NASA CONTRACTOR REPORT

NASA CR-1

c.1

NASA CR-1919

UNIVERSITY ROLE IN ASTRONAUT LIFE SUPPORT SYSTEMS: EXTRAVEHICULAR GUIDANCE AND STABILIZATION IN SPACE

by Lonnie C. Von Renner

Prepared by
MAN-VEHICLE LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Mass. 02139
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1972

1. Report No. NASA CR-1919	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle UNIVERSITY ROLE IN ASTRONAUT LIFE SUPPORT SYSTEMS: EXTRAVEHICULAR GUIDANCE AND STABILIZATION IN SPACE		5. Report Date March 1972
		6. Performing Organization Code
7. Author(s) LONNIE C. VON RENNER		8. Performing Organization Report No.
9. Performing Organization Name and Address MAN-VEHICLE LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY CAMBRIDGE, MASSACHUSETTS 02139		10. Work Unit No. 970-12-30-41-10
		11. Contract or Grant No. NGR-22-009-312
12. Sponsoring Agency Name and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION WASHINGTON, D. C. 20546		13. Type of Report and Period Covered Contractor Report
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

THIS REPORT DEALS WITH THE REVIEW OF TWO PROBLEM AREAS: (1) THE NATURE OF AND APPROACH TO THE EVA MISSION AND (2) THE GUIDANCE AND STABILIZATION REQUIRED OF SUCH A MISSION. THE REPORT INDICATES SEVERAL BROAD AREAS IN WHICH ADDITIONAL RESEARCH IS NEEDED TO PROVIDE AN ADVANCE TO THE STATE-OF-THE-ART. MOREOVER, THE RESEARCH PROBLEMS CITED WERE CHOSEN FROM AMONG MANY AS THOSE MOST AMENABLE TO RESEARCH AND STUDY IN THE UNIVERSITY ENVIRONMENT.

17. Key Words (Suggested by Author(s)) MANEUVERING UNITS ASTRONAUT MANEUVERING UNIT WORK PLATFORMS	18. Distribution Statement UNCLASSIFIED - UNLIMITED		
19. Security Classif. (of this report) UNCLASSIFIED	20. Security Classif. (of this page) UNCLASSIFIED	21. No. of Pages 73	22. Price* $3.00

FOREWORD

The Bioenvironmental Systems Division, NASA Office of Life Sciences, Office of Manned Space Flight, is vitally interested in fostering academic research which will advance the technological base of life support and crew equipment systems. Both exploratory and applied research is needed to improve the state-of-the-art and evolve advanced concepts. Many excellent ideas and operating systems have been brought to fruition in NASA laboratories and by associated contractors. However, involvement of academic laboratories and graduate student study programs has not been as great as was originally hoped. Perhaps, this has been due to the fact that academic personnel were not aware of the critical problem areas in life support and crew equipment systems, nor were they cognizant of the fact that NASA is interested in joining with colleges and universities to develop new ideas to solve space flight problems.

This brochure on Extravehicular Guidance and Stabilization in Space is intended to introduce you to some of the existing technology involved in guidance and stabilization of extravehicular maneuvering systems and to pinpoint areas where problems exist. We encourage you to study this brochure. If, in your research, you have already developed new ideas, theories, and processes, which would be applicable to NASA's efforts, we hope you will feel inclined to contact us to see where a joint research effort can be initiated. Approved efforts will be funded as grants with funding sufficient to support the principal investigator and several graduate students research assistants. Graduate students are encouraged to participate as research assistants and to conduct the graduate research under such a cooperative effort.

Walton L. Jones, M.D.
Deputy NASA Director
for Life Sciences

SUMMARY

The field of Extravehicular Activity is multi-disciplinary
to the point where one report cannot hope to cover in detail
the several broad areas of knowledge upon which this subject
is based. Therefore, this is a review primarily about two
problems: 1) the nature of and approach to the EVA mission
and 2) the guidance and stabilization required of such a
mission. The intent here is to reveal several broad areas
in which additional research is needed to provide an advance
to the state-of-the-art. Moreover, the research problems
cited were chosen from among many as those most amenable to
research and study in the university environment. As a rule,
they represent basic questions as yet unanswered, new
approaches as yet unproven. They are less hardware-oriented
than other current problems in the field. Some, perhaps,
are more free-wheeling than those currently receiving the
attention of private industry; others require descending
toward microthoughts aimed at improving existing procedures
or suggesting new ones. All share in common the need for
fresh and enthusiastic inquiry.

These areas are reiterated below.

Area	Problem
The Nature of EVA	1. Standard definition of EVA tasks and timelines
	2. Load transmission device
EVA System Approach	1. Non-anthropomorphic suit
	2. Definition of Optimal System
EVA Guidance and Stabilization	1. Subjective effort model
	2. Postural reflex model
	3. Electromyographic control
	4. Timing controller evaluation
	5. Optimal manual control technique

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

I. INTRODUCTION

On March 18, 1965, with the era of manned space flight
extending back less than four years, Lt. Col. Alexsei
Leonov stepped outside his spacecraft to become the first
man to directly encounter space. The first "space walk"
was short, lasting only ten minutes, and at all times the
cosmonaut was attached to vital life-support systems of his
spacecraft by an umbilical cord. Nonetheless, the feat
demonstrated that men properly suited and supplied with life-
giving oxygen could survive exposure to the weightless vacuum
of space.

From that day to this, research and development in the
field of extravehicular operations have proceeded in this
country and elsewhere, to fulfill requirements for future
missions in which man's ability to work outside his spacecraft
will be essential. The following review will cite the scope
and trends of this work in the particular area of Guidance and
Stabilization of an EVA astronaut. On the basis of current work
status, this report will endeavor to list pertinent problems
for university study and research.

The Nature and Necessity of Extravehicular Activity

Extravehicular activity (EVA) is defined as any activity
by a space crew member conducted outside the parent spacecraft(s)
in support of operational missions or scientific and engineering
investigations. Thus, EVA encompasses exploration of the lunar

terrain by astronaut-explorers as well as orbital "space walks." This study will concentrate on the problems and hardware associated with performing work in zero or low gravity environments in which a planet's atmosphere or surface does not play a part. It does not include an examination of "moon rovers" or other planetary vehicles, nor does it consider the vast array of space "tools" currently under development.

Extravehicular activity will be useful in insuring the safety of a primary vehicle system and in assisting in the accomplishment of future missions. The role of orbital EVA as a back-up for intra-vehicular transfer in the Apollo Program has been described by Bond, et al. (4). The orbital missions which appear likely for implementation during the 1969-1980 period have been reviewed (34, 51, 67, 79). They may be listed under eight broad Headings.

Table 1: EVA Orbital Missions 1969-1980

1. Environmental Survey

2. Biomedical Experiments

3. Earth Sensing

4. Orbital Operations Development

5. Astronomical Sensing

6. Orbital Assembly

7. Satellite Inspection and Repair

8. Orbital Launch Vehicle Assembly

Some assignments, such as the astronomical sensing mission, will require a high degree of astronaut mobility and manual dexterity in performing tasks such as changing the lens on an orbiting telescope (73). Others, such as the orbital launch vehicle assembly, will require EVA to checkout and correct any malfunctions of a presumed automatic assembly procedure (6). In other cases it is difficult to extrapolate precise information from a described mission of the EVA support required. At present, no standard exists as to an accurate format for describing the desired EVA. In all of the listed categories, man's contribution can be analyzed as falling within three distinct domains: observation (sensory), decision (mental), and activity such as construction, repair, modular replacement, adjustments, fluid connections (physical)(65).

From the missions listed in Table 1, typical support activities can be defined.

Table 2: EVA Support Activities (45)

Maintenance	Resupply - fluids
Assembly	Rescue
Resupply - packages	Personnel transfer

These activities, in turn, suggest that certain attributes will be required of an EVA astronaut. Others, while required for some missions, may be omitted for others. These are listed in Table 3. Taken as a group, these define the scope of EVA as it is currently envisioned.

3

Table 3: EVA Requirements (34)

Life support extension	Tool bin (optional)
Communications	Work aids
Mobility - dexterity	Manipulators (optional)
Power source (optional)	Umbilical capability
Fixed work base	Rescue provisions

Environmental Constraints

Two factors determine the needs of the extravehicular astronaut. These are the type of work which he must perform and the constraints imposed by the environment. Having studied the mission requirements, the environment in which they will be executed is here considered.

Four conditions which most seriously affect an EVA mission in orbital space are:

1. Mechanics

2. Vacuum

3. Illumination

4. Radiation, Thermal and Micrometeoroid Protection

These will be considered individually.

Mechanics

The mechanics of motion in a zero-gravity environment pose several problems, among which are: untethered object scattering, peculiar inter-object navigation requirements, and changing relative bearings between objects. Costick has determined in simulation that a two pound force applied for

one-tenth of one second by an astronaut against his space-craft will cause him to drift beyond arm reach within thirty seconds (9). The force of an ordinary sneeze is sufficient to tumble the unrestrained individual at a rate of one-fifth of a revolution per minute provided, of course, he is not wearing a helmet with faceplate. The effects of weightlessness on a human being from a dynamical point of view have been studied (80). Medical effects of the weight-less environment have also received considerable attention. (See, for example, 3, 49, 54.)

Trout and Hill have observed that the lack of traction encountered in space accounts for much of the degradation in EVA performance as experienced by astronauts in the Gemini Program (53, 55, 76). The metabolic cost of doing work in zero gravity is much greater than that of doing the same work on earth or even on the moon, as the results of Apollos 11 and 12 indicated. To see this consider the following analysis (84). Let:

E = efficiency

ΔQ_m = metabolic cost of work

Q_w = amount of energy used in performing useful work on earth

Q_{wc} = energy spent in counter-active force

Q_{wr} = energy to restore body to a prework position (torque)

Q_s = energy stored as body heat

Q_n = net heat loss

Then

$$\Delta Q_m \cdot E = Q_w \quad \text{(earth)}$$

$$\Delta Q_m = Q_w + Q_{wc} + Q_{wr} + Q_s + Q_n \quad \text{(space)}$$

Thus, the inherent absence of traction in zero-g causes energy parameters to rise and efficiency to be lowered.

-Vacuum

The vacuum of space affects an EVA astronaut in the following ways (42):

1. Forces man into a space suit or other airtight enclosure (47).

2. Poses special problems for maneuvering from one enclosure to another (airlock design).

3. Requires radiative heat dissipation.

4. Necessitates communication by wire, contact, or electro-magnetic radiation.

-Illumination (63)

The sources of illumination in space differ in extremes. When viewed from outside the earth's atmosphere the sun is almost twice as bright as from the earth's surface (7×10^8 millilamberts vs. 4.4×10^8 mL). The earth's day side is a brilliant surface with a luminance as great as 9.4×10^3 mL. When compared to a full moon viewed from earth (8×10^2 mL) or white paper in good reading light (2×10^1 mL), the intensities of space illumination are apparent.

The brilliance has two optical effects. The first is
on visual adaptation; the eye must be shielded and given time
to adapt before it will respond to low intensities such as
stars. If observing an object illuminated on one side by
the sun, the other side cannot be seen, even if illuminated
by the moon or by the earth. Filters do not help this problem.

The second optical effect is the potential injury of
retinal burn if the eye's field of view includes the unfiltered
sun for more than a few seconds.

-Radiation, Thermal, and Micrometeoroid Protection

The existence of radiation in space has been reviewed (52).
Cosmic rays, the Van Allen Belts, and the radiation spewed
from solar flares all pose hazards to the EVA astronaut. Their
effects on the human being have been extensively treated in
other reports (20, 52). Protective shielding is required for
an astronaut during EVA. Such shielding must be so designed
as to provide a comfortable range of temperatures.

Recommendations for University Research

- Review major EVA missions and timelines with goal in each case of reducing required EVA for successful operation.

- Determine a standard set of specifications to be imposed by NASA upon contractors for use in defining EVA missions required in support of projects.

- Determine an acceptable format to use for establishing EVA timelines for each mission based on tasks to be done, distances traversed, etc.

- Design a system, using engineering applications of statics, kinematics, and dynamics, of load transmission devices that will improve the efficiency of zero gravity work to permit metabolic rates comparable to those experienced on earth.

II. APPROACHES TO AN EVA SYSTEM

An extravehicular system is a small self-contained unit
operating in space or on a planet for a short period of time,
usually measured in hours, at a limited distance from a parent
spacecraft. Several types of EVA systems have been proposed
and they can be roughly classified according to size, complex-
ity, and endurance.

The first such classification, least complex and providing
shortest available working time is the space suit with back-
pack life support system. This design is currently being used
in the Apollo Program. Operational time is determined by,
among other things, suit discomfort (four to eight hours)
(31, 34).

The second configuration is that of the non-anthropomorphic
space suit, that is, one which encapsules the entire astronaut
in a form-fitting shell. This concept has not been demonstrated,
but theoretically it offers several advantages over conventional,
form-fitting suits: limited comfort time is greatly increased,
self-feeding and waste disposal becomes practical, and self-
repair is made possible.

A space suit with backpack maneuvering unit and life
support system is a third system currently receiving much
attention. Operational time is determined by life support
and propulsion requirements (three to four hours).

A space suit with work platform incorporating maneuvering
and life support capability is yet another classification.

9

Tools could be carried along, and the platform would have a variety of plug-in modules for use in particular missions. A capacity for remote retrieval would be highly desirable. An artist's conception of the platform appears in Figure 1. The astronaut would perform in a space suit exposed to the environment and could exit from the front to operate at umbilical distances. At other times, he would be restricted in the platform by a belt which would permit him to work with little leg exertion. The primary advantages of such a system include: increased propulsion capacity, (i.e. range) increased tool storage area, added mechanical aids, improved guidance and stabilization, ability to anchor at work sites, work illumination, heavy duty power supply, TV and telemetry channels, umbilical power and communications for remote operations, and the ability for remote recall.

The last concept considered here is that of a shuttle or work boat with pressurized compartment enclosing an astronaut with back-up spacesuit. The most sophisticated of all designs mentioned, it has the chief advantage of extending EVA operating time to several days and increasing working distances from the main spacecraft to several miles (34).

Recommendations for University Research

- Determine a practical operational time for use with a non-anthropomorphic space suit and determine the need, if any, for EVA operations of this duration.

- On the basis of the above study, determine the requirements to support an astronaut for this period, not to exceed eight hours as a practical work limit.

- Evaluate designs which would satisfy the above requirements for a non-anthropomorphic suit.

- Determine the EVA system(s) of maximum efficiency in meeting the total requirement of EVA missions, including rescue. Consider: 1) the optimal usage for each system thus far presented, 2) comparison with total requirements and integration of system concepts where possible, 3) identification and solution to the particular problems associated with each system such as airlocks, rescue, astronaut interface, use of manipulators, 4) a study of modular concepts for versatility in task performance through easy introduction and removal of different subsystems, 5) close coordination with specific missions currently planned by NASA for the rest of the century.

III.   EXTRAVEHICULAR SUBSYSTEMS

An EVA system resembles a small manned spacecraft with a
limited duty cycle. Its major difference from a parent space-
craft in addition to size is the absence of any re-entry
capability. Extreme reliability over a long period is required,
however, for each of several subsystems. These include Life
Support, Power, Communication, Propulsion, and Guidance and
Stabilization. While each of these systems is worthy of
extensive study, the remainder of this report will be
confined to a review of problem areas in Guidance and
Stabilization.

Guidance and Stabilization

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 tranlational thrusters can also serve as an
inertial reference system. The specification of this subsystem
involves first listing of requirements placed on it by the pro-
posed 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. Each of these steps are reviewed below.

Requirements

Any 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 that angular velocities should be available at levels from 5 to 30 deg/sec and angular accelerations between 10 and 15 deg/sec^2. Possible disorientation due to vestibular effects determine the upper extreme (22). Translational acceleration between .2 and .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 tech-

niques for translation and rendezvous with a target are
available, but all require the astronaut to monitor his
approach and make necessary corrections.

Consider the following guidance scheme which neglects
second order orbital effects (13).

1) The EVA astronaut establishes the initial conditions
and measures range, range rate, and cross-range velocities,
with the help of sensors and perhaps a small computer.

2) The astronaut, using his knowledge of these conditions,
thrusts toward the target to attain a predetermined range
rate (or relative velocity) v.

3) Due to thrust misalignments and residual cross-range
velocity there will be some error angle E between the line-of-
sight and the relative velocity. This angle is measured in
the plane of the target, interceptor, and relative velocity.
This plane, shown in Figures 2 and 3, may change after each
corrective thrust.

4) Immediately after thrust, the astronaut will note the
bearing of the target; when the bearing changes by angle, l,
(the threshold), the Law of Sines gives $\sin(l+E) = \sin l/(k/R)$.
Since the astronaut knows R and V and can measure time from
start until the bearing changes, t_1, he can find k as follows:
$k = vt_1$. Using this value he can find l+E from the expression
for its sine function above.

5) The vector diagram of Figure 3 shows that $\Delta v = v\tan(l+E)$.
Since for angles up to 200 milliradians tan x differs from sin x

by less than five percent, and since all the angles are in this range, then $\Delta v \approx v l R/k$.

6) In order to complete the solution, steps 2) through 5) are iterated, with R replaced by (R - k), as many times as necessary.

7) When the astronaut sees that he is approaching the target, he will apply braking thrust.

The consensus among investigators is that the astronaut will be able to judge distance accurately at fifty to two hundred feet, but that during retro-thrust he will be too busy to make normal corrections to the guidance system for the last fifty feet. It is also assumed that he can adjust for errors of up to two feet by arm reach. A two foot error subtends an angle of forty milliradians at fifty feet. This, then, is the upper limit for the threshold. A safety factor of two can be introduced, and the nominal threshold is determined at twenty milliradians ($\pm 1.2^{\circ}$) (13). This represents the accuracy which must be available in attitude control, neglecting insignificant errors in state-of-the-art optical sighting devices.

Other guidance and rendezvous techniques have been described elsewhere (60). Tests performed in a six-degree of freedom simulator indicate that flight maneuvering within two hundred feet of the spacecraft should be accomplished with ease (87).

Unstabilized (Open-Loop) System Designs

- 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 repre-
sentation of biomechanical properties is approximate, several
studies have proved useful as a basis for estimating dynamic
response. DuBois developed a semi-analytic technique based
on computer analysis of data in a double axis compound
pendulum test of subjects (14). Whitsett developed a
distributed mass model based on the USAF "mean man" which
Drissel extended to a suited astronaut (13, 80). Five
postural variations were defined. The effect of a homogeneous,
weight-distributed one hundred-ninety pound backpack was also
determined. Math models of the human body were developed (43, 24).

On the basis of such data, 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 (37, 62). 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. Nonetheless, analytical treatment of the human body as a non-rigid mass has become important. Experiments and actual flight data in the Lunar Module have demonstrated that torques induced by limb motions are sufficient to cause difficulty in maintaining automatic stabilization.

Limited maneuvering by judicious handling of an astronaut tether has received some attention (1). 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.

- 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 (53, 54). A summary of Gemini X HHMU characteristics appears in Table 4.

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 4 (54)

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	667
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. Another logic preferred by some pilots employed six decoupled control positions for six degrees-of-freedom. Pure rotations were not possible but performance was improved (87).

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

- 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 hover-
ing vehicles (91). 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 ac-
celerates the rug backward. In essentially this manner can
one control, in theory, a jet thrust device attached to the
feet. See Figure **4**.

On the basis of early successful flights of man standing
on a jet-supported platform, tests were made to determine the
flight qualities of a man standing on a platform supported by
a teetering rotor (30). Controllability was improved when
the two fans were counter-rotated to negate angular momentum
vectors and when the rotor assembly was spring-restrained.
Additional study has continued at Langley Research Center to
determine the impingement forces, moments, and centers of
pressure on a flat plate produced by small jets operating in
a vacuum (35). Work has also proceeded on the development of
an automatic balancing system for such platforms (25). Balance
is achieved by measuring the difference in total impulse

exerted by opposite torquers used for attitude control in each axis during some time interval of limit cycle operation. The system then moves a small weight by an appropriate distance to compensate for the measured imbalance.

In projects of a similar nature, Bell Aerosystems Company has modified their "flying felt" hardware to provide various body-controlled fixed-thruster vehicles for application in low-gravity environments (2). This work, and that of rocket lift devices by Aerojet-General Corporation are well documented (68).

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 (75). 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 adaptation of the original flying platform to lunar rovers (29). 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. A system block diagram appears in Figure 4 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 adaptation 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 in order 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 trans-lational 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) (40). 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. Translaton artifacts due to un-balanced force vectors were cancelled by the addition of thrust-ers to form a pure couple. Results were optimistic and sub-sequent 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 in 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 spacial 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 (40).

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 (85). Shoe-mounted units, controlled by muscle action about the ankles, was envisioned. The principle of control moment gyros and their possible use in an EVA control system has received detailed scrutiny (7, 19, 55, 57). The simplest such system is a gimballed wheel rotating at constant speed. Newton's second law states that the total external moment, T, acting on a system is equal to the time rate of change of angular momentum with respect to inertial space:

$$T = I\alpha = dL/dt; \quad L = I\omega$$

where $L = L_{system} = L_{astronaut} + L_{CMG}$

See Figure 6.

To predict physical behavior of a simple single degree-of-freedom wheel consider the case where external torques are zero, T = 0. Then L = constant. Hence, rotation of the gyro through some small angle δ as shown in the figure causes a component of gyro momentum to appear in the +x direction. To first order approximation the Z component remains unchanged. If overall momentum is to be conserved, then the astronaut must assume some momentum in the -x direction. If this corresponds to a principal body axis, then he will rotate purely in that axis. The gimballed angle controls the change in momentum which, in turn, is proportional to the time integral of the created torque. So the torque is proportional to gimbal angle

rate. In the absence of external torques, the astronaut
could create a small rotation rate by moving the gimbal through
some small angle, and then could stop the motion by restoring
the gimbal to its former position. A block diagram of a CMG
attitude control system appears in Figure 7.

The proposed shoe employed two identical wheels, as
shown in Figure 8 , to eliminate cross-coupling with large
angles. The two degree-of-freedom mounting in each shoe was
figured so that one shoe would control pitch and yaw rotations,
the second pitch and roll. Four wheels would, thus, be
available in pitch where maneuverability is desirable and the
astronaut's inertia is high. Three operational modes were
envisioned. If the torque shaft were locked to the platform,
the platform could be rotated freely in space without exhibit-
ing gyroscopic torques. A spring restrained shaft would pro-
vide angular rate sensing which would be used to provide
precessional feedback forces applied tactilely to the foot.
The torque shaft would also be powered by the astronaut's foot
motions: toes down or up, right or left, and sidewise rota-
tion. See Figure 9.

Two shortcomings characterize this system despite ex-
tensive 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.

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 (90). A subject's subjective angular velocity as a function of time is shown in Figure 10. 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.

Stabilized (Closed-Loop) System Designs

- 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 (43, 50, 53, 54, 56). The operational requirements and unit characteristics are listed in Tables 5 and 6.

Table 5 :   AMU Operational Requirements (56)

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 - 285 fps

6) MMU redundancy philosophy

7) Stabilization and control

> auto stabilization - 3 axes
> rate command orientation - 3 axes
> automatic/manual mode

The propulsion system chosen was one of hydrogen peroxide with a total impulse of 3500 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

Table 6:   Gemini IX-A AMU Characteristics (53)

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, lb x sec   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

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 (43, 54).

    - 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 desire 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

33

means of control. Such means, each with its own control
logic, should be traded off against the hand controller concept
which is identical in technique to that of a spacecraft and
therefore requires less training. In addition to the re-
quirements 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 (13). 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 (13). 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 7 . Two rules were established:

- In attitude, continuous utterances command continuous rotation. Silence commands constant attitude.

- 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 led to the definition of a completely mechanized system which is currently under assembly (27). 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).

Table 13: Suggested Vocabulary for Speech Controller (13)

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

Pairs of electrodes placed around the eye will sense its rota-
tion 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

37

functions is a disadvantage to be considered. The visual

capability of a suited astronaut is shown in Table 8 and the

neck mobility in three axes in Table 9.

Table 8 : Range of Vision (Suited) (78)

Horizontal plane	120°left, 120°right
Vertical plane	105°down, 90°up

Table 9 : Maximum Neck Mobility Requirements (78)

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 measure-

ment of these biocurrents is called electromyography, and is

being used now primarily in the operation of prosthetic devices

for amputees. Raw electromyographic signals are character-

istically 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.

- Shuttle

The stabilized shuttle or work boat offers great
advantages in terms of protection, range of operation, and, with
mechanical manipulators, greater ability to perform work. The
significant disadvantages include heavy weight (900-1600 lbs.),
high cost, and interface complexity which, in turn, could de-
grade reliability (82). Maneuvering and attitude control
requirements could be expected to be similar to that of a
larger spacecraft.

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 direct-
ly 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 (23). The treatment of these signals must be
determined to optimize a chosen set of parameters. The follow-
ing paragraphs will make note of the systems which have been
suggested both for automatic and manual control.

- Control Alternatives

Several traditional control techniques are available for
use (13, 34). Simple acceleration command applies the signal
directly to the reaction thrusters which apply a torque pro-
portional to signal strength. The resulting rotational ac-

celeration 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 possibiltiy 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 block diagram of this system appears in Figure 11.

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 (13).

- Comparative Studies

The analytic techniques through which a comparison of

approaches can be made is based in nonlinear feedback control theory. Nonlinear effects of hysteresis, dead zone, and thrust time delays on limit cycle characteristics were studied using the phase plane by Brown (5). The additional effects of pulse frequency and pulse width modulation for a fixed thrust level have been investigated (11). The effects of external torques must also be considered in developing a strategy for minimizing fuel consumption assuming position and rate sensing. Design charts for determining system parameters of an automatic discontinuous attitude-control system with linear rate and position feedback have been constructed (74). Figure 12 is a block diagram of such a system.

Other studies have considered the practical design aspects given the requirements of high torque capability and very efficient operation when no disturbing torques are present (21).

Finally, Ergin et al. have prepared a four volume report on the problem of nonlinear attitude control (17). Pulse modulation is here viewed as being essentially a compromise between proportional control, which is dominated by the limit cycling of the system about a reference command, and simple "bang-bang" control, which, if provided with sufficient thrust to satisfy torquing requirements, would then suffer high propellant usage rate when in a "steady state" mode of limit cycle operation (17).

Ergin also suggests the use of timing devices in lieu of rate sensing equipment to improve performance while increasing system simplicity. One such method measures the "on-time" during each firing of the jets and uses this information to

reduce the "on-time" of the next firing by some factor K. Ultimately, under quiescent conditions, the minimum jet "on-time", t_{min}, will be reached and will determine the steady-state limit cycle characteristics and the fuel consumption rate.

Another example of torque compensation by means of a timing device is that of a "staircase Torque generator". Here "rate" information is obtained by measuring the time between zero-crossing and torque-switching. When the attitude error reaches the dead-space value of the switch, an impulse is imparted to reverse the direction of travel. The magnitude of this impulse will be inversely proportional to the elapsed time between zero-crossing and the dead-space value. Such systems are capable of very low limit cycle rates. Further comparative simulations seem warranted.

- Manual Control

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 (10). 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 (16). 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.

Comparative studies in manual control of several EVA maneuvering units are being planned for the Orbiting Workshop Program (OWS) of the Apollo Applications Program. The object of Skylab Experiment 17-509 Astronaut Maneuvering Equipment is to investigate the utility of several maneuvering unit control concepts in the relative safety of a pressurized workshop area.

Among the control units currently planned to receive this evaluation are the AMU, the HHMU, and a modified foot-controller unit (80). Whitsett and other project planners will give particular attention to system performance and man's response to the overall handling qualities in the weightless regime. One secondary advantage will be the feedback information provided on the fidelity of current ground-based simulation techniques (48).

Recommendations for University Research

- Guidance and Stabilization

- Develop effective models for station-keeping dynamics, including consideration for gravity gradient perturbations. This is an area that has received no attention comparable to that given the dynamics of terminal rendezvous.

- Continue analysis of the human body as a non-rigid mass for the purpose of establishing such control system parameters as displacement and rate deadband adjustments.

- Perform experimental study with goal of identifying a postural control model for use in foot and waist-controlled attitude control systems (39).

- Consider the use of control moment gyros (CMG's) for use in both stabilization or attitude sensing and actual attitude control or motion. Explore mechanical or other means of torquing with the goal of minimizing the additional weight required.

- Design and perform experiments to determine precisely pilot subjective "effort" as a function of degree of ankle deflection, waist-banding, differential foot-lifting, torso twist, etc. as well as rotation rates in these modes. Clearly, subjective effort increases from zero to infinity at some finite deflection and rotation rate.

- Conduct computer-simulated tests followed by zero-g tests with subjects to determine feasibility of eliminating yaw rotation as a required capability for an attitude control system.

- Study proportional versus on-off control with respect to "naturalness" to the human reflex system and smoothness of operation.

- Work to improve existing hand controllers. One approach might include a single controller which can command both rotation and translation.

- Study the possible effects of variable spacecraft space suit atmospheres, background noise, and change of personnel in operation of a voice recognition system for use in attitude control.

-Design and evaluate a tone controller on a simple task capable of control by incremental inputs. Measure oxygen uptake. Determine the effect of sound initiation and the feasibility of using portamento. Determine the nature of any side reference that may be required, and evaluate its effect on the pilot and the overall system. Evaluate this

technique in various simulated "emergency" modes.

- Survey several approaches to eye position measurement for possible controller adaptation, given the restrictions which such applications impose on any measuring technique.

- Design a low-volume system for control using astronaut helmet position pick-offs in conjunction with a visual sighting device for "aiming". Conduct tests.

- Perform experiments to determine subjective "effort" as a function of head nods, turn, and tilts, their displacement and rates of turn.

- Design and conduct experiments to determine feasibility of electromyographic control using head movements. Determine optimal control technique and evaluate technique in terms of astronaut comfort, reliability, and helmet interface.

- Perform computer simulations to compare timing devices with traditional rate sensing based on optimization of several parameters.

- Conduct control tasks with subjects, comparing position and rate control, considering factors such as nature of task, shape of hand controller, and subject fatigue.

- Test acceleration command under simulated conditions of short and long range (greater than two hundred feet) rendezvous to determine the degree of ambiguity at greater distances between rotation rate and target translation. Test incorporated rate control with attitude-hold feature to optimize time lines and fuel consumption.

References

1. Beasley, Gary, P., "Investigation of a Simplified Maneuvering Technique," Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

2. Bell, Aerosystems Company, News Bureau, News Release, Sept. 17, 1968, Buffalo, New York.

3. Berry, C. A., "Preliminary Clinical Report of the Medical Aspects of Apollos VII and VIII," Aerospace Medicine, Vol. 40, No. 3, 1969, pp. 245-254.

4. Bond, Robert L., and Goodman, Jerry R., "In-Flight EVA for Mainline Apollo Missions," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, August 1968, Las Vegas, Nevada.

5. Brown, Stuart C., "Predicted Performance of On-Off Systems for Precise Attitude Control," NASA TN D-1040, July 1961.

6. Brownell, Charles, and Schofield, J. N., "EVA Associated with the Assembly and Services of Large Structures," Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

7. Chang, Dr. K. T., and Yarber, G. W., "Application of Control Moment Gyroscope to Stabilization and Attitude Control in Space," Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

8. Coffin, C. L., "Space-Suit Thermal Conditioning Techniques for Future Extravehicular Missions," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, August 1968, Las Vegas, Nevada.

9. Costick, John F. III, "The Necessity for Development and Use of Fastening Devices with Special Characteristics for Space Use," Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

10. Crawford, Billy, M. and Kama, William N., "Remote Handling Research and Potential Space Applications," Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

11. Dahl, P. R., Aldrich, G. T. and Herman L. K., "Limit Cycles in Reaction Jet Attitude Control Systems Subject to External Torques," Proceedings of Guidance, Control and Navigation Conference, August 1961, Stanford, California.

12. Davis, Jefferson C., "Advanced Aspects of Pressure Suit Developments," Lectures in Aerospace Medicine, 6th Series, AD 665 107, February 1967, Brooks AFB.

13. Drissel, W. E., Haines, R. L., et al., "Study of an Attitude Control System for the Astronaut Maneuvering Unit," NASA CR-198, March 1965.

14. DuBois, J., "The Determination of the Moment of Inertia of the Living Human Organism," NA-62-135, 1962.

15. Elkins, William, "Hard Shell Suit Performance as it Relates to Space Maintenance and Other Extravehicular Activities," Processdings of National Conference on Space Maintenance and Extravehicluar Activities, March 1966, Orlando, Florida.

16. Emerson, Jerome E., "Simulation Studies of EVA Missions," Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

17. Ergin, E. I., Norum, V. D., and Windeknecht, T. G., "Techniques for Analysis of Nonlinear Attitude Control Systems for Space Vehicles," ASD-TDR-62-208, Vol. I-IV, June 1967.

18. Fraser, Dr. T. M., "Philosophy of Stimulation in a Man-Machine Space Mission System," NASA SP-102, 1966.

19. Freeman, H. E., and DeSonne, G., "Application of Control Gyros to Astronaut Maneuvering Units," Proceedings of Second National Conference on Space Maintenance and Extra-vehicular Activities, August 1968, Las Vegas, Nevada.

20. Galiana, H. L., "Ionizing Radiation and Magnetic Fields: A Review of Their Effects on the Nervous System," MVLS-69-1, February 1969, Man-Vehicle Laboratory, Massachusetts Institute of Technology, Cambridge, Massachussetts.

21. Gaylord, R. S., and Keller, W. N., "Attitude Control System Using Logically Controlled Pulses," Proceedings of Guidance Control and Navigation Conference, Aug. 1961, Stanford, Calif.

22. Graybiel, A., "Orientation in Space with Respect to the Vestibular Function," Environmental Effects on Conscienciousness, Schaeffer, Karl E. (ed.), McMillan, 1962.

23. Haeusserman, Walter, "Recent Advances in Attitude Control of Space Vehicles," ARS Journal, February 1962, pp. 188-195.

24. Hanavan, Jr. Ernest P., "A Mathematical Model of the Human Body," AMRL-TR-64-102, Oct. 1964, Wright-Patterson AFB, Ohio.

25. Hatcher, Norman M., and Young, Richard N., "An Automatic Balancing System for Use on Frictionlessly Supported Attitude-Controlled Test Platforms," NASA TN D-4426, 1968.

26. Herrala, Thomas W., and Sutton, James G., "Advanced Portable Life Support Concepts," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, August 1968, Las Vegas, Nevada.

27. Herscher, M. B., et al., "Voice Controller for Astronaut Maneuvering Unit," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, August 1968, Las Vegas, Nevada.

28. Hewes, Donald E., "Analysis of Self-Locomotive Performance of Lunar Explorers Based on Experimental Reduced-Gravity Studies," NASA TN D-3934, 1967.

29. Hewes, Donald E., "Studeis of Piloting Problems of One-Man Flying Units Operated in Simulated Lunar Gravity," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

30. Hill, Paul, R., and Kennedy, T. L., "Flight Tests of a Man Standing on a Platform Supported by a Teetering Rotor," NASA RM L54B12a, 1954.

31. Howard, Douglas C., "Engineering Design Study of a Space Suit with an Integrated Environmental Control System," AD 680-826, October 1968.

32. Huber, W. C. and Finn, R. W., "A Summary of Hand-Held Maneuvering Unit Development," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, August 1968, Las Vegas, Nevada.

33. Interian, Alfred, and Kugath, Donald, "Remote Manipulators in Space," Astronautics and Aeronautics, May 1969, pp. 40-51.

34. Iribe, P. and Lieske, "Study of Extravehicular Protection and Operations," NASA CR-773, July, 1966.

35. Janos, Joseph J., and Hoffman, Sherwood, "Forces and Moments Produced by Air and Helium Jets Exhausting Parallel to Flat Plate in a Near Vacuum," NASA TN D-4408, 1968.

36. Johnston, Richard, S., Correale, James V., and Radnotsky, Matthew I., "Space Suit Development Status," NASA TN D-3291, 1966.

37. Kane, Thomas R., "Self-Rotation of Astronauts by Means of Limb Movements," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

38. Keller, T., and O'Hagan, J. T., "Vehicular Control Using the Human Balancing Reflex," GRD-102, 1963.

39. Keller, T., and O'Hagan, J. T., et al., "An Outline of Proposed Research Into the Use of the Human Balancing Reflex for Control of Vehicles," RP-162, 1963.

40. Keller, Thomas L., and Breul, Harry T., "Hands-Free Precision Control for EVA," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities," Aug. 1968, Las Vegas, Nevada.

41. Kephart, J. F., and Walker, S. C., "A Comparison of Propulsion Concepts for Astronaut Maneuvering Units," Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

42. Lieske, J. A., and Iribe, P., "Extravehicular Environment and Mobility Constraints on the Configuration of an Anthropomorphic Space Suit System," Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

43. Lindemuth, Robert W., "Performance Analysis of an Astronaut Maneuvering System," Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

44. Loats, Harry L., Jr., et al., "Correlation Study of the Simulation of Gemini Extravehicular Activity with Flight Results," NASA CR-1146, February 1969.

45. May, C. B., and Holmes, A. E., "An Evaluation of Man's Capability to Perform Support Functions in Space," Proceedings of 17th International Astronautical Congress, 1966, Madrid, Spain.

46. May, Chester B., and McCarty, Harlan, "EVA Requirements in Support of Scientific and Technical Earth-Orbital Space Activities," Second National Conference on Space Maintenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

47. McIver, Robert G., "Bends in Simulated Extravehicular Activity," Lectures in Aerospace Medicine, Sixth Series, AD 665-107, Feb. 1967, Brooks AFB.

48. McMann, Harold J. Jr., Moran, Jon W. and Whitsett, Major C. E. Jr., "Maneuvering-Unit Development Programs," Joint National Meeting: American Astronautical Society and Operations Research Society, June 17-20, 1969, Denver, Colorado, Paper No. XIII E.2.

49. Miller, Perry B., "Medical Problems of Weightlessness,"
    SAM TR 66-200, 1965.

50. Monroe, G. M., and McMillan, W. C., "Description of the
    Astronaut Maneuvering Unit," Proceedings of 17th Inter-
    national Astronautical Congress, 1966, Madrid, Spain.

51. Mueller, George E., "Beyond Apollo," Astronautics and
    Aeronautics, August 1965.

52. National Aeronautics and Space Administration, "Compendium
    of Human Responses to the Aerospace Environment," NASA
    Contractor Report CR-1205, November 1968, Albuquerque,
    New Mexico.

53. National Aeronautics and Space Administration, "Gemini
    Summary Conference," NASA SP-138, February 1967.

54. National Aeronautics and Space Administration, "Summary of
    Gemini Extravehicular Activity," NASA SP-149, 1967.

55. O'Connor, B. J., and Morine, L. A., "A Description of the
    CMG and its Application to Space Vehicle Control,"
    Proceedings of AIAA Guidance, Control and Flight Dynamics
    Conference, 1967.

56. Parker, Frank W., and Garnett, Robert J., "The Astronaut
    Maneuvering Unit," Proceedings of National Conference on
    Space Maintenance and Extravehicular Activities, March 1966,
    Orlando, Florida.

57. Phillips, James P., "Control Moment Gyro Characteristics
    and Their Effects on Control System Performance," AIAA Paper
    No. 68-875, 1968.

58. Prince, R. Norman, and O'Reilly, William J., "Development
    of the Portable Environmental Control System," Proceedings
    of Second National Conference on Space Maintenance and
    Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

59. Prodan, John, and Gaskins, Darius W., Jr., "Extravehicular
    Activity Training in the T-27 Space Flight Simulator,"
    Proceedings of National Conference on Space Maintenance
    and Extravehicular Activities, March 1966, Orlando, Florida.

60. Puri, Dr. N. N., et al., "Unmanned Rendezvous, Station-
    Keeping and Docking for Extravehicular Space Activities,"
    Proceedings of Second National Conference on Space Maintenance
    and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

61. Reid, R. C., and Richardson, D. L., "Portable Life Support
    Systems for Extravehicular Activities," Proceedings of 61st
    Annual Meeting on Life Support Systems, American Institute
    of Chemical Engineers, Dec. 1968, Los Angeles, California.

62. Riddle, C. and Kane, T. R., "Reorientation of the Human Body by Means of Arm Motions," NASA CR 95362, Feb. 1968.

63. Runyan, T. L., and Dick, J. M., "Illumination for Extra-vehicular Tasks, Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

64. Samson, J. H., EVA Support of Scientific and Technical Experiments," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

65. Schuerch, H., "Some Considerations of Manned Extravehicular Activities in Assembly and Operation of Large Space Structures," NASA CR-871, 1967.

66. Schwinghammer, Robert J., "Tool Experiments for Assembly, Maintenance and Repair in Space," Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

67. Seale, Dr. Leonard M., "Space Extravehicular Operations: A Review of the Requirements and Alternate System Approaches," Proceedings of 17th International Astronautical Congress, 1966, Madrid, Spain.

68. Seale, Dr. Leonard M., "Manned Propulsion Devices and Their Applications on Earth and in Space," Lectures in Aerospace Medicine, Sixth Series, AD 665-107, Feb. 1967, Brooks AFB.

69. Seely, R. B., "Automatically Stabilized Maneuvering Unit UASMU)," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

70. Sewell, H. E.,"Preliminary AMU Simulation Program," LTV Astronautics Division Report No. 00.775, Nov. 1964.

71. Spady, Amos A., Jr., and Harris, Randall L., "Effects of Pressure Suits and Backpack Loads on Man's Self-Locomotion in Earth and Simulated Lunar Gravity," NASA TN D-4464, 1968.

72. "Study of The Thermal Processes for Man-in-Space," NASA CR-216.

73. "A System Study of a Manned Orbital Telescope," D.2-84042-1, October, 1965, Aerospace Group, The Boeing Company; Seattle, Washington.

74. Taylor, Lawrence W. Jr., and Smith, John W., "An Analytical Approach to the Design of an Automatic Discontinuous Control System," NASA TN-D-630, April 1961.

75. Thomas, David F., Jr., et al., "Jet Shoes – An Extravehicular Space Locomotion Device," NASA TN D-3809, 1967.

76. Trout, Otto F., Jr., and Hill, Paul R., "Human Work Performance in Space," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

77. Tucker, Elton M., "NASA Programs for Advanced Space Suit Development," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

78. Van Dyke, W. J., "Performance?Design and Product Configuration Requirements, Extravehicular Mobility Unit for Apollo Block II Missions," Master End Item Specification, NASA-EMU-CSD-A-096, Manned Spacecraft Center, Houston, Texas, January 1966.

79. Van Schaik, Peter N., "Man's Changing Role in EVA Space," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

80. Whitsett, Charles Edward, Jr., "Some Dynamic Response Characteristics of Weightless Man," AMRL – TDR – 63-18, 1963.

81. Whitsett, Charles E., Jr., "Experiment M-509 Astronaut Maneuvering Equipment," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

82. Willoughby, A. J. et al., "A Summary of Research as of January 1966 in Extravehicular Maneuvering Techniques for Space, "Proceedings of National Conference on Space Maintenance and Extravehicular Activities, March 1966, Orlando, Florida.

83. Wortz, Dr. E. C., et al., "Study of Astronaut Capabilities to Perform Extravehicular Maintenance and Assembly Functions in Weightless Conditions," NASA CR-859, Sept. 1967.

84. Wortz, Dr. E. C., "The Mechanics of Work in Reduced-Gravity Environment," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

85. Wrench, E. H., and Greensite, A. L., "EVA Stabilization Shoes," GDC-ERR-AN-1107, 1967.

86. Wudell, A. E., and Tobey, W. H., "A Six-Degree-of-Freedom Simulation for Evaluation of Space Mobility Aids and Tasks," Proceedings of Second National Conference on Space Main- tenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

87. Wudell, A. E., and Tobey, W. H., and Whitsett, Major C. E., "EVA Maneuvering Unit Comparison," Joint National Meeting: American Astronautical Society and Operations Research Society, June 17-20, 1969, Denver Colorado, Paper No. XV J. 2.

88. Yost, Vaughn H., "Mechanical Devices for Zero Gravity Simu- lation," Proceedings of Second National Conference on Space Maintenance and Extravehicular Activities, Aug. 1968, Las Vegas, Nevada.

89. Young, Gerould A., Major, USAF, and Torvik, Peter J., "Simulation of Unstabilized Maneuvering Units," Proceedings of Second National Conference on Space Maintenance and Extra- vehicular Activities, Aug. 1968, Las Vegas, Nevada.

90. Young, L. R., "A Control Model of the Vestibular System," Proceedings of Symposium on Technical and Biological Problems in Cybernetics, September 1968, Yerivan, Armenia, USSR.

91. Zimmerman, C. H., Hill, P. R., and Kennedy, T. L., "Preliminary Investigation of the Flight of a Person Supported by a Jet Thrust Device Attached to his Feet," NACA Research Memorandum L52D10, January 1953.
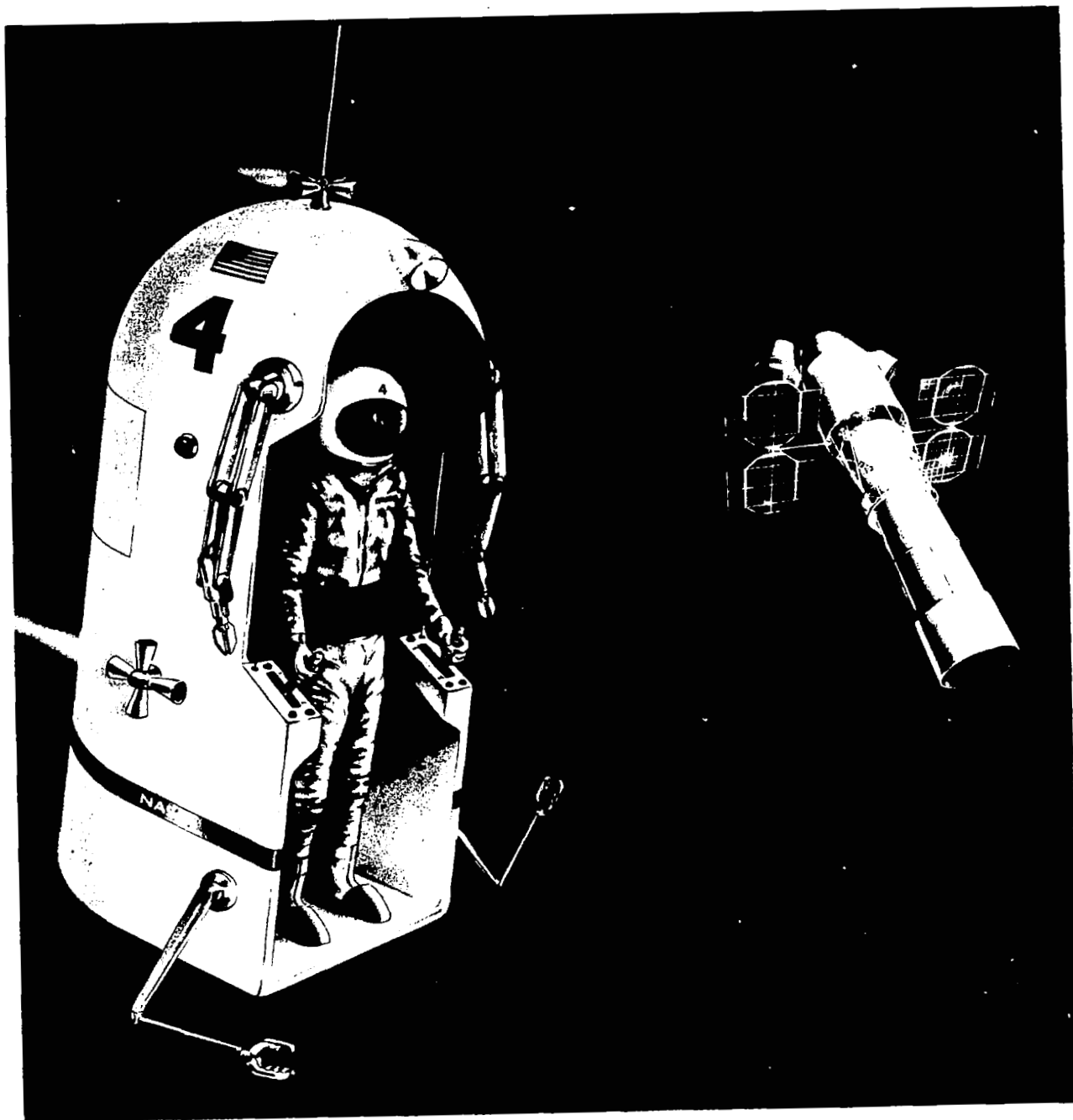
Figure 1: Work Platform (34)
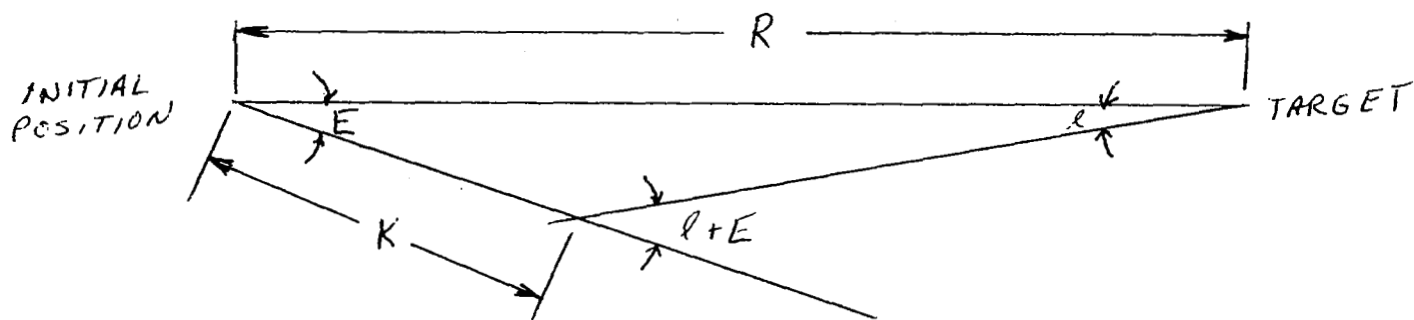
Figure 2 :   Rendezvous. Geometry (13)
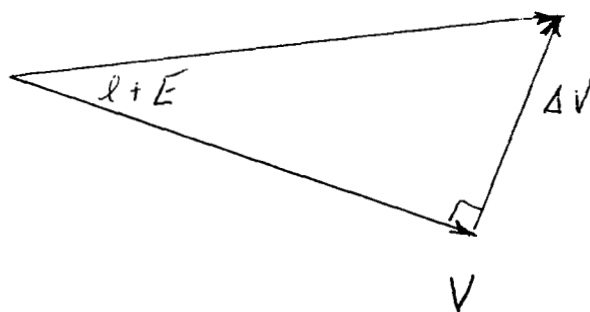
Figure 3 :   Vector Diagram (13)

Negative
control moment

Thrust

Thrust

Ankle
movement

(a) Translation only
no rotational control

(b) Rotational control
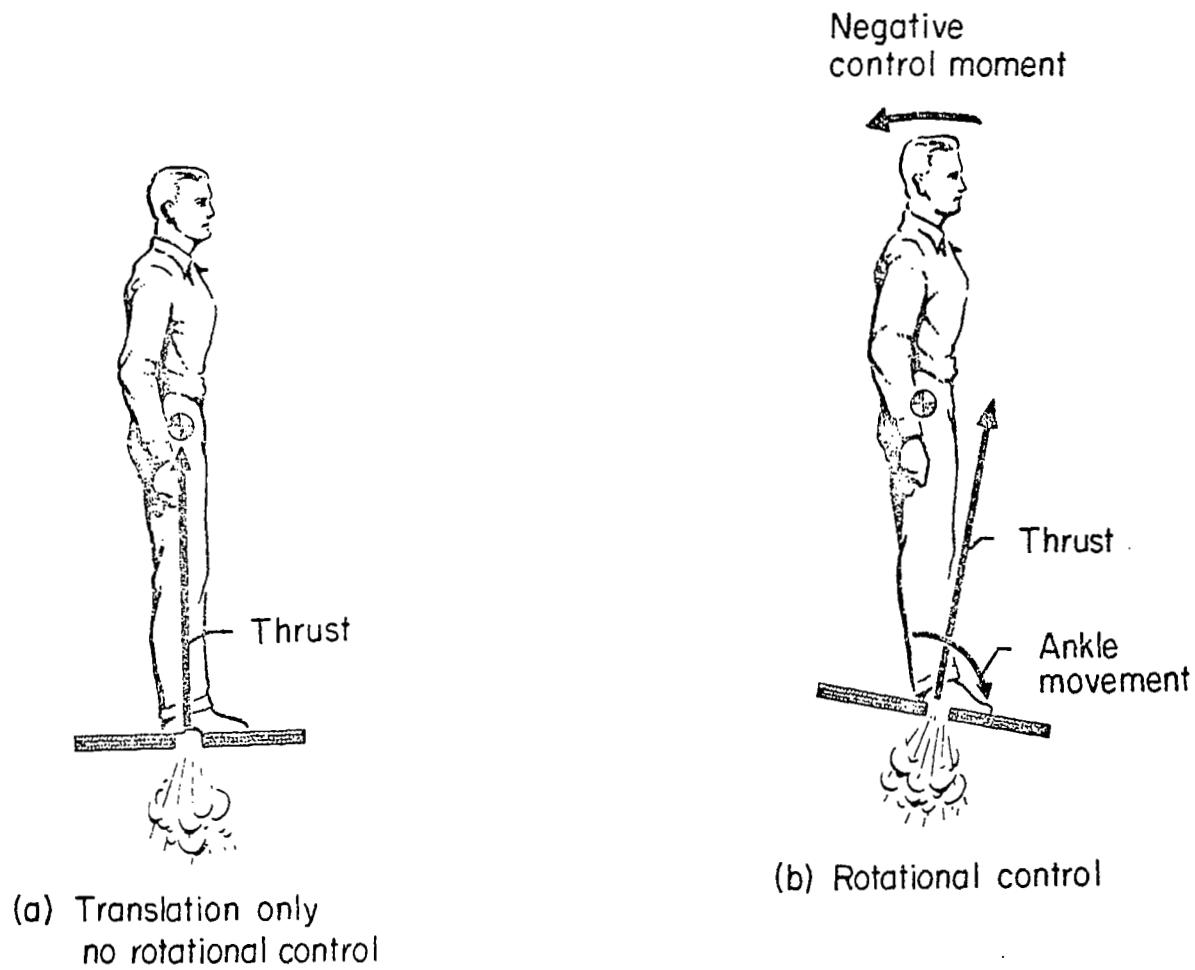
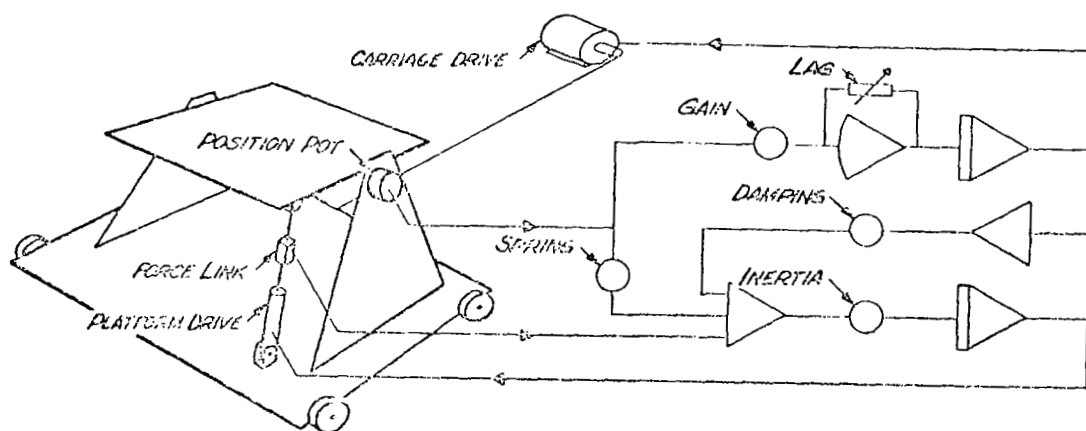Figure 4:   Force and control moments resulting from rotation of ankles. (75)

Figure 5:   Platform for Balancing Reflex Expts . (38)

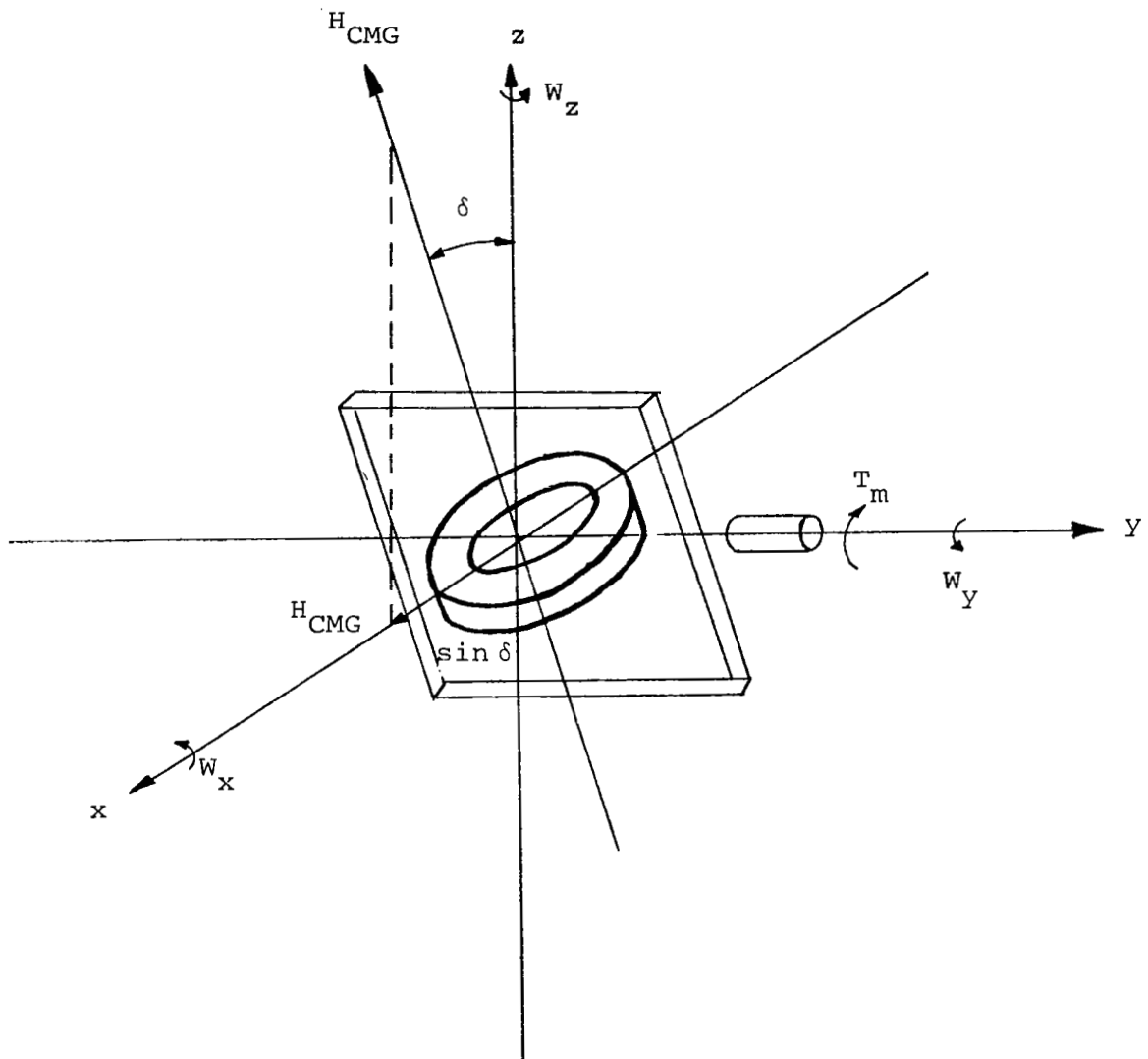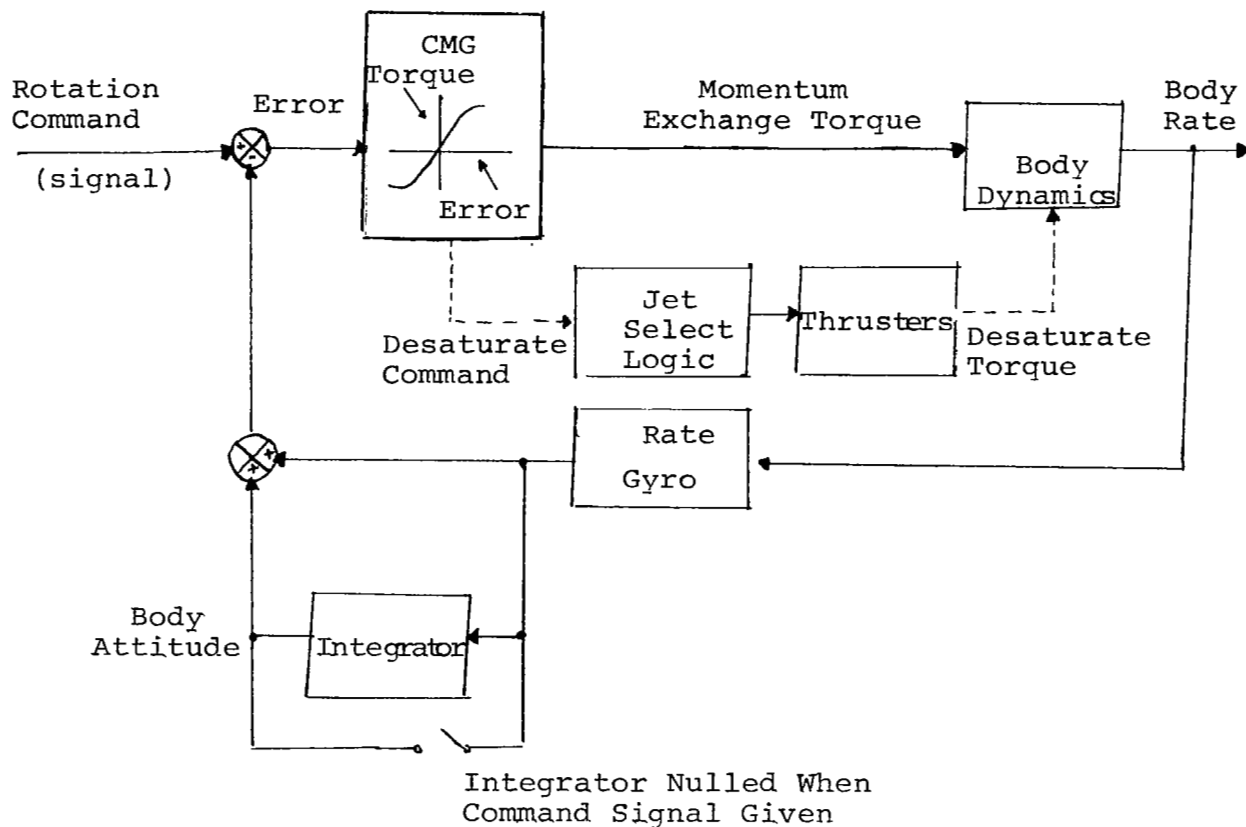Figure 6: Single Rotor Single Degree of Freedom CMG

Figure 7:   Typical Control Moment Gyro Type
             Attitude Control and Stabilization
             System Utilizing Rate Gyro Feedback (64)

TORQUE SHAFT
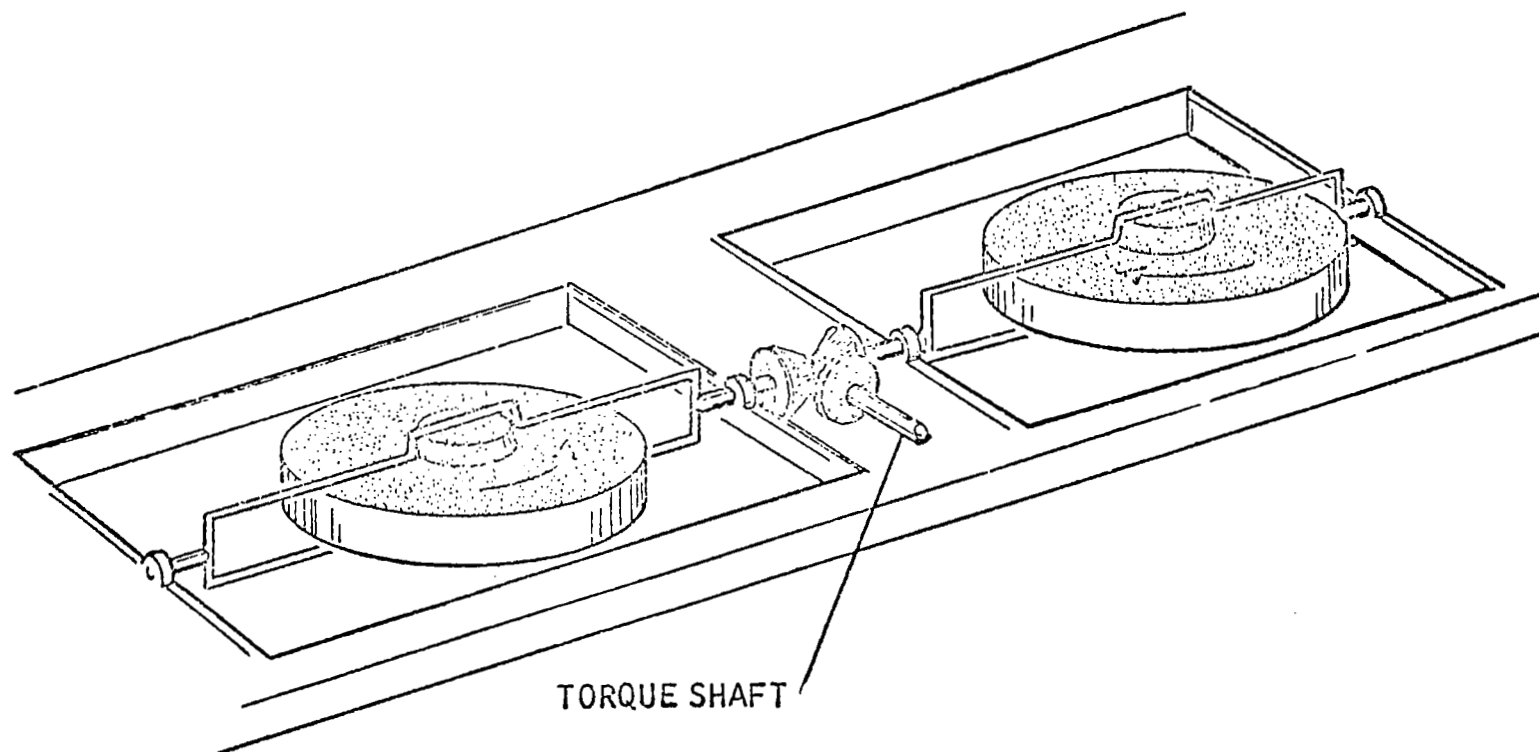
Figure 8 :   Momentum Control System.   (85)
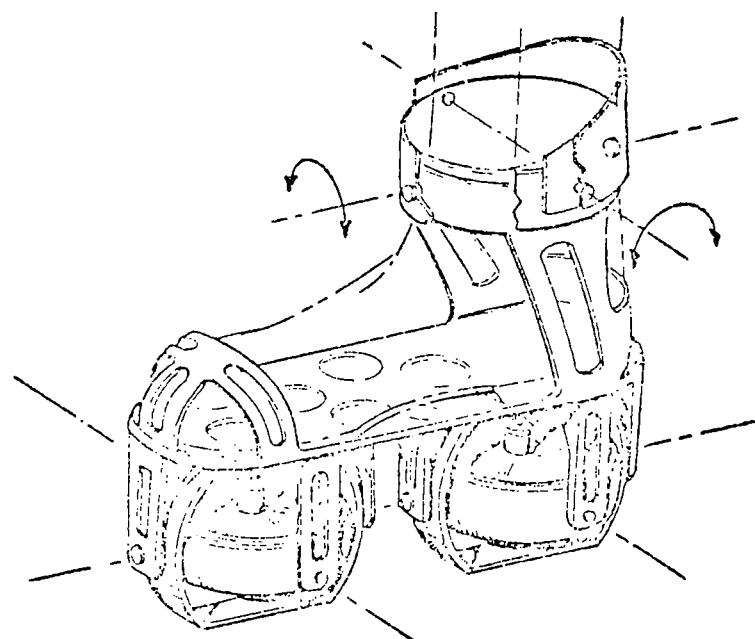
NORMAL POSITION-ZERO MOMENTUM
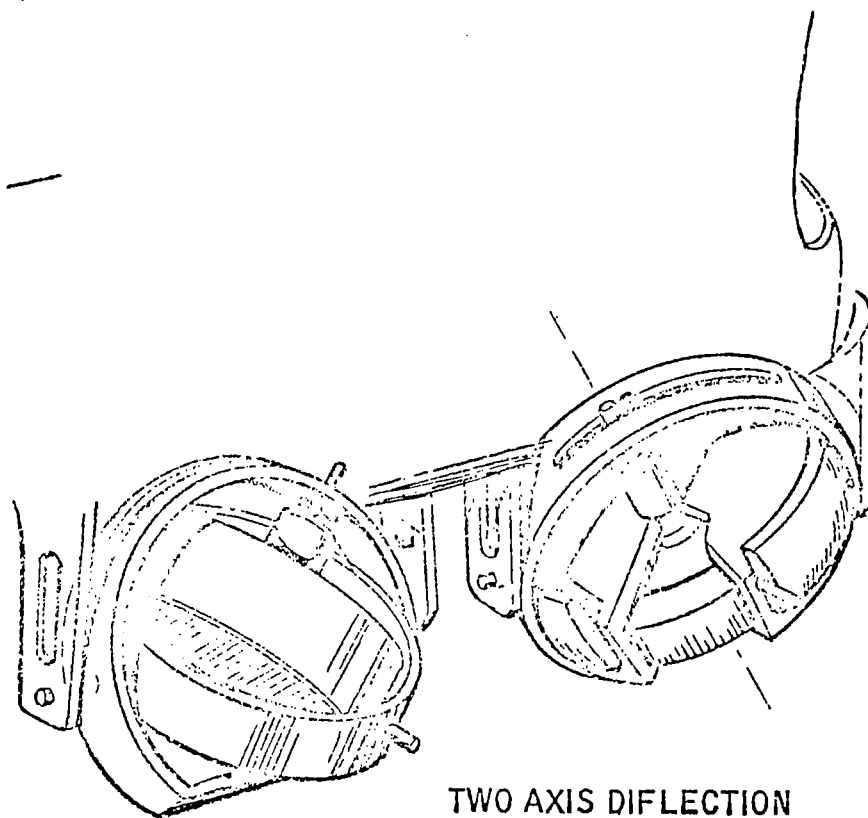
TWO AXIS DIFLECTION

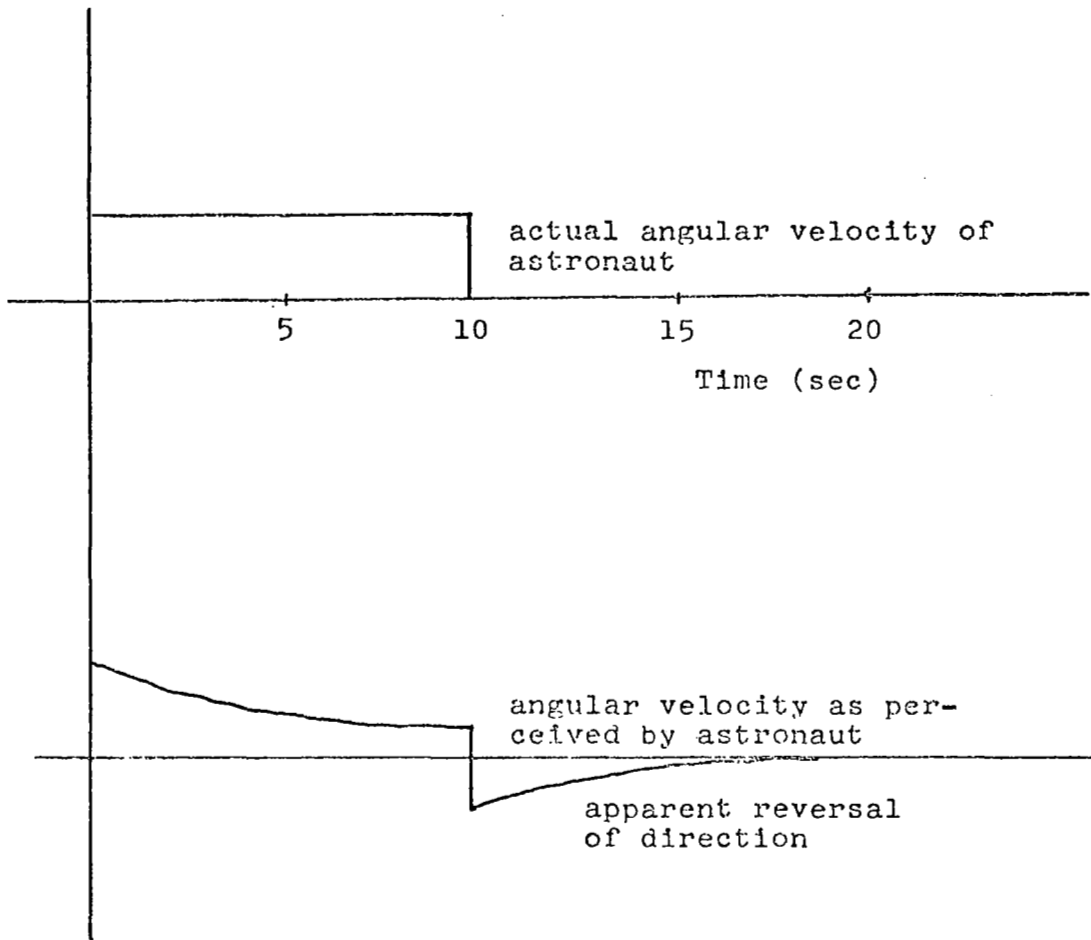Figure 9 : Experimental Configuration, Artist Conception (85)

Figure 10

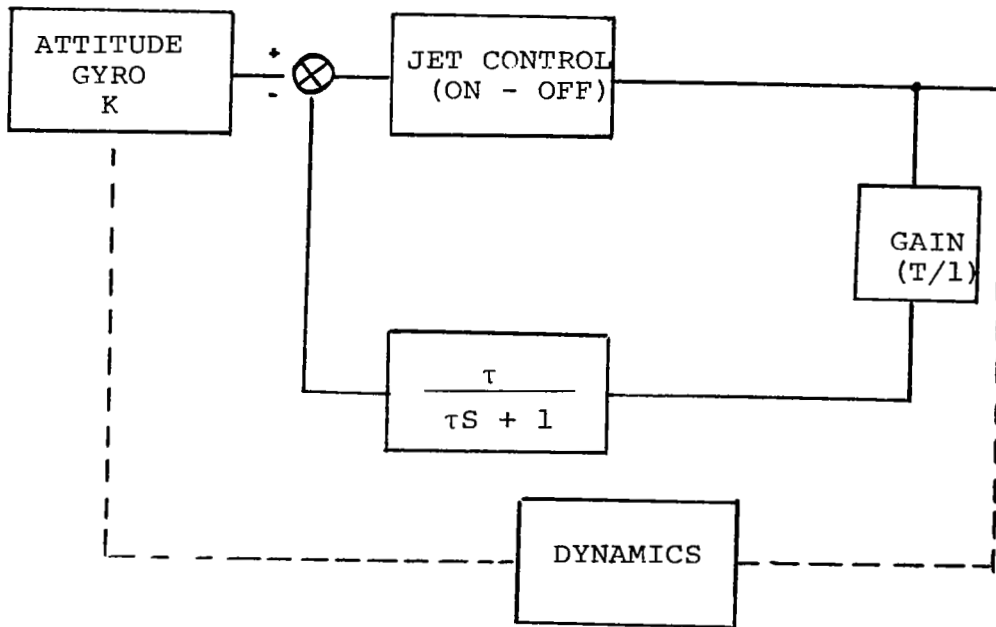Actual vs. Subjective Angular Velocity (90°)

Figure 11: Pseudo Rate Control Block Diagram (13)
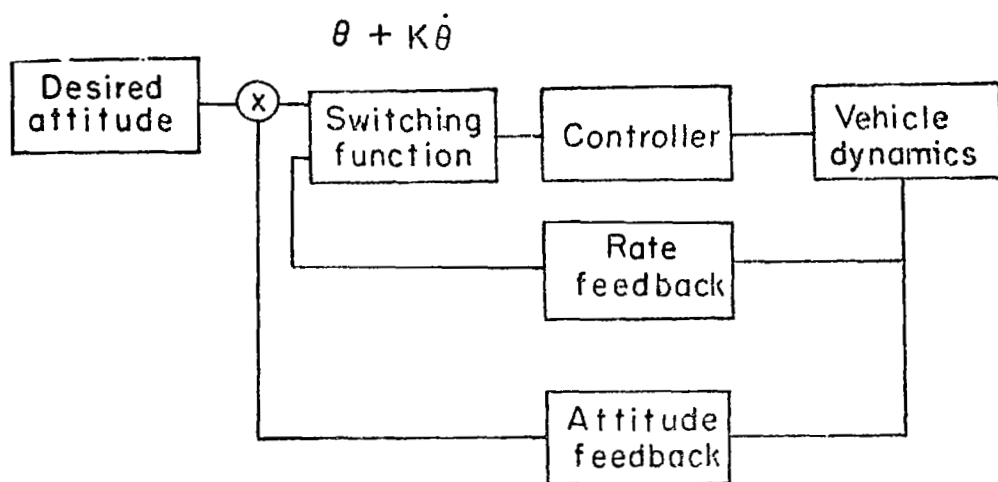
$$\theta + K\dot\theta$$

Figure 12- Block diagram of an automatic discontinuous attitude-control system with linear rate and position feedback. (74)