control. However, EMG performance was in all cases poorer than equivalent tests conducted using a stick. This probably resulted from the large deadband ($\pm 45°$ normally) which existed in the physical angle of turn required of the head to produce a measurable signal. Recommendations are made for describing function analysis of the data and the investigation of other, mechanical methods for using head position as a control signal source.

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CHAPTER 1

INTRODUCTION

1.1 Background

Man's story is, in part, an account of the slow growth of technology and economic capacity to support the limitless projects of his imagination. Few examples of this process are more clear and inspiring than the advent of manned space-flight. Too costly for individuals, indeed, for all but the wealthiest nations, and technically impossible as recently as a decade ago, it is the fulfilment in our age of a time-less dream.

Despite its youth, the Space Age has already collected an impressive list of important dates and events. One such event occurred on March 18, 1965 when Lieutenant Colonel Aleksei Leonov stepped outside his spacecraft to become the first man to "walk" in space. This first excursion was short, lasting only ten minutes, and at all times he was attached to vital life-support systems of his spacecraft by an umbilical. Nonetheless, the feat demonstrated that men, properly suited and supplied with oxygen, could survive exposure to the weightless vacuum of space.

Merely to "float among the stars" as Leonov did is but a primitive gesture toward man's aspirations, as revealed in the fantasies of Buck Rogers and Flash Gordon, to move at will through this non-medium, maintaining control over position and attitude. Research and development have proceeded in this country and elsewhere to improve man's ability to work outside his spacecraft. Any such activity conducted by a crew member outside the parent spacecraft (s) is called extravehicular activity (EVA). Where used in the context of this report, EVA will refer to orbital "space walks" conducted in a weightless vacuum and not to lunar or planetary surface explorations in which all objects have weight.

Planning requirements have entailed defining which missions will require extravehicular activity (EVA), and has demanded attention in each of several subsystems: life support, power, communications, propellants, guidance and stabilization. It has included the design of training simulators and methods for earthbound prediction of EVA timelines. It has included design of space tools, and improvements in biotelemetry devices.

This study is restricted to the particular problem of EVA mobility and, therefore, is concentrated in the guidance and stabilization subsystem of the EVA system. The next section will outline the direction of current thinking in this area and will serve as an introduction to Chapter II which treats the subject more thoroughly.

1.2 EVA Attitude Control

The attitude control subsystem of the EVA integrated system is essential, for without the means of controlling one's attitude and position with respect to a work site, little can be accomplished. Attitude control for target viewing and for aiming translational thrusters can also serve as an inertial reference system. The specification of this subsystem involves first listing requirements placed on it by the proposed mission. Next, one of two basic systems must be chosen. The first, referred to as unstabilized or open-loop, relies for its successful performance on the astronaut who has complete control over such aspects as timing and vectoring of thrusters, for example. The second system, called stabilized or closed-loop, describes a condition whereby attitude-hold, translation, and attitude changes can in some way be programmed into an automatic control system which then effects the assignment and retrieves some feedback information for reference. Within these two categories one must choose the precise controller which will be used to activate the system. Finally, a controller technique or strategy must be chosen such as to optimize the "feel" of the system for the EVA astronaut.

An attitude control system (ACS) must have a 360° command capability in each axis so that the astronaut can orient himself in any direction. Experiments in the simulation of various maneuvers have shown this capability should be available at levels from five to thirty degrees per second (55). Possible disorientation due to vestibular effects determine the upper extreme (26). Translational acceleration of .5 ft/sec^2 is desirable.

Presuming some attitude error in manual or open-loop control, and the existence of an error dead-band limit cycle in the closed-loop configuration, a limit must be set as to the size of such errors. The determining factor is found in the accuracy required for translational maneuvers. Several techniques for translation and rendezvous with a target are available, but all require that the astronaut monitor his approach and make necessary corrections. On the basis of one such scheme, a nominal threshold of twenty milliradians ($\pm$ 1.2°) was established (18).

Given the requirements outlined above, one can investigate the several open-loop and closed-loop methods which have been studied, as well as control strategies. This survey is the subject of Chapter II.

1.3 The Problem

Despite a vast expenditure of time and talent in the field of EVA operations, a few important problems remain. One of these is clearly the need for a simple controller by which an astronaut could order a change in his attitude or, alternatively, could resist change if he so desired. Those controllers which are currently receiving most attention require the use of one or both hands, a serious inconvenience if one is engaged in the fine adjustment of an orbiting telescope, for example. Or they include in their design "arm rests" which add volume to the overall system and do, themselves, restrict motion. Of the many alternate controllers which have been conceived, that of the head provides an enticing picture. To effect a ninety degree left turn by, for example, simply turning the head left would be a simple, natural control which, when provided with a lockout device for those times when head motions are not for the purpose of attitude change, appears attractive. Can the head be utilized effectively as a controller of one's attitude? This is the basic question addressed by this study.

At least two approaches to answering the question are possible. While the experiments to be described deal with only one approach, a second is discussed in a later chapter.

1.4 Results

Experiments were performed in which subjects attempted to control their yaw attitude while seated in a chair free to rotate about its vertical axis. A random input signal was sent to the chair's torque motor which resulted in left-right rotations. Each subject attempted to counteract this motion and keep the chair stationary by sending a compensating control signal to the chair. Control signals were generated by both a conventional stick and by electromyographic impulses induced by left-right head movements.

Subjects were able to control their attitude using electromyographic signals. While performance was worse than with simple stick control, a measure of "performance index" was found to be in the same order of magnitude in both cases.

On the basis of collected data in one axis, attitude control by means of head motions appears feasible. The main problem encountered was that of a significant "dead zone" of electrical inactivity from +45 degrees to -45 degrees of head angle. Experimentation to shorten that gap is one of several recommendations made in conclusion.

1.5 Outline

Chapter II provides a survey of EVA attitude control devices which serves as the context for the remainder of this investigation. Chapter III contains a review of electromyography, its history and present state-of-the-art. Chapter IV describes the experiments which were performed in the Man-Vehicle Laboratory at MIT to test the use of electromyography (EMG) in attitude control. Chapter V summarizes the results of these tests, and Chapter VI suggests recommendations as well as an alternate approach to the basic question of head motion as a controller.

CHAPTER II

EXTRAVEHICULAR GUIDANCE AND STABILIZATION

2.1 Introduction

This chapter includes a description of the various attitude control devices which have been suggested for EVA. Open-loop configurations are mentioned first, followed by closed-loop designs. Alternate controllers are next reviewed, and a brief discussion of control techniques or strategies completes the chapter.

2.2 Unstabilized (Open-Loop) System Designs

2.2.1 Self-Rotation Techniques

The simplest possible means of attitude control and translation in space is that of self-locomotion, without the assistance of any propulsive or stabilizing device. A knowledge of the inertial characteristics of the human being is essential in planning for this system, as well as for all subsequent systems. Anthropometric data must be gathered before dynamic response characteristics can be determined for a body in weightless free-fall. While any analytical representation of biomechanical properties is approximate, several studies have proved useful as a basis for estimating dynamic response. DuBois developed a semianalytic technique based on computer analysis of data in a double axis compound pendulum test of subjects (19). Whitsett developed a distributed mass model based on the USAF "mean man" which Drissel extended to a suited astronaut (18,61). Five postural variations were defined. The effect of a homogeneous weight-distributed one hundred-ninety pound backpack was also determined.

Based on these data, the principal moments of inertia as expressed in body coordinates for each position were determined.

Given such models, research was conducted at Stanford University to determine the change in orientation of the human body in weightlessness resulting from specified motions of the limbs relative to the body. A computer program assisted the evaluation (36,52). The mobility restraints inherent in currently used soft space suits places a severe limitation on such a system and effectively challenges the overall practicality of the technique.

Limited maneuvering by judicious handling of an astronaut tether has received some attention. Motion is restricted to certain transfers and poses several significant problems in accuracy and even astronaut safety.

Manual locomotion techniques may be practical where the tasks are confined to a spacecraft surface such as inspection and maintenance.

2.2.2 Hand-Held Maneuvering Unit

Among the simplest propulsive devices used in conjunction with body motions for orbital locomotion is the Hand-Held Maneuvering Unit (HHMU). Like most unstabilized control schemes, the HHMU offers a relatively light means for achieving short distance translations and for carrying small payloads. First flown aboard Gemini IV and further evaluated on later Gemini flights, this variable-thrust device has received extensive review (47,48). A summary of Gemini X HHMU characteristics appears in Table 1.

In determining the dynamics of an astronaut using the HHMU, it was suggested that an astronaut operating at the end of a tether would be less likely to encounter large rotations in any axis other than that of the tether itself. The explained reason is that the rotational energy causing wrap-up must be converted to translational kinetic energy for wrap-up to continue, which would eventually null the rotation.

Table 1 (48)

GEMINI X HAND HELD MANEUVERING UNIT CHARACTERISTICS	
Propellant, gas	Nitrogen
Thrust, tractor or pusher, lb	0 to 2
Specific impulse, sec	63
Total impulse, lb-sec	677
Total available velocity increment, ft/sec . . .	84
Trigger preload, lb	5
Trigger force at maximum thrust, lb	8
Storage tank pressure, psi	5000
Regulated pressure, psi	125 ± 5
Nozzle area ratio	51:1
Weight of usable propellant, lb (in spacecraft) .	10.75
HHMU weight, lb	3
Gross weight of extravehicular pilot, lb	260

Finally, the control logic employed by astronauts was simply to aim the thrusters constantly toward the target, positioning them with respect to the body as required to null out any disturbing torques.

Research has continued to perfect a hand-held hydrazine thruster which decomposes this fuel into nitrogen and hydrogen gas (32).

2.2.3 Foot Controllers

It should be clear that in addition to its relatively short lifetime, a major disadvantage of the HHMU lies in the requirement that one hand and arm be used exclusively for effecting such control. Other more desirable controllers can be suggested and will be discussed in greater detail later. The concept of foot controllers and foot-located thrusters is one such alternative; it will be discussed here because of the open-loop nature of most such systems which have been proposed. The preliminary research and development in this area has been accomplished primarily by three groups: 1) Langley Research Center, 2) Grumman Aircraft Engineering Corporation, and 3) General Dynamics/Convair. These three approaches will be treated below in turn.

The basis of all theory in foot controllers rests in the supposition that the human balancing reflex can be adapted for use under zero-gravity conditions. This view was first propounded by Charles Zimmerman of NASA in the early 1950's. His central thesis was that the learned pattern of reflexes used by a person in standing is essentially the same as that required to balance a force-vector supported platform and, hence, should be directly applicable to the control of hovering vehicles (65). His demonstration of this concept caused much interest and subsequent research among aeronautical engineers.

The word "reflex" is, perhaps, inaccurate as some physiologists believe the balancing ability to be the learned coordination of many simple reflexes. A person in a normal stance remains balanced by making continual fine adjustments of foot and leg muscles in response to various sensory inputs. For example, if a person is forcibly tilted forward or backward he instinctively varies the amount that he pushes with his toes to remain balanced. If he stands on a rug which is pulled gently forward, he is tilted gently backward; he instinctively responds with an appropriate decreased toe pressure. Conversely, when a person reduces his toe pressure he expects to be tilted forward. Suppose now, that the person can control the direction of this rug: pushing his toes down accelerates the rug forward; reducing his toe pressure accelerates the rug backward. In essentially this manner can one control, in theory, a jet thrust device attached to the feet.

A project which grew directly out of Zimmerman's early work was that of the "jet shoe" for use in extra-vehicular motion. The somewhat instinctive movement of feet and legs used by skin divers to maneuver in a medium that simulates to some extent the "free fall" condition of space suggested the concept of placing jets on the shoe soles of an EVA astronaut.

This was done at Langley Research Center (57). A switch was mounted in the toe of the shoe so that a downward flexing of the toes closed the switch and turned on the jet. Each jet shoe was independently controlled, and the nozzle of each was tilted forward thirty degrees from the perpendicular to make possible equal pitching moments in both directions. Tests to determine the feasibility of such a concept were performed on five facilities including two air-bearing facilities. In two of the later simulations, six degrees-of-freedom were achieved. Pilot control, allowing for simulator artifacts, demonstrated a potential for such a device. The chief advantages are simplicity and freedom of hands.

Several disadvantages are inherent to this system, however. No pure rotation is ever possible because a force couple does not exist. Pure translation is difficult to achieve because it requires a thrust vector passing directly through the center of gravity. All pure translations must be in a head-first direction. Retro-thrusts require first a rotation to reverse one's attitude.

An extensive research program continues in the adaption of the original flying platform to lunar rovers (30).

Grumman Aircraft Engineering Corporation followed up the work of Zimmerman described earlier with preliminary experiments designed to provide more information about the human balancing reflex. Keller and O'Hagan reported development of a hydraulically-driven carriage which permits a pilot to make limited (ten feet) excursions in response to small tilting motions of a control platform on which he stands (38). Provision is made for adjustment of platform height relative to its pivot point and for simulation of parameters such as spring, damping, and moment of inertia. Early experiments located optimal positions for system gain (carriage acceleration per unit platform tilt), platform height, and a preference for acceleration rather than velocity as a response to platform tilt. A second series of experiments dealt with other parameters. The addition of platform inertia, for example, was found to be highly detrimental, contributing to overshoot and difficult low frequency oscillation.

The basic goal toward which Grumman researchers had worked was the adaption of successful one-g platform control of five degrees-of-freedom to a zero-g environment. The first simulated zero-g test of the system, however, revealed that little control "feel" was experienced by the subjects and, therefore, control was difficult. This was attributed to 1) the low gains (angular acceleration per degree of ankle deflection) which were required to prevent bizarre motions, and 2) the very brief periods of thruster "on-time" required to produce rotation. These weaknesses exist as well in the "jet shoe" concept discussed above, and strongly suggests that such a system would be restricted to accomplishing translational thrusts without precise controllability. The use of a single thruster to control five degrees-of-freedom in a weightless environment does not now appear practical.

New tests were prepared and carried out on a three degree of freedom air-bearing platform (one rotational, two translational degrees in the horizontal plane) (37). A subject was positioned on his side in the "zero-g scooter" and tests in uncoupled pitch rotation were conducted using ankle defection as a controller. Translation artifacts due to unbalanced force vectors were cancelled by the addition of thrusters to form a pure couple. Results were optimistic and subsequent tests were performed on fore-aft translations (bending the torso forward to cause forward motion) and up-down translations (legs stretched for upward motion, semi-squat for downward). All three degrees-of-freedom were next tested simultaneously, and the results were highly encouraging. Yaw control was tested on a separate stationary platform capable of rotation only. Body twist was found to be a "natural" control in yaw. Roll motion controlled by differential foot lifting was also tested.

The question of whether proportional acceleration control or on-off control is best in such tests is unanswered. On-off control is a simple mechanism. The control strategy assumed by subjects using on-off control has a tendency toward sequential attendance to the various degrees of freedom as opposed to the more smooth, simultaneous operation characterized by proportional control. Also, simultaneous operation in three-degrees-of freedom in a plane does not necessarily mean that spatial operation will be feasible. Finally, the question of space suit interference has yet to be satisfactorily addressed. Test results imply that the body deflections required for motion are quite small, but full-dress simulations are clearly called for. Despite these questions, the concept of separate uncoupled control of several degrees-of-freedom looks promising. The desirability of locating thrusters adjacent to the corresponding "control elements" of the human body is evident from the results of such tests; in this position they function also as a means of providing proprioceptive feedback (37).

A somewhat related approach was taken by investigators at General Dynamics/Convair. Wrench and Greensite proposed a system using twin two degree-of-freedom control moment gyros (63). Shoe-mounted units, controlled by muscle action about the ankles, was envisioned.

Two shortcomings characterize this system despite extensive theoretical development. Maneuvers are limited to sequential rotations if cross-coupling is to be avoided at large gimbal angles. Momentum saturation is always a limiting factor in such systems. While the CMG can handle cyclic torques for extended periods, an EVA astronaut is likely to encounter constant external torques. These, in turn, produce a constant gimbal angle rate and cause the CMG to reach maximum capacity. Some active source is required to desaturate the CMG implying an additional weight penalty. Reaction control jets might possibly perform this function by 1) torquing the system at times dependent on gimbal angle or rate, or 2) using fixed-time pulses initiated by gimbal angle. This, of course, requires the introduction of thrusters into the attitude control system and makes questionable the advantage of CMG's. Slow steady-state rotation rates and the present uncertainty of the degree to which an astronaut could "naturally" or otherwise control such a system make its use in the near future appear unlikely.

2.2.4 Summary of Open-Loop Designs

The previously discussed studies of a passive system for extravehicular attitude control have demonstrated high potential for future use, but also some limitations. Among the latter is the fundamental stability problem encountered when a system is designed in the "pusher mode", with thruster behind the astronaut's center of gravity. In addition, passive systems rely on the capacity of the human vestibular system to accurately sense angular rate, since one can expect that frequently visual inputs will be minimal. The semicircular canals have dynamics similar to that of an overdamped, second order torsion pendulum (64). A subject's subjective angular velocity as a function of time is shown in Figure 1. Notice that were an astronaut to encounter a constant velocity spin and subsequently succeed in stopping it, he would feel that he had begun rotating in the opposite direction. Corrective action based on this false information could cause him to re-enter the original spin.

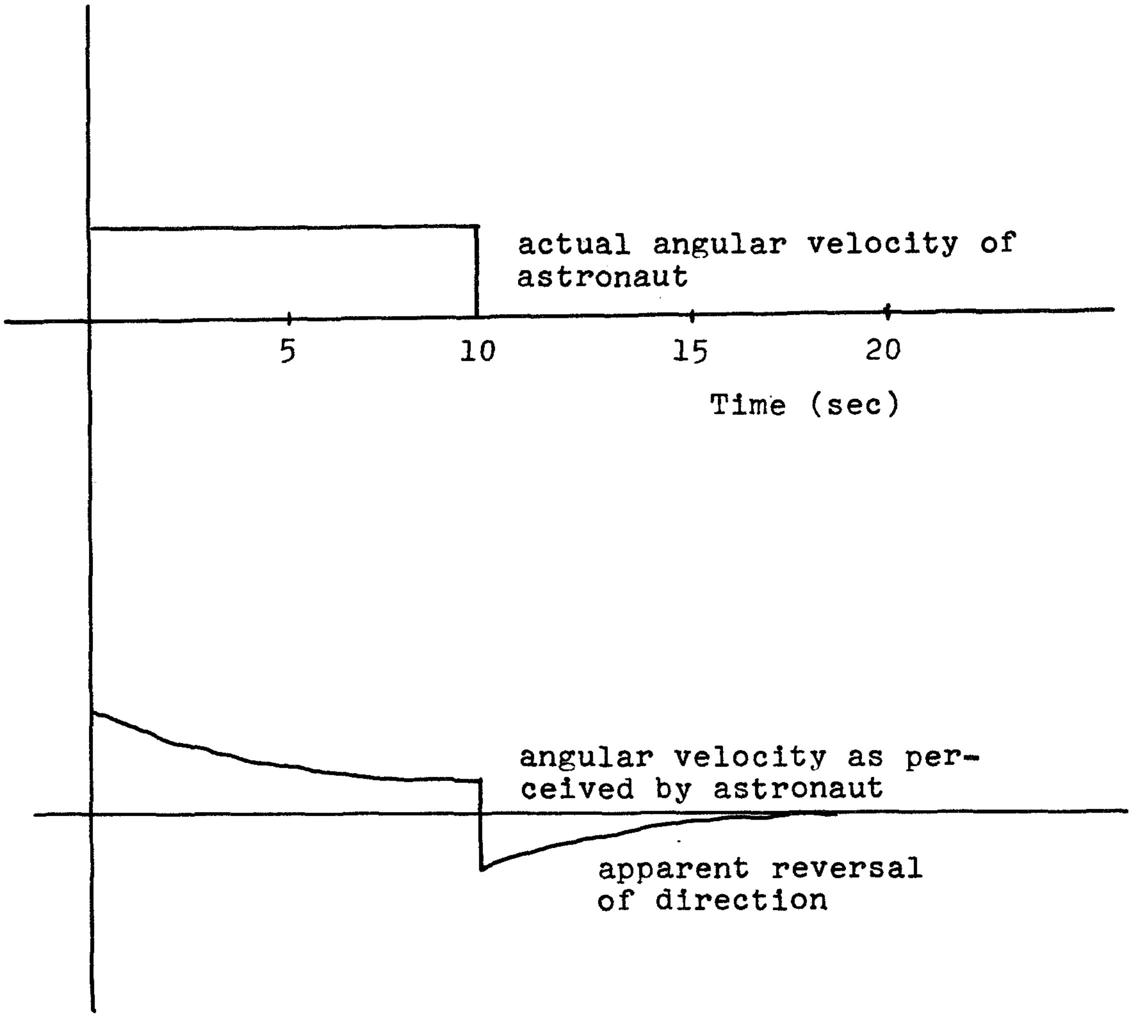

Figure 1
Actual vs. Subjective Angular Velocity (64)

2.3 Stabilized (Closed-Loop) System Designs

2.3.1 The Astronaut Maneuvering Unit

The limitations of a passive EVA maneuvering system emphasize the potential of active systems in providing a means for long range (less than one mile) translations. The term Astronaut Maneuvering Unit (AMU) has generally been associated with the attitude-stabilized backpack designed for this purpose. The AMU provides life support, propulsion, communications, and automatic attitude stabilization; and it permits the astronaut to operate as an independent small maneuverable spacecraft system. An orthogonal arrangement of fixed thrusters located symmetrically about the astronaut/AMU center of gravity assures precise control. Combined with automatic stabilization, it provides great versatility.

The Modular Maneuvering Unit (MMU) and the AMU built by LTV Astronautics Division for the Gemini Program have been described extensively (41, 45, 47, 48, 49). The operational requirements and unit characteristics are listed in Tables 2 and 3.

Table 2

AMU Operational Requirements (49)
1) Extravehicular mission duration - 4 hours 2) Multiple mission capability - 6 missions 3) Maneuvering range - 1000 feet 4) Payload weight - astronaut + 168 lbs. 5) Total velocity change - 235 fps 6) MMU redundancy philosophy 7) Stabilization and control auto stabilization - 3 axes rate command orientation - 3 axes automatic/manual mode

Table 3

Gemini IV-A AMU Characteristics (47)	
Propellant	90 percent hydrogen peroxide
Total thrust (fore-and-aft or up-and-down), lb	4.6
Pitch moment, in.-lb	63.5
Roll moment, in.-lb	44.2
Yaw moment, in.-lb	47.7
Specific impulse, sec	169
Total impulse, lbxsec	3100
Total available ΔV, ft/sec	250
Controller characteristics:	
Breakout:	
Fore-and-aft, lb	4.5
Up-and-down, lb	4.5
Pitch, lb	4.0
Roll, lb	4.0
Yaw	small
Maximum force:	
Fore-and-aft, lb	9.75
Up-and-down, lb	9.75
Pitch, lb	10.5
Roll, lb	10.5
Yaw, in.-lb	13.0
Maximum deflection, deg:	
Fore-and-aft	6
Up-and-down	6
Pitch	6
Roll	6
Yaw	4.5
Attitude-limit cycle periods, sec:	
Pitch	59
Roll	50
Yaw	3.2
Attitude deadband, deg . . . . (3 axes)	± 2.4
Maximum control rates, deg/sec:	
Pitch	18
Roll	27
Yaw	18
Maximum nitrogen tank pressure, psi .	3500
Regulated hydrogen peroxide pressure, psi	455
Nozzle-area ratio	40:1
Weight of propellant, lb	24
Weight of Astronaut Maneuvering Unit, lb	168
Weight of extravehicular pilot, lb . .	407

The propulsion system chosen was one of hydrogen peroxide with a total impulse of 3500 pound-seconds. Twelve thrust chambers provided 2.3 pounds of thrust each. The flight control system provided manual and automatic three-axis attitude control and stabilization and manual translation in two axes. Two redundant systems were available. Control commands were made manually through the control handles located on the controller arms. The left-hand controller provided translation commands; the right-hand controller provided attitude control. The left-hand controller included a mode selection switch which was used to choose between automatic and manual control. In the manual control mode, translational inputs resulted in accelerations of .35 ft/sec^2 for the duration of the input.

Pure translation was difficult because of the offset of the center of gravity from the center of thrust. In the automatic (stabilized) mode, pure translations could be obtained from translation inputs, but the acceleration level was approximately halved due to attitude control requirements on thrusters. The translation controller would produce constant linear acceleration (interrupted to make automatic attitude corrections) for as long as it was activated. A priority was incorporated on the jet-select logic for the forward and aft-firing thrusters which gave yaw first priority, pitch second, and translation third. The AMU did not include lateral thrusters. Pulse width modulation was utilized, with thruster on-time directly proportional to the input signal. Above a certain error level (called saturation) thruster firing was continuous; below this level thruster firing became intermittent with thruster ON pulses becoming shorter and further apart as the error decreased until below a certain level (threshold) the thrusters were off continuously. The resultant motion was an average angular acceleration proportional to the error in the region between the saturation and threshold levels. When a rotation was commanded, the error was the difference between the preset fixed rate for the commanded rotation and the actual rate.

Rotational inputs in the manual mode resulted in angular accelerations of 11, 13, and 25 degrees/sec^2 in roll, pitch, and yaw respectively for the duration of the input. Pure rotation was not possible in the manual mode but could be attained in the automatic mode. Accelerations would occur on command at the levels specified until an angular rate of 18 degrees/sec in pitch and yaw, or 26 degrees/sec in roll was achieved. Angular acceleration would then stop, and a continued input to the attitude controller would result in this rate being maintained. Releasing the controller head would allow it to return to a neutral position and deceleration would begin. When rotation ceased, the system would go into an attitude-hold mode, maintaining attitude within ± 2.4 degrees/sec in each axis. When the sum of the angular displacement and the angular velocity about a given axis exceeded ± 2 degrees (deg/sec) an attitude correction would be made about that axis. Thus automatic attitude corrections were made dependent not only on the angular displacement but also on the rate of angular displacement. A system of rate and integrating gyros sensed these parameters about all three axes. In the absence of external torques, the period of limit cycle operation within this deadband was greater than twenty seconds (41, 48).

2.3.2 Alternate Controllers

While the AMU described above fulfilled the requirements of the scheduled Gemini IX-A EVA, it relied upon the use of both hands for successful control. In this respect, it was less practical for use in performing space work than some other systems already described. In addition to the need to minimize use of the hands in controller operation, it is also necessary to preserve body and limb dexterity, to the degree that is possible given an inflated soft space suit. Controller "arm rests" on either side of the AMU pilot limited arm motion; they could also interfere in a cramped work site condition. The need exists for the development of alternate means of control. In addition to the requirements already mentioned, a system cannot either obstruct visibility or interfere with normal voice communication.

W.E. Drissel, et al. conducted a survey of controller concepts for use in an AMU (18). Hand, oral, eye, and body controllers were studied and compared for such traits as command capability, accessibility, accuracy, "naturalness", and reliability. Hand controllers have already been discussed. Oral controllers offer a variety of alternatives because of the number of elements available for use: the lips, tongue, the teeth, breath, speech, whistling, etc. Only breath, tone and voice controllers appear acceptable to pilots and these are now considered.

Breath controllers possess attractive features: complete hand freedom, simple mechanization, and the on-off, incremental, or (in the case of a set of actual mouthpieces), proportional commands. The disadvantages include an increased burden on the environmental control system in terms of both oxygen supply and water removing capability, the space limitations inside a helmet, and the artificiality of the control code. This last factor may not be important, except that under conditions of great stress regression occurs, during which highly artificial relationships are temporarily forgotten. Similar disadvantages attend the use of a singing or humming tone for control purposes.

The operational simplicity of a voice (speech) controller is at once attractive; ten natural language words could conceivably suffice. This approach was chosen for a detailed feasibility study (18). Thirty-six commands were determined as fulfilling requirements; several of these utilized repeated words of the vocabulary to restrict the number of actual words to ten. This vocabulary is listed in Table 4.

Table 4

Suggested Vocabulary for Speech Controller (18)	
Word	Primary Function
Roll	Denotes roll rotation
Pitch	Denotes pitch rotation
Yaw	Denotes yaw rotation
X	Denotes translation along X axis
Y	Denotes translation along Y axis
Z	Denotes translation along Z axis
Plus	Denotes positive direction of motion
Minus	Denotes negative direction of motion
Stop	Removes all commands from ACS
Cage	Places ACS in synchronous mode

Two rules were established:

1) In attitude, continuous utterances command continuous rotation. Silence commands constant attitude.

2) In translation, continuous utterances command continuous acceleration; silence commands constant speed (a special case of which is zero speed relative to the astronaut's parent vehicle). An output logic was developed and the system was simulated using a computer to control an oscilloscope pattern. Voice commands were relayed to a human controller who would enter the commands into the computer in normal fashion. Results were encouraging. Subsequent development has lead to the definition of a completely mechanized system which is currently under assembly (29). The primary disadvantage of this system lies in the need for a computer program to perform tasks in voice-recognition and logic.

The use of the eye in attitude control was investigated from three approaches: sensing the deflection of a beam of light reflected off some portion of the eye; sensing the vector position of the front-to-back potential of the eye; and sensing the action potentials of the eye muscles. Specific problems of the first approach are the excessive equipment required and the precise initial alignment which must be maintained. The second approach utilizes the fact that the eye behaves like a small battery, being electrically positive at the front (cornea) and negative at the back (fundus). Pairs of electrodes placed around the eye will sense its rotations in terms of altered potentials. The need for frequent calibration and the variations made possible by galvanic skin response and other extraneous signals make this approach questionable in value. Similar arguments are used against sensing eye muscle action potentials. The primary advantage of using the eye is that it acts as an optical self-correcting error-detecting device. It is not, however, a controller in the strict sense but merely an aiming device that could provide steering information to the AMU. The ACS still needs command inputs to remove or insert the eye in the control loop, to provide an "execute" signal at the proper time, and to command a fast or slow speed of execution. More research in this area could produce encouraging results, however.

The use of the body as a controller has already been considered somewhat with an earlier discussion of leg and foot control. In addition to the difficulties cited earlier such a mechanism could entail a loss of worker mobility at the work site. Torso controllers appear to be impractical due to the strong mechanical intercoupling between the AMU and the torso. This leaves only the head as a possibility.

The head may be used for control in two ways: with and without a visual sighting mechanism. When used in conjunction with sight, this concept is similar to eye controllers. Pickoffs sensing the relative position of the helmet to the AMU would provide signals to the ACS translating the astronaut to the observed target. As with the eye controller, auxiliary controls would be required.

The second method of using head position is to instrument the helmet so that signals are generated by nods, turns, and tilts of the head. These could be made to command pitch, yaw, and roll, respectively. Speed level, execution, and lockout controls would be required. Possible interference with visual capability of a suited astronaut is shown in Table 5 and the neck mobility in three axes in Table 6.

Table 5

Range of Vision (Suited) (59)	
Horizontal plane	120°left, 120°right
Vertical plane	105°down, 90°up

Table 6

Maximum Neck Mobility Requirements (59)		
Flexion (forward-backward)	120°	zero torque
Flexion (left-right)	30°	zero torque
Rotation (Abduction-Adduction)	140°	zero torque

Still another possible use of the body lies in the field of myoelectrics. Most processes in living organisms are accomplished by electrical changes. Actions of voluntary muscles in operating the limbs exhibit such changes. The measurement of these biocurrents is called electromyography, and is being used now primarily in the operation of prosthetic devices for amputees. Raw electromyographic signals are characteristically spiked, having amplitudes in the low milli-volt range. A practical, reliable technique must be found for sensing, amplifying, filtering, conditioning, and decoding these voluntary signals for command and control purposes. Such signals would undoubtedly be useful for command and control where the human operator finds normal manual control impractical due to restraint or other use of the limbs.

2.4 Control Techniques

Once a controller has been chosen, it is necessary to determine the technique by which attitude will be maintained. If the system is open-loop, a signal will be generated directly by the astronaut; if a closed-loop or stable system a signal will automatically be generated when certain chosen parameters exceed pre-set limits. Haeusserman has reviewed in detail the types of sensors available for this purpose in automatic systems (27). The treatment of these signals must be determined to optimize a chosen set of parameters. The following paragraphs will make note of the systems which have been suggested both for automatic and manual control.

2.4.1 Control Alternatives

Several traditional control techniques are available for use (18, 34). Simple acceleration command applies the signal directly to the reaction thrusters which apply a torque proportional to signal strength. The resulting rotational acceleration is likewise proportional from the formula

$$T = I\alpha$$

Angular rate command or rate feedback is the traditional technique used in airplane autopilots but is subject to a high power requirement. Another technique is known as the orbit mode which uses fixed pulse widths of rocket thrust corresponding to a set of predetermined angle errors. This method provides for low residual rates and low propellant consumption at the cost of complex circuitry and large errors in the presence of disturbing torques. Derived rate control employs a lead network to feed a rate plus attitude signal to jets. Disadvantages include the noise sensitivity which is produced by the lead network and the possibility of saturation. Pseudo-rate feedback lags a signal proportional to angular acceleration in a pseudo-integration process and sums this signal with that of attitude. The result is a pseudo-rate control signal which is less noise sensitive than rate feedback and capable of reducing limit cycle rates to a low figure with small impulses.

A study conducted by Honeywell, Inc. for an AMU resulted in selection of a combination of orbit mode control and pseudo-rate control, the latter being initiated when the error continued beyond a certain range deemed wholly within the capability of orbit mode (18).

2.4.2 Comparative Studies

The analytic techniques through which a comparison of approaches can be made is based on nonlinear feedback control theory. Several studies have been performed in this field (12, 16, 56, 22, 21).

Selection of an optimum control technique for an automatic attitude control system depends on which parameters are to be maximized or minimized and to what values. For a manual, open-loop control system, selection must rely heavily on how each candidate system "feels" to the pilot and how his performance compares. The response of a manual system is very dependent, as well, on the minimum impulse that a pilot can activate. Recent studies of remote manipulators have been made to determine an optimal system (33). Crawford and Kama conducted four groups of experiments designed to produce an ordered list of preferred manipulator control techniques based upon performance of a human operator at a given task (15). The results demonstrated a preference for proportional rate systems over a fixed rate on-off controller. A comparison between position control and rate control was difficult to assess, and more research was deemed necessary which would consider such factors as operator fatigue.

Control of a remote manipulator is different from control of one's own attitude and work must be done in this area to determine the optimal manual system. Simulations conducted by Emerson demonstrated that angular acceleration command would maintain adequate attitude control if center of gravity thruster misalignments were small and accelerations were not large (20). A rate command system is sufficient according to these studies unless, at great ranges from the target, drift rates in the ACS are misinterpreted as real translational velocities of the target and "corrected" accordingly. The incorporation of an attitude-hold feature such as afforded by inertia-exchange devices or a system of reaction jets was found by simulation to be an effective means of overcoming the need for precise rate control. Further experiments involving human operators are called for, featuring a visual simulation of variable range.

CHAPTER III

ELECTROMYOGRAPHY

3.1 Introduction

An electromyographic signal (EMG) is a manifestation arising from the transfer of nerve impulses to muscle impulses.

Galvani was the first to observe and record the phenomenon in the late Eighteenth Century in his famous experiments with frogs' legs. Interest in the field was not appreciable until the early 1950's when Norbert Weiner suggested the use of these signals in artificial limbs or prostheses. Subsequently, American research and development lagged behind that of England and the Soviet Union. In 1955 British scientists reported the use of EMG's for on/off control of a prosthetic hook (5). Around a year later, a Russian prosthetic hand was announced which opened or closed at a constant velocity or could remain in any intermediate position. This, too, was controlled by EMG's. (11)

During the period 1962-1966 work proceeded at the Massachusetts Institute of Technology on development of a prosthetic "Boston Arm" (1). Similar efforts were initiated by Reswick, et al. at Case Institute (50). In 1964 Bottomley and Cowell announced creation of a prosthetic hand whose velocity was controlled by EMG amplitude. When the hand encountered an object, then a force feedback loop dominated and force became proportional to EMG amplitude (8). This design, with that of the Boston Arm, were the first to use EMG's proportionally; all other projects employed the signal as a two-state on/off or three-state forward/off/reverse control. The development of proportional control required measuring techniques which could distinguish levels of muscular activity from a relaxed state to one of maximum effort (44).

Other uses besides prosthetic limbs have been suggested and explored. These include control of high acceleration aircraft where a pilot cannot physically move his limbs, and the field of orthopedic analysis and diagnosis (24).

3.2 Physiology

Two kinds of muscles are found in man. Skeletal muscles are responsible for all voluntary movement. Cardiac or smooth muscles are mostly involuntary and include the heart and other visceral bodies.

The connection between the body's thousands of nerve fibers and its thousands of muscle fibers follow a basic pattern; and therefore a basic functional unit may be defined. Each skeletal muscle contains thousands of muscle fibers; nerves are likewise comprised of 1) motor nerve fibers (axons) and 2) sensory nerve fibers (both afferent and efferent). Each motor nerve or axon arises from a nerve fiber in the spinal cord called a neuron. Each axon, in turn, branches and innervates single muscle fibers. The combination of one neuron, its axon and axon branches, and the muscle fibers stimulated by those branches comprise a basic functional unit called a motor unit (62). One should note that all muscle fibers in a single motor unit need not be effected each time an axon receives a signal.

The transmission of a nerve impulse to a muscle impulse is chemical (62). The appearance of a nerve impulse in the vicinity of a muscle fiber liberates acetylcholine which depoliarizes the muscle fiber membrane. This depolarization is propagated down the length of the muscle fiber resulting in an impulse longer in spike dura tion than the nerve impulse but traveling at a comparable speed (five meters per second). This traveling depolárized impulse causes a mechanical twitch to begin which continues in the muscle fiber after the first is gone. A sketch comparing the three types of impulses is shown in Figure 2.

Each muscle fiber produces a maximum contraction if at all. Therefore the strength of contraction is determined by 1) the number of motor units in action and 2) the rate of motor unit discharge. If two impulses to the same muscle fiber are separated by more than five milliseconds, two separate mechanical twitches can be perceived. If, however, the rate of discharge is such that impulses are separated by

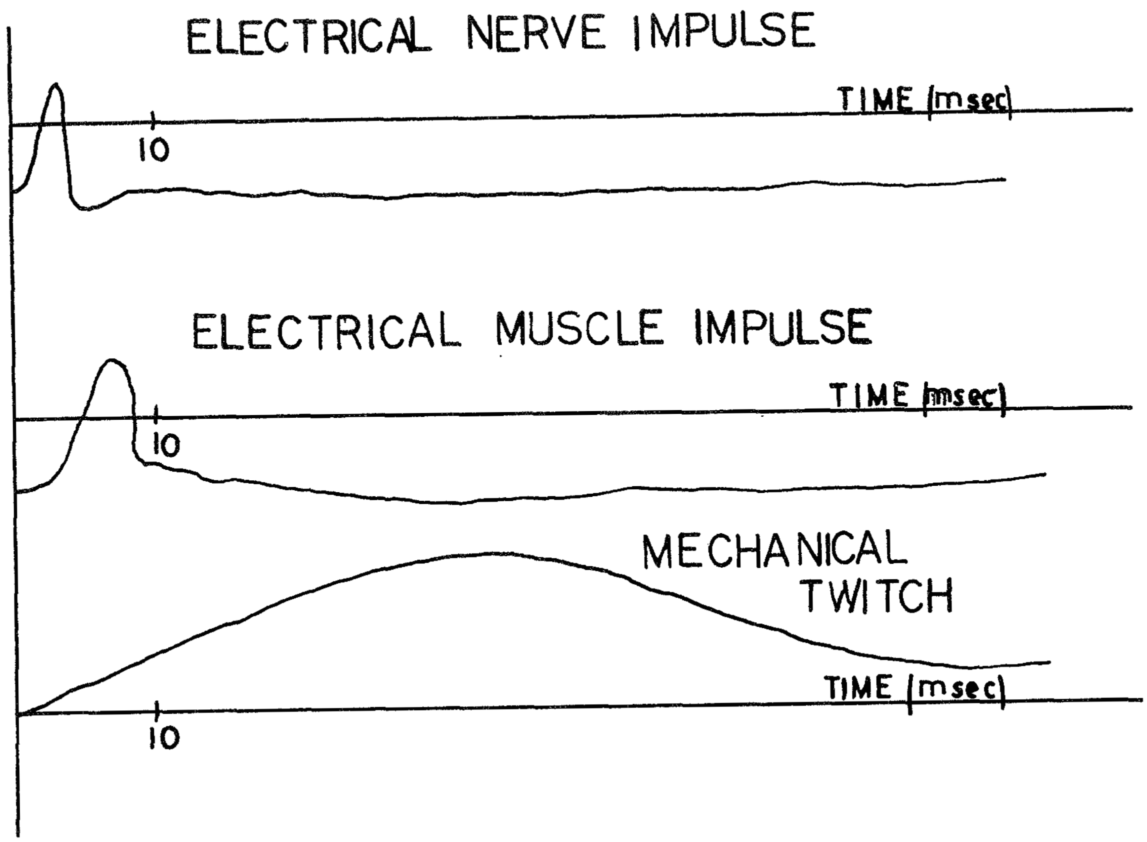

Figure 2

Nerve, Muscle, and Mechanical Impulse (1) less than five milliseconds, the effect will be to combine the two and produce a larger response. The motor units of a single muscle fire irregularly which allows some average rest period for each. If the stimulus rate of a single muscle fiber exceeds fifty per second, the muscle twitches thus superimpose to cause a maximum tension considerably exceeding maximum twitch tension. This state is known as tetanus.

The uniform tension of gross muscle is an average of "random" motor unit excitations. Any motor unit whose average excitation frequency is below that corresponding to tetanus produces an average tension which can be varied by varying the excitation rate.

A single muscle impulse is measured on the skin surface as a pulse of about a millivolt amplitude and five millisecond duration. Such a pulse constitutes the basic electromyographic signal. An EMG is actually a measure of the potential generated by the electric field which corresponds to a muscle fiber depolarization. Any pair of electrodes in the vicinity of this muscle activity will measure the combined effects of fields of all muscle fibers in a muscle.

3.3 EMG Measurement

An EMG as measured from the skin surface resembles the output of a noise generator and can reach an amplitude of a few millivolt rms. The simplest means to measure this signal is with surface electrodes in which the output impedance of skin and electrodes is as high as 50KΩ to 100KΩ.

Precise measure of a particular muscle or muscle area can be achieved by electrode implantation. Here the aim is to implant within a muscle, but no attempt is made to go inside a muscle fiber. Surgical implantation has been performed as well as the insertion of a pair of thin wires into the muscle through the skin by any of various techniques. There are monopolar, coaxial, and bipolar needle electrodes (54, 3).

Several difficulties exist with implanted electrodes. They are much more sensitive to signals from a small number of motor units with which they are in close proximity and less sensitive to others farther away. One report states that the signal attenuates in a single motor unit to one tenth of its maximum value at a distance of .38 millimeters from the center area of fiber distribution (60). Given the random nature of motor unit firings, it is likely that certain muscle contractions would register little or no activity as measured by a highly localized electrode. Work is continuing, however, on the design and fabrication technique for multi-channel, physiologically implantable telemetry systems for bio-measurements including EMG's (31).

Surface electrodes offer several obvious advantages. No skin piercing is required. The ratio of distance from electrodes to the farthest motor unit versus nearest is not as great. One should expect a less biased average measurement. A major problem, however, is the noise artifact induced by skin motion. In recent years, this problem has been minimized by development of recessed electrodes and the use of electric paste to make the signal to noise ratio higher and permit full-day use without drying.

The separation distance between two surface electrodes affects the signal measured. A greater bandwidth results in a smaller time constant required to measure accurately the root mean square value of a signal. It was found that the measured EMG acts like filtered noise and a decrease in electrode distance from twenty to one millimeter separation increases the bandwidth from 100 to 500 Hz. The resulting improvement in time constant is seventy percent (35).

Current popular models of skin electrodes require first a thorough skin cleansing with acetone in the selected area of study followed by slight abrasion with a pin to lower skin resistance. The metallic disc which is the electrode is at the bottom of a cavity which must be filled with a saline electrode paste. Contact is thus from the skin to paste and then to the electrode itself. A double-sided adhesive is used to apply the electrode holder to the skin and serves also to maintain an airtight pocket for the paste which prevents drying. After use, simple rinsing with distilled water is all that is required.

A search has continued for material and methods of dry electrode technology (53). An obvious advantage to this system would arise in cases of measuring the EMG of astronauts, aquanauts, burn patients, and other situations in which skin preparation is either impossible or undesirable.

3.4 EMG Characteristics

An understanding of the relationship between the EMG and muscle activity is essential if one is to make use of the former as a voluntary control signal. Many studies have been conducted on this question and their results are summarized here. When the term "EMG" is used below, it implies a particular interpretation of the raw EMG. All the results to be presented are based on the same method of signal interpretation. This interpretation, along with others, is described in the next section.

The condition in which muscle length is constant is known as the isometric condition. For the isometric condition, the EMG is roughly proportional to tension. The relation is nonlinear (7, 43). The relaxation path depends on the maximum tension achieved and causes a hysteresis effect as seen in Figure 3.

There is, however, an EMG component related to muscle velocity as well. Therefore, if for some constant tension, there is a velocity tending to shorten the muscle, then the EMG rises as the velocity becomes greater. Alternatively, if for constant tension there is a velocity which tends to

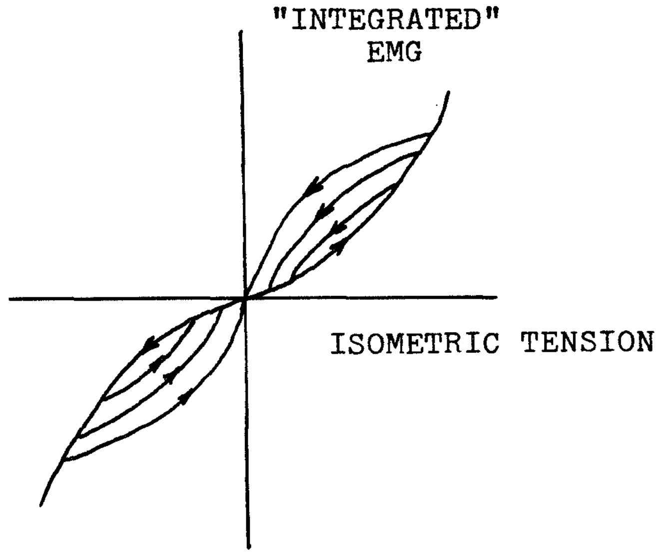

Figure 3

Isometric Tension Level in the Bicep-Tricep Muscle Pair Versus Surface Electrode EMG (1) lengthen the muscle, then the EMG drops with increased velocity (7).

The frequency spectrum of the EMG for most normal muscles lies between ten and 1000 Hertz. Excessive muscular demand leads to fatigue which causes a shift to lower frequencies, presumably due to synchronization of muscle fiber discharges (2, 13). The frequency response of the trapezius muscle is shown in Figure 4.

For short muscle requirements, the mean frequency as well as the average power rises with tension in the isometric case. See Figure 5 (9).

Kreifeldt has shown that the EMG noise to signal ratio is high for low-level signals and monotonically decreases to a minimum at 25% of maximum voluntary contraction (39).

Although the EMG is nonlinearly related to isometric tension, the function is monotonic. A human being can tolerate the nonlinearities and learn to control his own signal. Subjects who "hear" or view their own EMG can be trained to fire individual motor units in skeletal muscles (4). Later these feedbacks can be removed and subjects are able to control devices such as small motors which are being operated from an EMG. On such experiments are based the variety of recent developmetns in prosthetic devices as well as the experiments described in the next chapter.

3.5 EMG Signal Conditioning

Once the EMG has been successfully detected, the

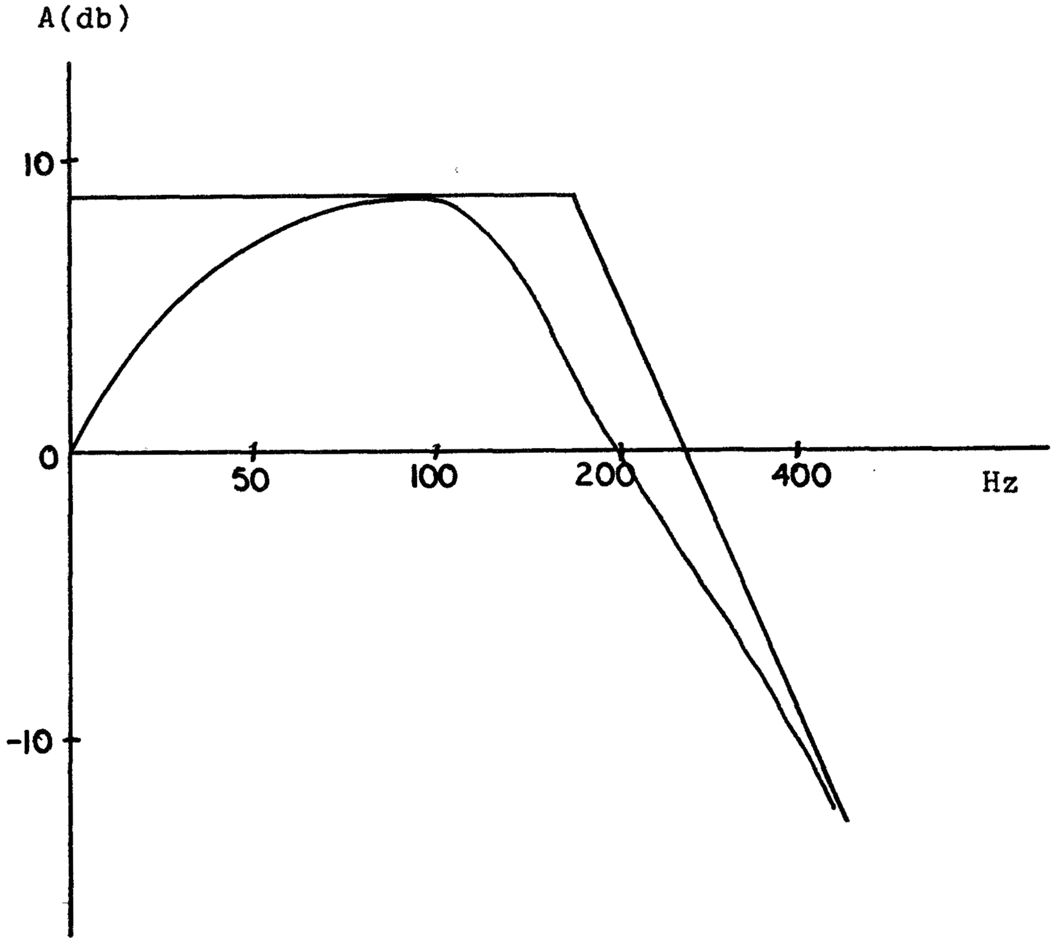

Figure 4

EMG Frequency Response (Trapezius Muscle) (28)

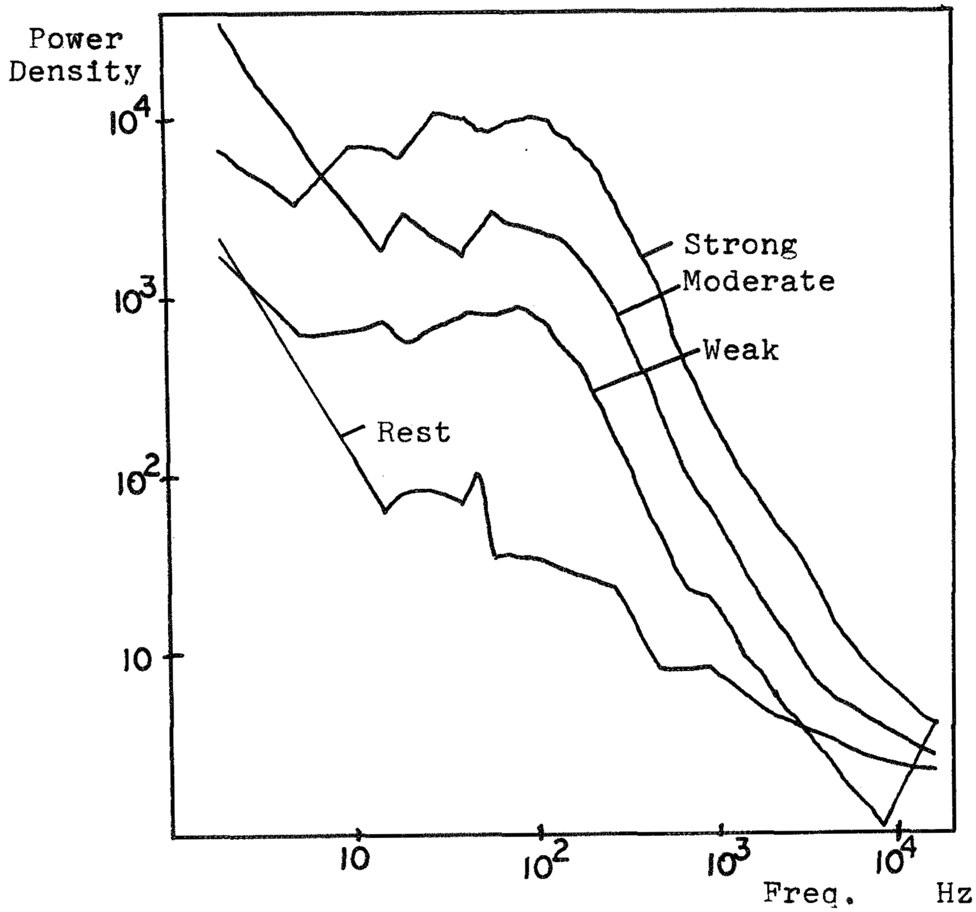

Figure 5

EMG Power Density and Mean Frequency as a Function of Muscle Tension (9) problem remains of how to decode or interpret it. The desired output is a statement of electrical activity; the usual approach is to consider some average measure of its activity. The two most common methods either count the frequency of relative maxima or determine an "integrated" EMG.

The first method of conditioning raw EMG's is that of calculating the number of relative maxima per unit time. This method produces an output equivalent to the integrated method except when fatigue and motor unit synchronization occur. Then it deteriorates in its accuracy as a measure of over-all activity (6). Figure 6 depicts the system.

The "integrated" EMG is arrived at by rectifying the raw signal and then low pass filtering it with some time constant which is long relative to the dominant frequency of the signal. The time constant is normally around 300 milli-seconds. This method has been used both in the British myo-electric hand and in the Boston Arm. The problem of signal cross-talk between two electrode sites is eliminated by taking signals from two opposing groups, rectifying and smoothing to get a D.C. level representing intensity of the original A.C. signal, then subtracting in a differential amplifier. Because a muscle produces stronger signals through electrodes on its surface than through its antagonist muscle, the relative magnitudes determine whether the output is positive or negative. A simple diagram of this system is seen in

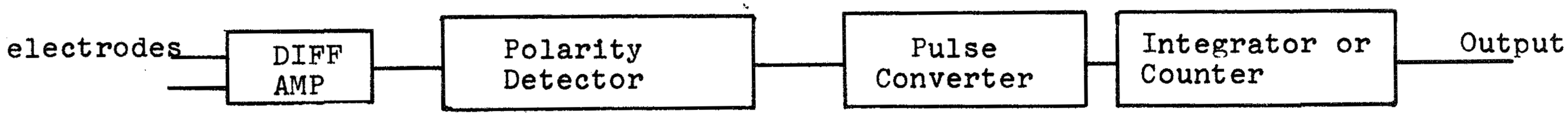

Figure 6

EMG Processing based on mean frequency (23)

Figure 7; it is seen to be a signal output based on the power of the raw EMG.

A problem with the "integrated" signal is that of smoothing the rectified output. Random fluctuations exist, even with longer time constants. Given any EMG one can estimate that it varies over about twenty percent of its average value. So in one experiment, a closed loop force servo was developed wherein error between the last instantaneous value of raw signal and its current value is ignored unless that error exceeds a certain minimum value which itself will increase with the signal (10). The technique is the electrical correlation to the backlash phenomenon and is called "autogenic backlash". Figure 8 is a sketch of the system.

The final stage in making use of an EMG as a control signal is that of designing some control logic which will act on the basis of the conditioned signal. The simplest such logic system is an on/off control in which any level of EMG above some preset threshold causes a system to turn on to some constant and similarly preset value.

Next in complexity is a three state control with the design objective of having on/off control of two functions using the same EMG control site (58). Here two thresholds would be required. A signal strength below the lowest threshold would correspond to the "off" position of both functions; a level between the first and second threshold

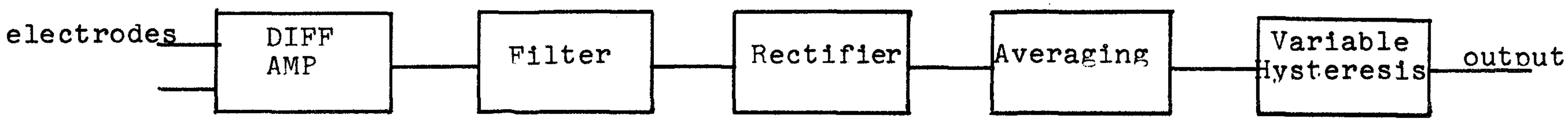

Figure 7

EMG Processing based on Power (9)

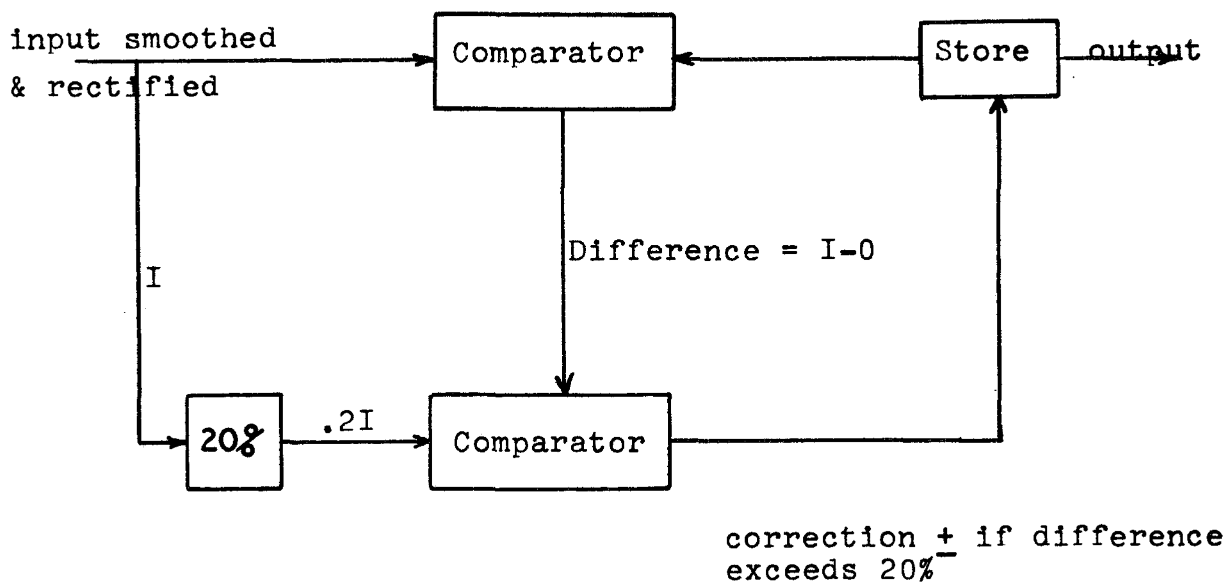

Figure 8

The Autogenic Backlash (10)

would cause one function to be on, the other off. Above the second threshold the two functions would reverse status.

Still a third control system is that of three state variable control. Again two thresholds are used. A signal level between the two would result in proportional control of one function while the second function would remain off. Above the second threshold, the signal would simply cause the first function mentioned to be off, the second on. Such a system permits control of parameters such as closing force and speed of a prosthetic device, for example (17).

A final control variation has been suggested in which rate control is used. Whereas the previous example employed signal amplitude, this system would be sensitive to the rate of signal growth. Beyond a certain limit, control would switch from a proportional to a digital channel. The digital pulse would have a preset value greater than that normally attainable by proportional control (14).

CHAPTER IV

THE EXPERIMENT

4.1 The Goals

In seeking to answer the basic question of this study, it was necessary to determine experimentally several features inherent in an EMG-based attitude control system.

First, one or more pair of muscles had to be identified which would provide the desired electrical response and which would be acceptable for attitude control in space. To the extent that more than one set was sought, each pair had to be relatively independent of the others if confusing commands were to be avoided.

Second, although satisfactory methods of "integrating" the raw EMG signal had been developed, no knowledge was available as to their usefulness in such a control task. Therefore, an appropriate signal conditioning process had to be found.

Third, the use of individual limbs or muscle parts to control one's attitude could, conceivably introduce second order effects of physical motion which would have to be nulled. Thus, an actual experiment in attitude control was deemed a necessity.

4.2 Muscle location

Preliminary experiments were performed to seek appropriate muscle sets for control purposes. As was stated earlier in the discussion of EVA attitude control, several advantages of head control made this area the prime point of study. Surface electrodes were applied to a number of proposed sites on the neck, facial area, and upper back. Signals were received and rough processed by filtering, rectifying, and low-pass filtering. The resulting curve was portrayed on a chart recorder in view of the subject being tested. In this way, visual feedback was provided by which one could attempt to learn control of a muscle.

Proceeding in this fashion, three independent sets of muscles were located which, in addition to satisfying the requirements of decoupled and controllable EMG signal output, also were somewhat logical choices for attitude control. The sites of these three sets are depicted in Figures 9, 10, and 11. They are 1) the left and right sterno-cleido-mastoideus at a point just above the common carotid artery (Fig. 9), 2) the left and right trapezius at a point along the top of the shoulder and at the base of the neck (Fig. 10), and 3) the combination of the facial muscle of the forehead and that of the platysma immediately above the collarbone (Fig. 11). Signals for the first set were independently induced by simple left-right flexion of the head; a leftward motion generated an output from the right sterno-cleido-mastoideus. Motions

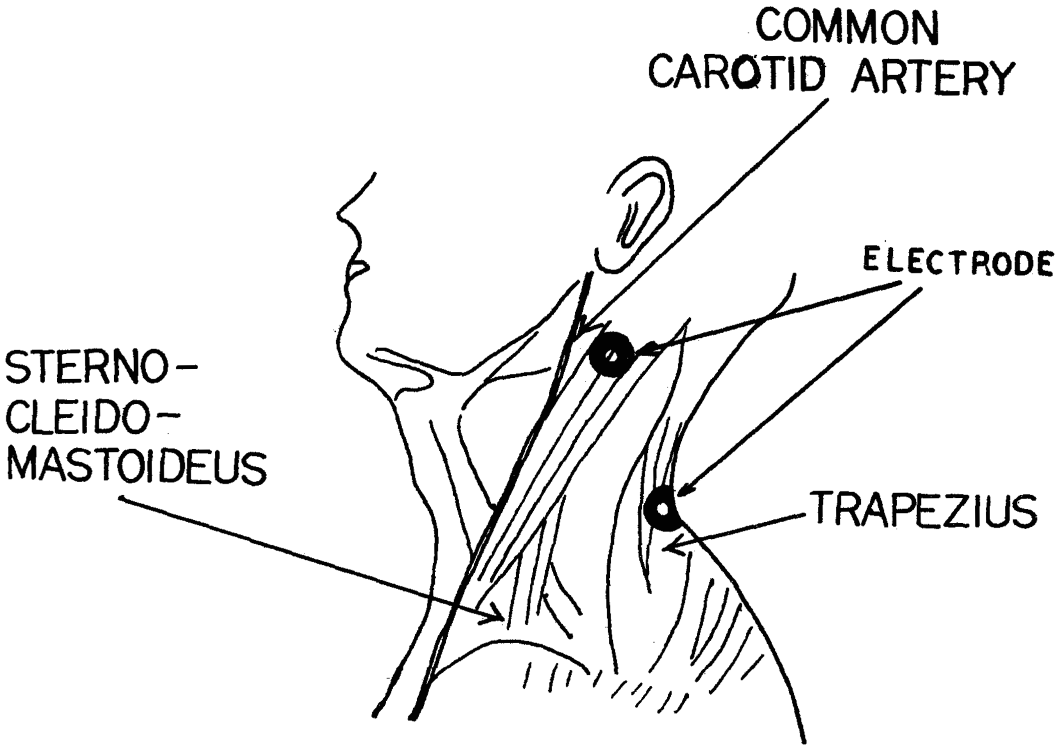

Figure 9

EMG Muscle Sites: Yaw and Roll Control

(Pictorial from 25)

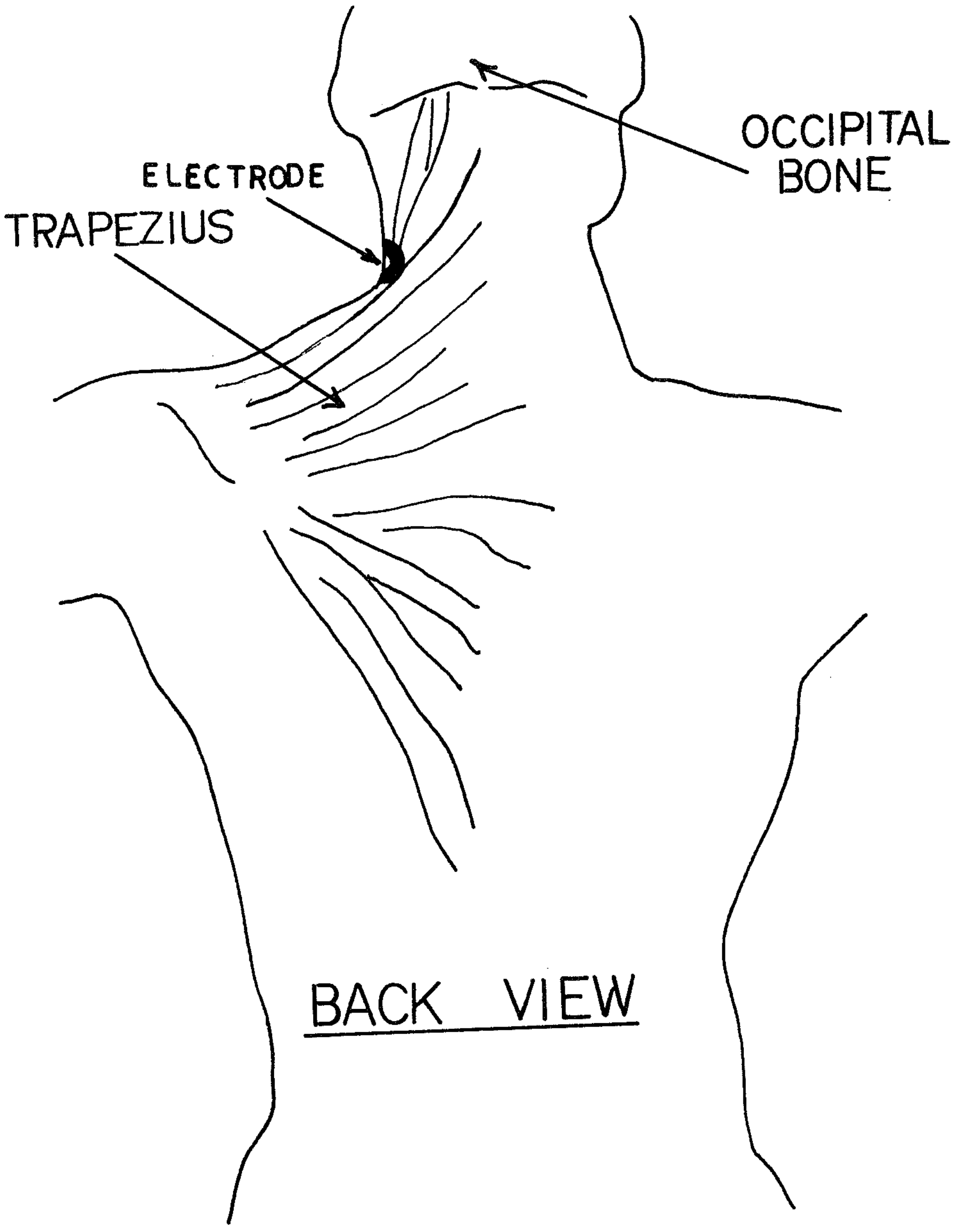

Figure 10

EMG Muscle Sites: Roll Control

(Pictorial from 25)

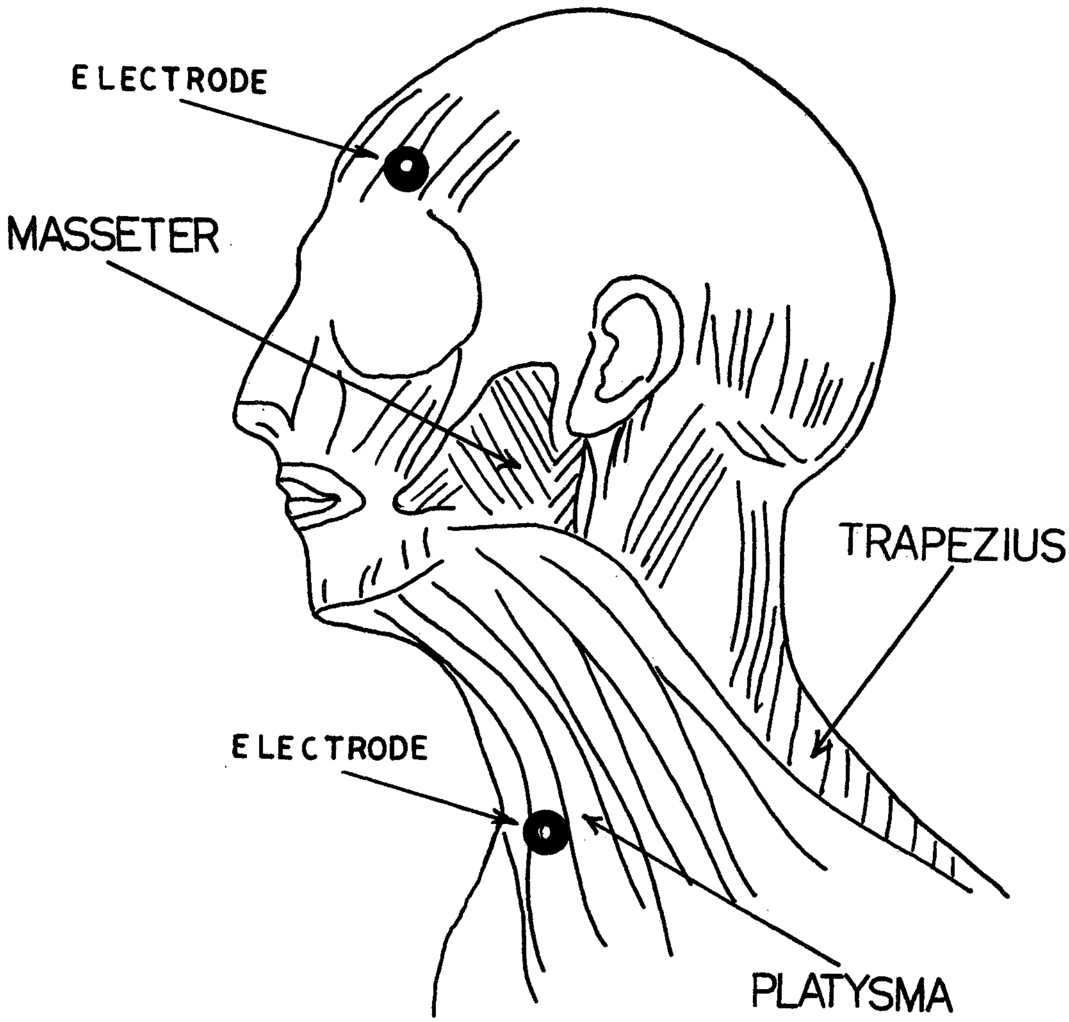

Figure 11

EMG Muscle Sites: Pitch Control

(Pictorial from 25)

as slight as fifteen degrees would be registered as EMG output. The left and right trapezius recorded signals when either the left or right shoulders, respectively, were raised upward toward the neck. These two signals were found to be independent of each other and of the motions which generated an output from the previously discussed pair. The forehead source was active when the subject "wrinkled" his forehead by raising his eyebrows. The platysma generated a response when the subject exercised his lower neck as if in response to a tight collar. Needless to say, these motions are independent of each other and of those previously described.

Proportional control was roughly possible for all six sites; a subject could learn to control the position of the pen recorder for any muscle being tested. As a result of these tests, it seemed reasonable to suggest that use of the sterno-cleido-mastoideus be made for left-right attitude control (yaw) because of the desirable self-compensating effect of this particular head motion with respect to axis controlled. Trapezius control, which is to say shoulder flexion upward, was regarded as practical to assume for roll control. The "upward eyebrow" would be assigned control of pitch up; the platysma would generate pitch down. All six motions are within constraints outlined earlier for an EVA astronaut. However, the best proportional control for the sterno pair (left-right) was found for angles above thirty degrees, the maximum head motion designed for the EVA helmet.

This constraint was not considered further in the actual testing because it was felt that improved signal measuring techniques, including the possible use of implantable electrodes, would make wide-range control possible with head motions below the maximum design limitations.

4.3 Motion Cues

In view of the complexities of signal conditioning circuits and the limited facilities available for experimentation, the decision was made to test one axis control only. This would provide data from which the feasibility of EMG attitude control as a concept could be measured but not as an overall, three-axis operational system. The axis chosen for testing was yaw. Motions in yaw were provided by a rotating chair designed and built by staff at MIT's Man-Vehicle Laboratory. The chair is supported through its center of mass by a shaft which is attached to a torque motor. Signals to the motor provide left-right rotation of the chair. The combined chair and motor combination acts as a poorly damped second order system. With a one hundred-sixty pound subject riding the chair, the system is represented in the block diagram of Figure 12.

A pseudo-random input made from the sum of ten sine functions at frequencies from $w_1 = .019$ rad/sec to $w_{10} = .83$ rad/sec was supplied to the system in which the human operator was controller. This input is displayed in Figure 13. The subject was provided with a pencil-stick with

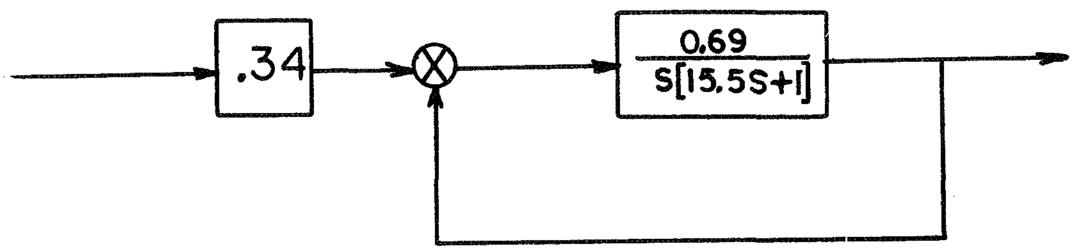

Figure 12

Block Diagram of Rotating Chair Dynamics
with one hundred-sixty pound passenger

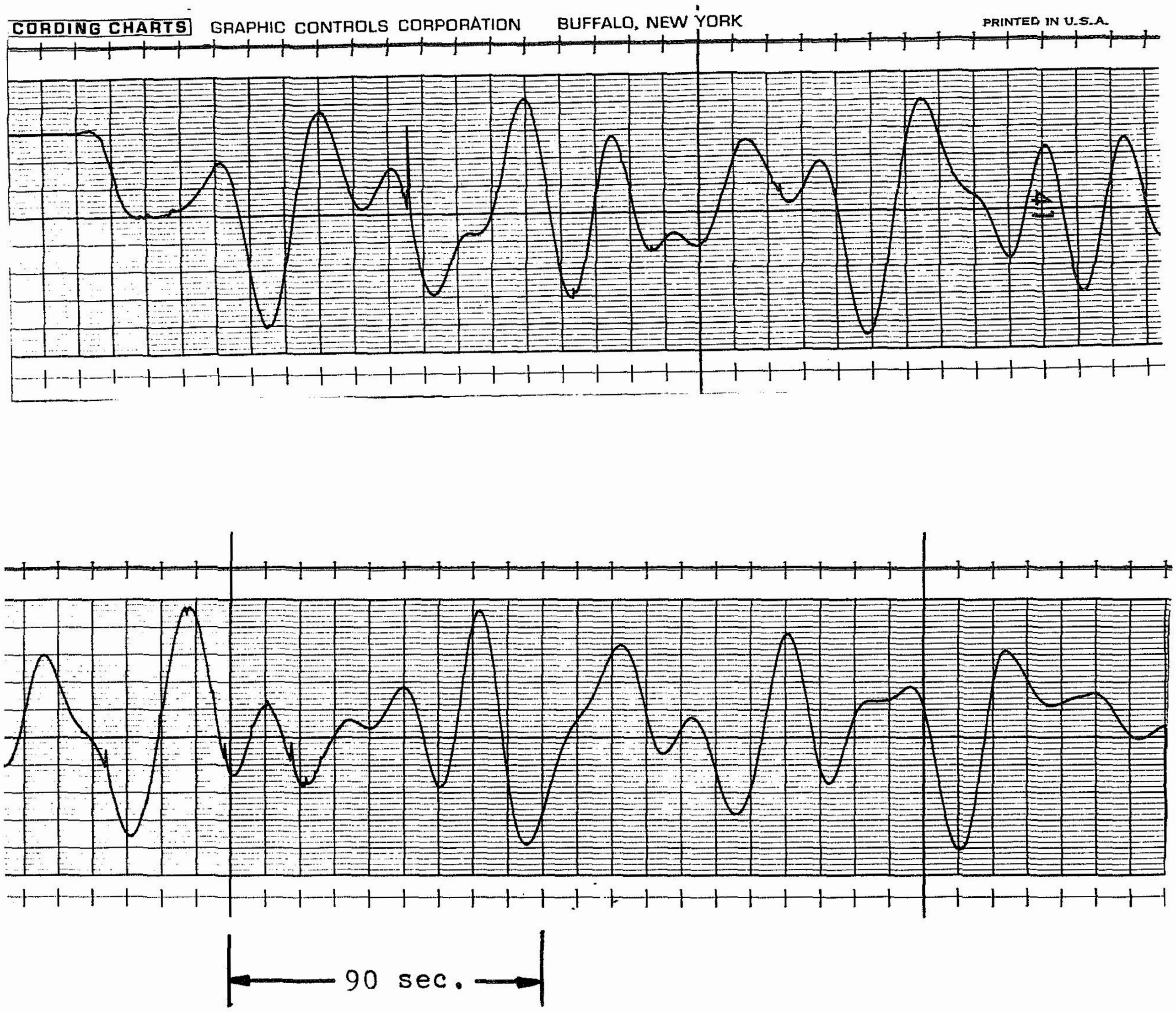

Figure 13

Graph of pseudo-random input

which to compensate for the random input to maintain a constant yaw attitude. This conventional means of control was also substituted by EMG control. The error was displayed to the subject as some angle from a known null chair position.

4.4 EMG Conditioning

A long period of trial and error was required to optimize the path which changed raw EMG's into reliable control signals. Because of the previous experiments which had been successfully performed both by this author and others using "integrated" processing technique, this method was chosen for the actual control experiment.

Signals were measured using Beckman surface electrodes (Type 331429). The application procedure was described earlier and is shown in Figures 14 and 15. The signals were carried by wire to a Biolink Telemetry System (Biocom, Inc. Model 334 PWM) pictured in Figure 16. Attached to the subject's waist, the unit includes a pulse width modulator, FM radio transmitter, and battery pack. Signals entering the system were subsequently differentially amplified, superimposed on a high frequency audio oscillator, pulse width modulated and transmitted via a radio transmitter tuned to the standard FM band.

Theoretically, the signal can be received and properly interpreted from as far as one hundred yards. For this experiment, it was received roughly ten yards away by a

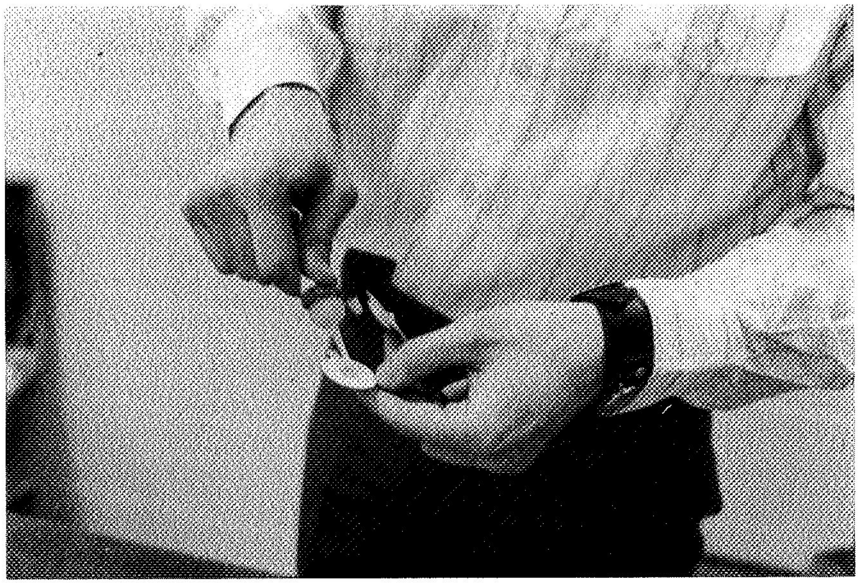

Figure 14

Application of Electrode Paste to Beckman Surface Electrode

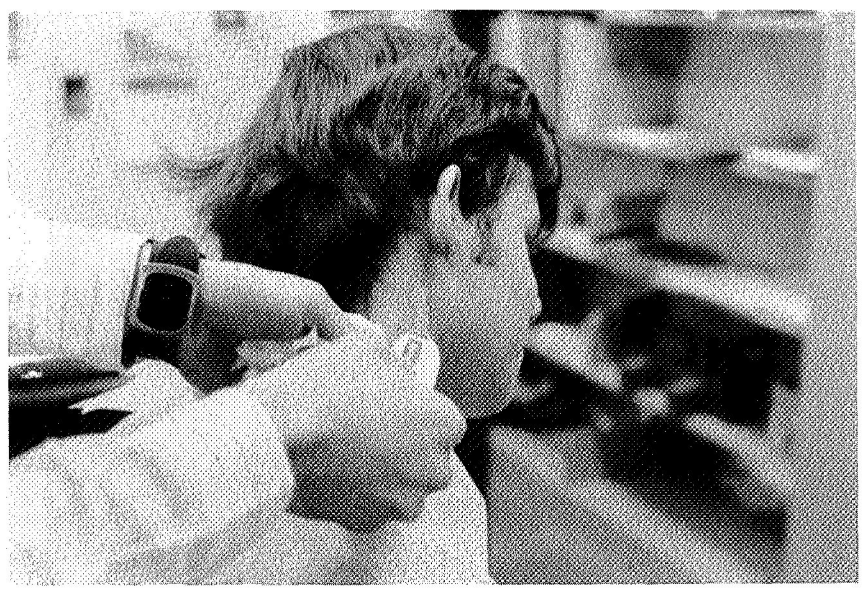

Figure 15

Skin Preparation

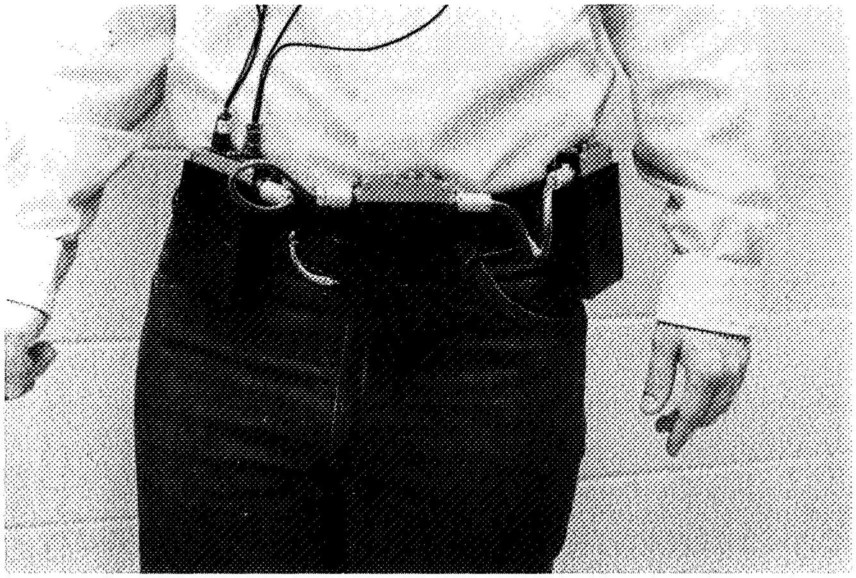

Figure 16

Biolink Telemetry System

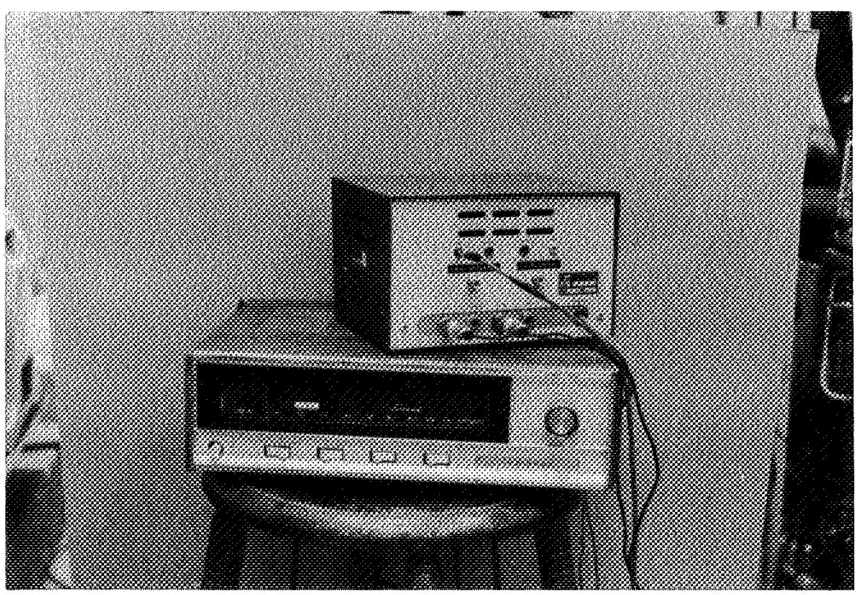

Figure 17

FM Receiver and Demodulator

standard FM receiver and demodulated. The receiver/demodulator system is seen in Figure 17. From here, the signal was carried over conventional trunk lines to an adjacent facility for further work. To have carried the weak EMG directly by wire was prohibitive due to the excessive noise induced by several large pieces of electrical equipment in the area. The FM telemetry system provided immediate amplification and effective low-pass (lag) filtering. The resultant signal was of sufficient strength as it was received and demodulated to allow normal treatment by trunk lines.

The demodulated signal was routed into the patchboard of a GPS Corp. 290 hybrid computer facility which is interfaced with a Digital Equipment Corporation PDP-8 digital computer (Figures 18 and 19). The PDP-8 is a single address, fixed word length, 12-bit arithmetic computer with a cycle time of a 1 1/2 microseconds. The analog computer contains integrators, amplifiers, potentiometers, comparators, multipliers, electronic switches, limiters, and a digital voltmeter. Each integrator may be separately wired for a rate of 1, 10, 100, or 1000 volts/sec. The digital logic includes NAND gates, flip-flops, inverters, NOR gates, Schmitt triggers, and pulse delays.

Seven channels respond to a programmed command to convert or transfer data from the digital to the analog computer. Similarly, eight channels convey information from the analog to the digital.

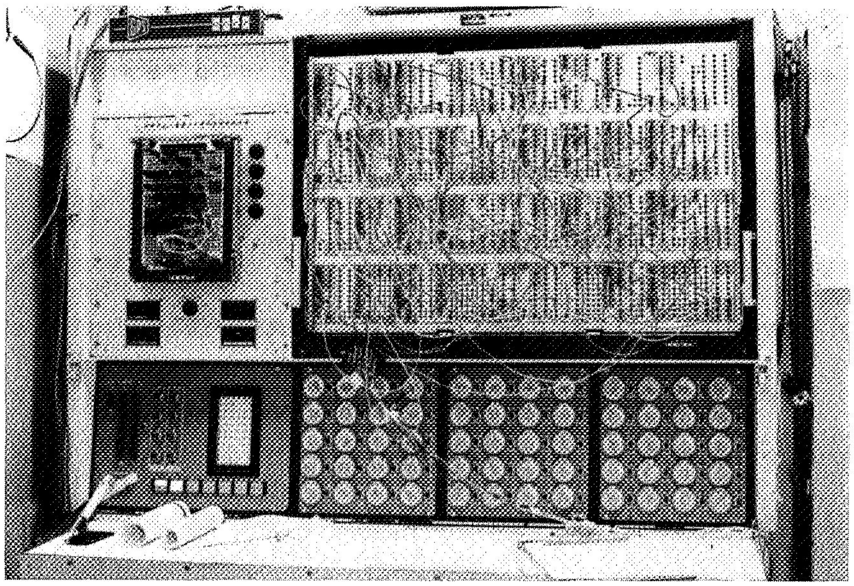

Figure 18

GPS Corp. 290T Hybrid Computer

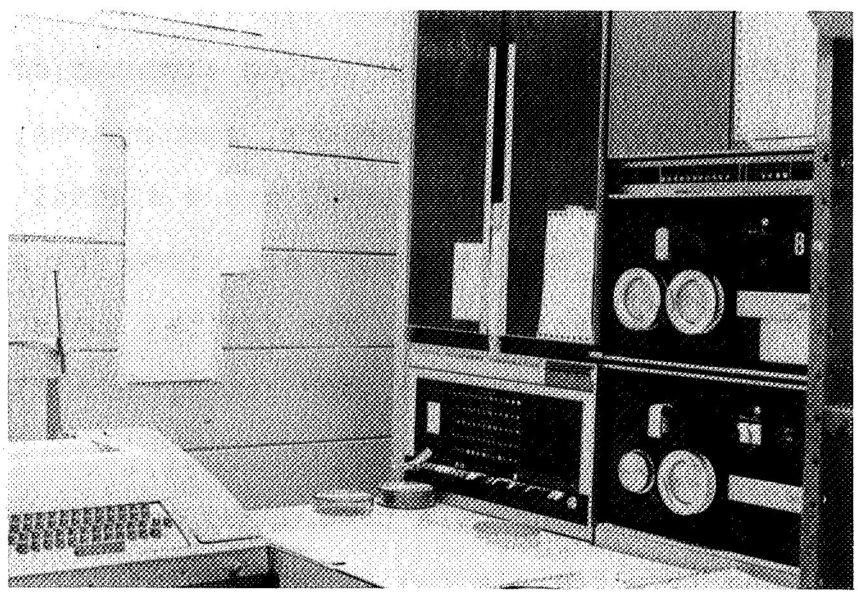

Figure 19

Digital Equipment Corporation PDP-8 Digital Computer

EMG signals received by the analog portion were amplified and high-pass (lead) filtered with a corner frequency of ten Hz. A second corner frequency of one hundred Hz was provided by the telemetry unit. Together the two acted as a "window filter" in the appropriate range for EMG response.

Full-wave rectification followed. A low pass filter was next installed and tested at various time constants. The desired effect was a smooth integrated envelope resulting from filtering the rectified signal. The "smoother" the envelope, the longer was the required time constant. A trade-off between smoothness and response time resulted in an experimentally determined optimum time constant of 300 milliseconds.

At this point, the conditioned signal was acceptable if all conditions were correct; that is, if a strong electrode-muscle contact existed, if no significant skin or other artifacts were manifest, and if accumulated noise levels were low. This, however, was not always the case, with the result that there was in general an overlay of noise approaching anywhere from ten to thirty percent of average signal value. Work was reported earlier on threshold filters including the "autogenic backlash" (10). A variation of this method was employed by devising a digital threshold filter program. The main feature of this program was the ability to set, in a pseudo on-line procedure, three separate absolute thresholds. For a simple ramp function into the digital computer, a step function would be the output, with step size equal to the programmed threshold. For an EMG signal overlaid with noise, the output would be a smooth signal which would not change unless the input exceeded a certain value, presumably upon voluntary command of the subject. Note that this did not serve to improve the signal to noise ratio; it did, however, provide a relatively smooth control signal and one which could much more easily be voluntarily controlled within any arbitrary set of values. The digital program appears in the Appendix. A detailed sketch of the conditioning process is on Figure 20.

4.5 Plant Dynamics

Subjects were asked to control the motion of the rotating chair using both the pencil-stick provided and EMG control. Cascaded to the dynamics of the chair were either proportional or 1/S plants. The random input, stored on magnetic tape, was supplied to the system through the analog computer. A full schematic of the control loop appears in Figure 21.

4.6 Test Procedure

Four male subjects in their early to mid twenties, were tested, two of whom were engineers familiar with control systems. The nominal test time for each subject was two three-hour periods. Subjects were prepared for EMG control; then followed a period of EMG observance and threshold value decisions. The subject was then seated in the rotating

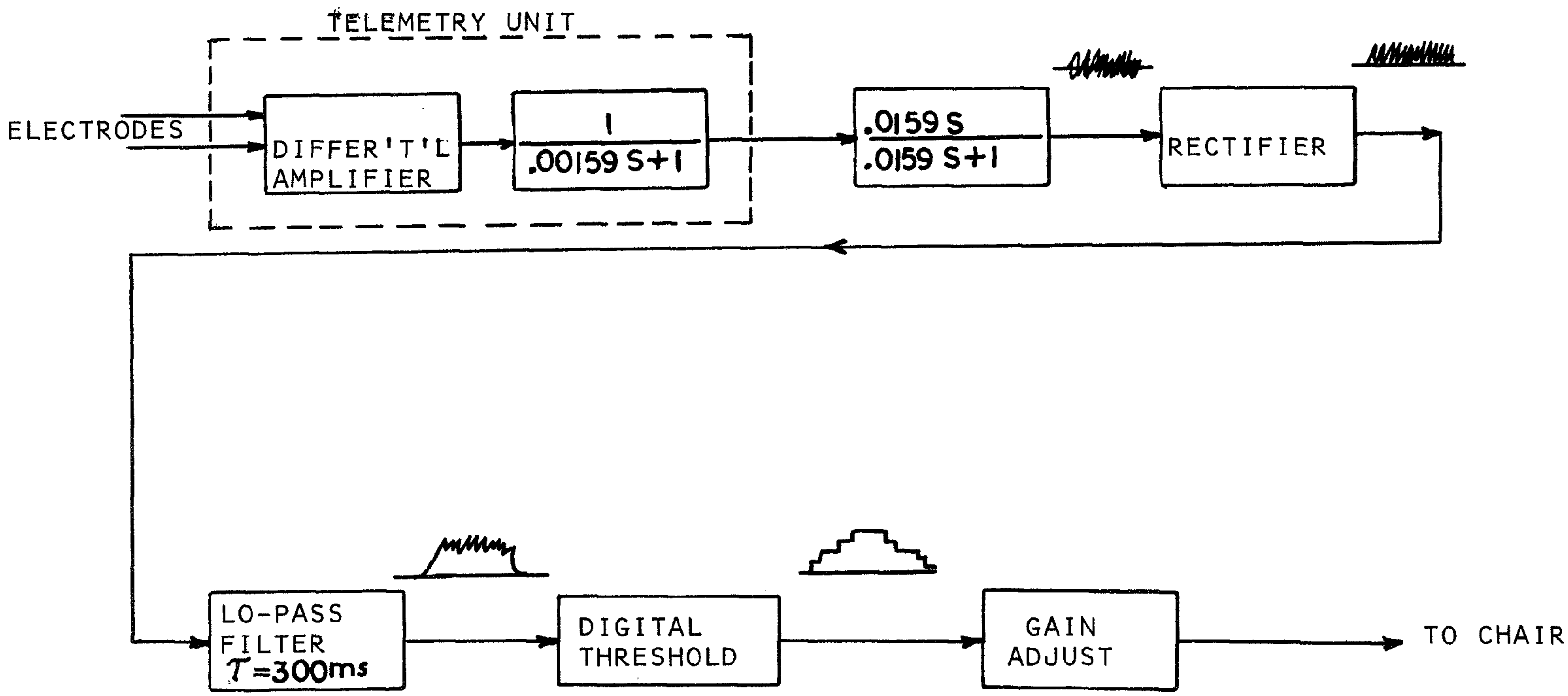

Figure 20

Block Diagram of EMG Conditioning Process

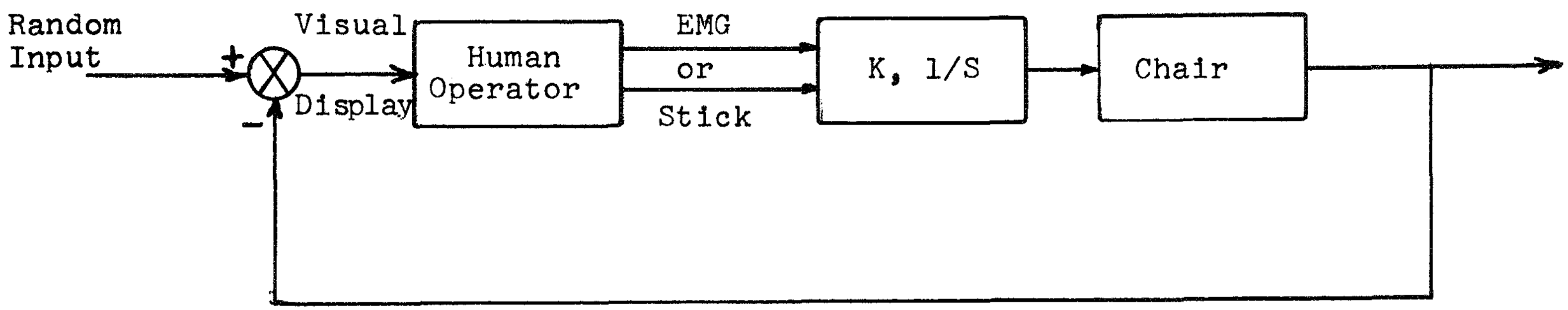

Figure 21

Block Diagram of EMG/Stick Control System chair. Instructions were given to maintain the chair's position with respect to a visual reference established in the room. The four combinations of EMG or stick control with proportional or 1/S plant were each tested. A random sequence was established by which the order of these tests varied for each subject to eliminate any possible overall effect on results due to test order.

For each of the four tests, the subject was given several practice runs of two minutes duration. As with the data runs to follow, records were made of random input, fully treated EMG signals or the corresponding stick control signal, chair position, integrated squared random input, and integrated squared chair position error. The last parameter was divided by the integrated squared input to arrive at a performance index by which to compare runs and intra-subject performance. A sample of the recorded output is in Figure 22.

When the performance index values leveled to a constant after several trial runs, it was assumed that the subject had reached the level region of his learning curve. Data were then taken for the next five runs. Each run was of two minute length; however, data was recorded only for the last ninety seconds to avoid initial transient artifacts. The pseudo-random input was found to be sufficiently close to zero mean along any two minute segment; thus, the starting point of the random input varied with each run. Between any two runs, the subject was given two minutes to rest. At the

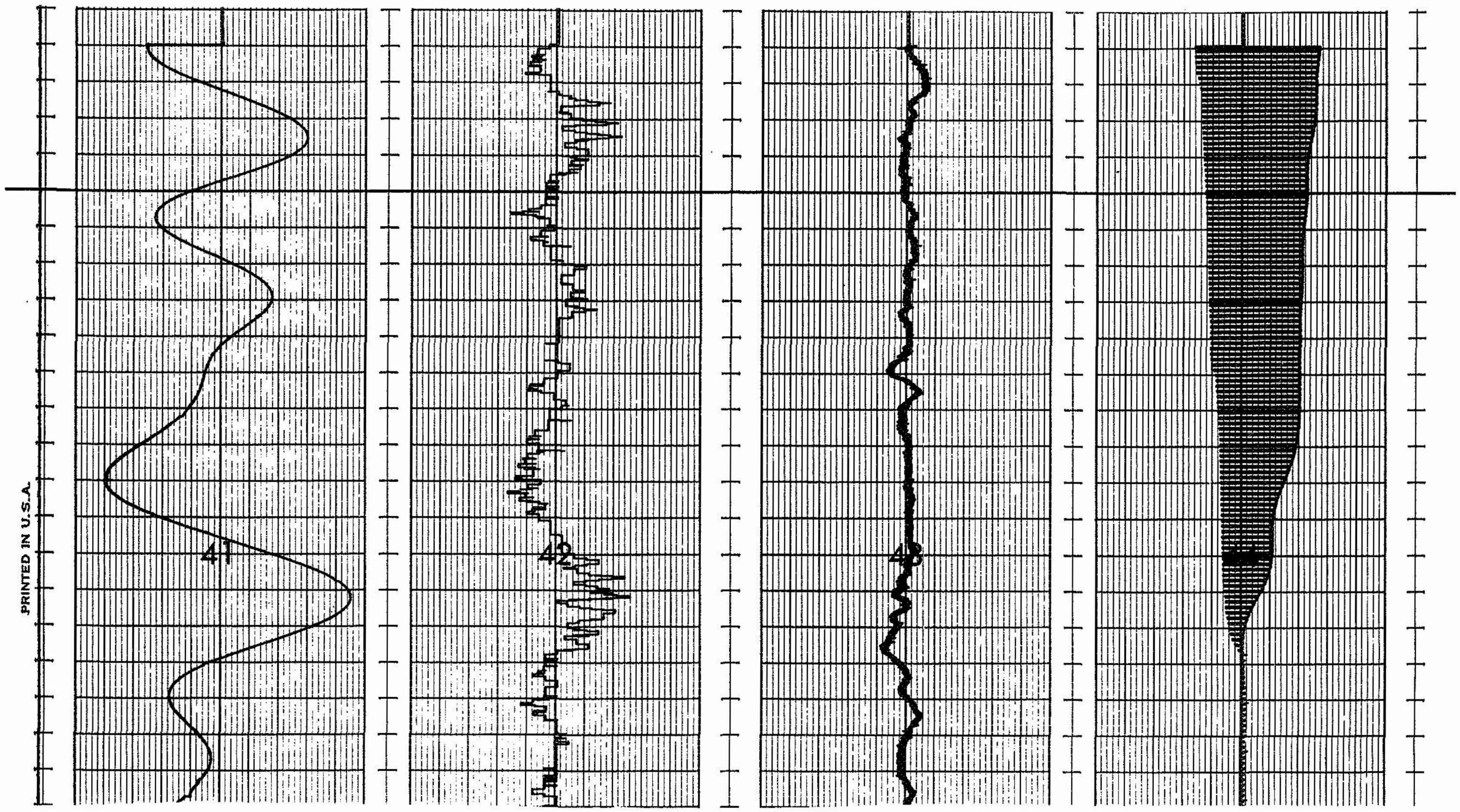

Figure 22

Sample of Recorded Output

conclusion of each complete test, a break of five to fifteen minutes was standard.

All runs were scaled so that the maximum input amplitude corresponded to a rotation of no more than two full revolutions. The result was a typical maximum angular velocity of ten to fifteen degrees per second, within those limits of EVA attitude control recommended.

Views of a subject and the rotating chair appear in Figures 23 and 24.

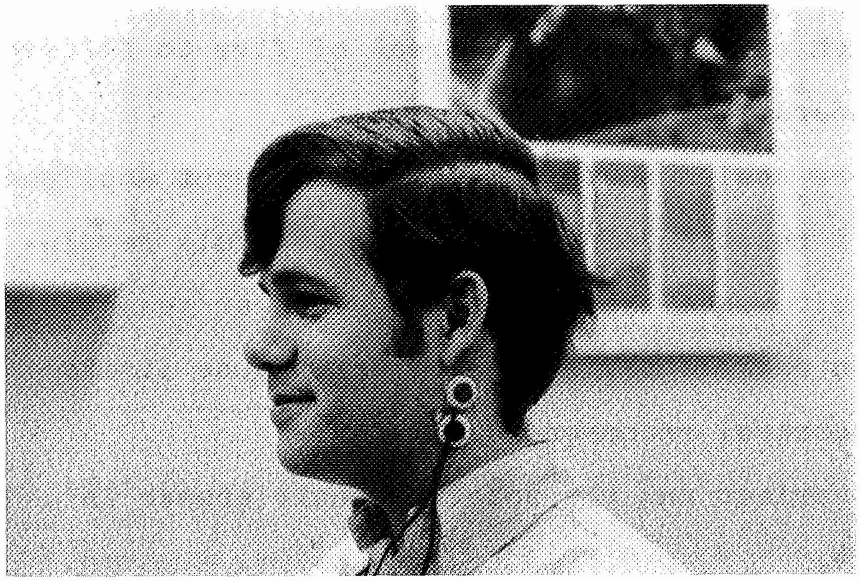

Figure 23. Subject Prepared for EMG Yaw Control

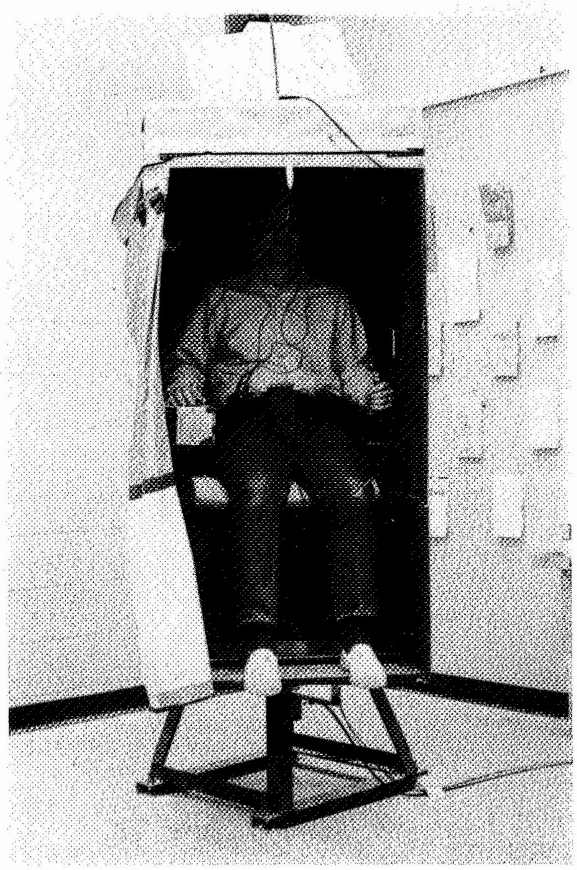

Figure 24

Subject Inside Rotating Chair. (Note antenna above and alternate side stick controller)

CHAPTER V

RESULTS

5.1 Presentation of the Data

The data gathered from the experiments outlined in the last chapter appear in Table 7. The mean performance index and standard deviation of the mean is listed for each subject along with composite scores.

5.2 Data Analysis

A comparison of the composite results for the four tests clearly indicate that EMG control resulted in poorer performance than stick control for both K and 1/S plant dynamics. This was, in fact, the case for each of the four subjects. The mean performance index of the composite for Test "B" was roughly 14 times that of "A", indicating poorer performance. "D", however, was less than 6 times that of "C". This striking difference in comparative levels of difficulty requires explanation. All of the runs for "B" were conducted with levels of maximum EMG signal ranging between .35 volt to .50 volt. This was adequate to counteract the maximum value of the random input (.33 volt). "D" runs, however, were considered more difficult for all subjects and so the decision was made to help offset the difficulty by increasing the

Table 7

Data				
Subject	K-stick "A"	K-EMG "B"	1/S-stick "C"	1/S-EMG "D"
JA	.126±.016	4.52±.077	.160±.025	1.19±.158
PHL	.049±.007	1.07±.141	.92±.176	3.82±1.42
KT	.069±.006	.524±.095	.407±.110	4.36±1.73
CHG	.279±.043	1.08±.058	.240±.051	.424±.263
COMPOSITE	.131±.077	1.79±1.59	.522±.289	2.87±1.75

maximum EMG signal applicable to between .75 and 1.25 volts for the same magnitude random input. This increase in control signal gain may account for the smaller jump in difficulty between "C" and "D" and would, therefore, provide useful information on ease of operation as a function of signal gain. Such is also the case in comparing composite results between "A" and "C" and "B" and "D". The first set represent a growth in difficulty by a factor of four; the second, a factor of 1.6. Stick gain was constant in the first set; EMG available gain grew for "D". This function of signal gain was not explicitly sought in these experiments but may have been, in part, implied by the observed results.

In general, performance for "A" was better than that for "C"; "B" better than "D". This is as expected. Subject JA did not comply with this pattern; however his particular difficulty in becoming accustomed to the normal "D" plant system caused the author to reduce the system gain to one-half that for all other "D"'s and "C"'s. This makes it difficult to compare his "C" and "D" runs with that of other subjects. (Composite scores for "C" and "D" were based on three subjects only.) Subject CHG likewise did not comply with the general rule stated above, but the expected cause was unusual difficulty with the EMG signal on the "B" run which may have led to poorer performance on "B" than would otherwise have been the case.

Finally, subjects PHL and KT scored significantly worse in the "C" and "D" tests than the other subjects. This is interesting because these two were the inexperienced subjects who had no knowledge of control theory or the nature of a 1/S plant, for instance. Interestingly enough, such comparison does not hold for the "A" and "B" runs which used the simpler proportional dynamics.

5.3 Evaluation of the System

Close scrutiny of the above figures is less informative to this type of system feasibility study than a general analysis of the system's weak and strong points.

The most apparent difficulty with the method was one obvious to the casual observer. This was the need for the subject, whoever it was, to exercise extreme head motions to retain close control of chair attitude. Head motions in excess of seventy degrees from frontal position were not uncommon. In fact, few if any runs were performed in which the subject did not have to turn his head at least sixty degrees to evoke a controlled response.

The question arises as to the source of this problem. Earlier, it was reported that EMG traces were picked up for head movements of about fifteen degrees. This success was never repeated in experimental conditions, with the result that no EMG trace was ever recorded for less than about thirty-five to fourty-five degrees. Atop this signal was the noise level discussed earlier; thus, the remaining dead-zone of operation can be attributed to the backlash system of digital thresholds. It should be emphasized, however, that the loss in linear control was considered an acceptable price for the elimination of occasionally spurious, unintentional EMG spikes which were often due to such artifacts as the chair motion or the movement of another person in the experimental room.

Subjects seldom complained of this difficulty. Generally, they were sufficiently surprised and intrigued by the uniqueness of the control technique that they willingly put up with the added physical requirements inherent in the system. Each subject reported that as his head turned, he would simply keep his eyes directed to the reference line at the front of the chair. In rare cases when the subject lost sight of the reference due to extreme head turning, performance decreased immediately. This almost never happened, however, and subjects were generally satisfied with the system.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of Accomplishments

In response to a documented need to find a control system for EVA astronauts which was both natural and did not require the use of arms or hands, experiments were designed to test the use of EMG's for such applications. Three objectives were cited earlier: the identification of one or more muscle pairs which would provide the desired response in a natural way, development of an appropriate signal conditioning process, and actual experiments in control using the proposed system.

The first objective was met, it can be stated, with unqualified success. Three decoupled muscle sets were found with EMG response to acceptable motions of the head and shoulder. It is also believed that a successful signal conditioning process was utilized.

The third objective of experimental verification has begun. One muscle pair has been demonstrated to control one axis of rotation in a normal gravity environment. The major short-coming of the system tested was the need for head motions in excess of sixty degrees. A system is undesirable if motions which are too strenuous or unnatural are required to make it work. It is too soon to state whether this is the case for EMG head control. It is not unlikely that part of the problem stemmed from the inexact procedure by which electrode sites were found. Also, the use of implantable electrodes which are developing rapidly in state-of-the-art may provide proportional control over a much wider range than that which was possible using surface electrodes, and the most recent designs of implantable electrodes could prove comparable in convenience to surface electrodes for EVA missions.

Work should continue on the current experimental setup to evaluate the performance as a function of control signal amplitude. Subject describing functions for both EMG and stick control should be evaluated and compared. A broad range of dynamics should be tested to assure adequate knowledge of operator response to the various external conditions. And, perhaps, modes of control logic other than the threshold step function should be evaluated for final signal treatment.

Certainly before such a system could be of practical value in space, all three axes would necessarily be tested simultaneously on earth in simulators considerably more complex than the rotating chair employed for these tests. Only in this condition, could the full effect of coupling between the three muscle sets be evaluated.

6.2 Other Approaches to Head Control

Nothing has been mentioned heretofore about other approaches to employing head motions to attitude control. Perhaps the most obvious alternative to EMG control would also use the relative freedom of the head within the EVA helmet assembly. By devising a way in which head position with respect to a stationary helmet could be measured physically in three axes, one could generate signals proportional to displacement from some normative position.

Of the several devices for measuring displacement, the simple resistive potentiometer would probably prove most easily adaptable to the given situation. By designing circular resistive elements which would be attached to the inner surface of the EVA helmet, one could then design a soft inner hat to which the wipers could be attached. Such a soft hat could be made of conventional cloth and provided with protrusions made of a conducting alloy which would make contact with each of the three circular elements. While such a system would not work if the anticipated angles of operation were large, the gain could be adjusted to a sufficient level to permit all required control signals to be generated with a minimum of head motion in any one axis. Thus, the otherwise difficult problem of, for example, combined pitch and yaw head motions which could cause one or both of the sliders to leave the elements of resistance would be avoided. Such a system has obvious advantages over the EMG method at its current state of development but could, however, generate serious problems of its own including a constant aligning problem after each relatively long head excursion in any axis. Nonetheless, the system is worth further experimental studies.

Other devices for measuring displacement are possible which operate on the principle of induction forces. A primary coil through which an alternating current is passed will induce a voltage in a secondary coil. A movable iron core located within the secondary coil provides the mechanical input which is to be coupled to head motion. If the secondary coil is center-tapped, essentially two coils are formed. With the core at the null position, the inductance of both coils will be equal, and the difference between the two induced voltages is zero. A core motion from null causes a proportional change in inductance for each coil and, thus, a differential output voltage results. A rotary coil and core is available which provides less than one percent non-linearity over $\pm$ 45° range.

A rotational motion may also be used to change the capacitance of a variable capacitor. The resulting capacitance change can be converted to a useful electrical signal. Output voltage can be made directly proportional to the plate separation of a capacitor. The inner surface of the helmet could contain conductive surfaces to act as one set of plates. The second set could be designed into a soft helmet worn directly over the astronaut's head. Because of the high sensitivity of small voltages to plate separation, scaling to the desired limits of head motion in each axis would require thoughtful attention.

Other, more exotic displacement-measuring devices could be envisioned using piezoelectric or electro-optical principles.

APPENDIX 1

The following is the digital threshold program for filtering noise from the integrated EMG signal. It was written for the PDP-8 in the PAL machine language assembler.

```
                    *20    /REVISED EMG FILTER

                           /MAN-VEHICLE LAB, MIT, JANUARY, 1970

                               / SAMP RATE = 1000 PER SEC

0020  7604       LAS
0021  7041       CIA
0022  3136       DCA A / SET AMP THRESHOLD 1;
0023  7402       HLT          /0020 = 0.1V

0024  7604       LAS
0025  7041       CIA
0026  3137       DCA B / SET AMP THRESHOLD 2
0027  7402       HLT

0030  7604       LAS
0031  7041       CIA
0032  3140       DCA C / SET AMP THRESHOLD 3
0033  7402       HLT

0034  1141  CONT,TAD OUT1 /OUTPUT DATA FROM PREVIOUS SAMPLE
0035  6552       DAL1
0036  7200       CLA
0037  1142       TAD OUT2
0040  6554       DAL2
0041  7200       CLA
0042  1143       TAD OUT3
0043  6562       DAL3
0044  7200       CLA
0045  6461       SKIF
0046  7610       SKP CLA
0047  5045       JMP .-2
0050  6551       DACX
0051  6561       DACY
0052  6545       ADCC ADIC /SAMPLE EMG AMP 1
0053  6532       ADCV
0054  6454       CLAF
0055  6531       ADSF
0056  5055       JMP .-1
0057  6534       ADRB
0060  3144       DCA NPUT1
0061  1141       TAD OUT1 /CALC AMP DIFFERENCE 1
0062  7041       CIA
0063  1144       TAD NPUT1
0064  7510       SPA
0065  7041       CIA
0066  1136       TAD A /ABSVAL(AMP DIF 1) > A?
0067  7710       SPA CLA /YES, OUTPUT LAST  VALUE
0070  5073       JMP .+3 /NO, NO CHANGE, CONTINUE
0071  1144       TAD NPUT1
0072  3141       DCA OUT1
```

```
0073  6544      ADIC /SAMPLE EMG AMP 2
0074  6532      ADCV
0075  6454      CLAF
0076  6531      ADSF
0077  5076      JMP .-1
0100  6534      ADRB
0101  3145      DCA NPUT2
0102  1142      TAD OUT2 /CALC AMP DIFFERENCE 2
0103  7041      CIA
0104  1145      TAD NPUT2
0105  7510      SPA
0106  7041      CIA
0107  1137      TAD B /ABSVAL(AMP DIF 2) > B?
0110  7710      SPA CLA /YES, OUTPUT LAST VALUE
0111  5114      JMP .+3 /NO, NO CHANGE, CONTINUE
0112  1145      TAD NPUT2
0113  3142      DCA OUT2
0114  6544      ADIC /SAMPLE EMG AMP 3
0115  6532      ADCV
0116  6454      CLAF
0117  6531      ADSF
0120  5117      JMP .-1
0121  6534      ADRB
0122  3146      DCA NPUT3
0123  1143      TAD OUT3 /CALC AMP DIFFERENCE 3
0124  7041      CIA
0125  1146      TAD NPUT3
0126  7510      SPA
0127  7041      CIA
0130  1140      TAD C /ABSVAL(AMP DIF 3) > C?
0131  7710      SPA CLA /YES, OUTPUT LAST VALUE
0132  5034      JMP CONT /NO, NO CHANGE, CONTINUE
0133  1146      TAD NPUT3
0134  3143      DCA OUT3
0135  5034      JMP CONT
0136  0000      A,0
0137  0000      B,0
0140  0000      C,0
0141  0000      OUT1,0
0142  0000      OUT2,0
0143  0000      OUT3,0
0144  0000      NPUT1,0 /EMG AMPLITUDE, CHANNEL 1
0145  0000      NPUT2,0 /EMG AMPLITUDE, CHANNEL 2
0146  0000      NPUT3,0 /EMG AMPLITUDE, CHANNEL 3
A        0136
B        0137
C        0140
CONT     0034
NPUT1    0144
NPUT2    0145
NPUT3    0146
OUT1     0141
OUT2     0142
OUT3     0143
```

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