LANGLEY WORKING PAPER

A DISCUSSION OF CONTROL SYSTEMS FOR FOOT CONTROLLED SPACE MANEUVERING UNITS

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INTRODUCTION

In October 1966, the "jet shoe" concept was advanced as a candidate experiment to be conducted as part of the Orbital Workshop (OWS) experiments to be carried out in the Apollo Applications Program (AAP). This concept was based on preliminary experimental studies of a system of two small thrusters placed on the soles of an astronaut's boots to provide locomotion during extra-vehicular activities in space. Following the acceptance of the proposed experiment as Experiment T020, and as a result of further definition studies, the concept was modified to overcome some problems that were encountered with the original concept. This modified form which was named "Foot Controlled Maneuvering Unit (FCMU) replaced the two thrusters with two assemblies of four thrusters still operated by the feet but attached to a lightweight saddle-mounted structure between the astronaut's legs, as depicted in figure 1. Although not necessarily providing the most desirable maneuvering capability, this basically simple system was considered to be appropriate for the purposes of the exploratory studies intended for the OWS.

The purpose of this paper is to show how the concept of using the feet for pilot control inputs, once it has been demonstrated to be feasible by the AAP experiment, can be implemented into various systems of increasing complexity
and capabilities. As with most operational systems, many design compromises and trade-offs have to be made in order to arrive at a practical and yet near optimum or efficient system. By reviewing this family of alternate control systems some insight to the trade-offs to be made can be gained. Although one of the unique features of the FCMU is identified as providing hands-free operation of a maneuvering unit, it is not the intent of this paper to eliminate the discussion of hand-operated controls.

REFERENCE AXES AND SYMBOLS

The reference axes for the FCMU are the set of orthogonal axes passing through the center of gravity of the total system and aligned with the principal moments of inertia as indicated in figure 1. Motions of the feet are defined with respect to a set of axes indicated in figure 2.

- $F_Z$: foot travel, up-and-down translation of the foot by primary action of the hip joint
- $F_\theta$: foot pitch, toe-up and -down rotation of the foot by action of the ankle joint
- $F_\varphi$: foot roll, side to side rotation of the foot by action of the ankle joint
- $F_\psi$: foot yaw, side to side rotation of the foot by action of the knee joint
- $L$: left hand or foot
- $R$: right hand or foot
- $L+R$: both feet moved in the same direction
- $L-R$: both feet moved in opposite directions
BASIC PILOT CONTROL MOTIONS

In practically all man-operated systems, a group of discrete motions of the various body members is utilized in providing the control input functions necessary to operate the system. In many instances the selection of the particular group of control motions is based on past experience or custom and not necessarily on detailed studies of the most effective selection for the particular application.

In order to be useful for control purposes, a given body motion must be controlled accurately with respect to direction and magnitude. Historically, both the hands and feet have been used in operating the many forms of vehicles that have evolved. In most instances the operator's hand-arm motions have been assigned to the particular control functions requiring the higher degree of dexterity and coordination and the foot-leg motions to those control functions of a grosser and perhaps less repetative nature. For many applications this has led to logical, practical, and acceptable control systems. Because of the general overall success of this approach there has been a strong tendency to overlook or disregard other approaches in unique applications where because of design and other considerations such control concepts might be more effective.

The foot-leg muscle groups are quite capable of performing precise and continuous tasks as evidenced by the dependence of man on these for the necessary, daily tasks of standing, walking, running, jumping, and swimming. The distinct motions of the foot-leg complex that appear to be most useful for control purposes are as follows:

Ankle rotation. - This motion can be defined in general terms as consisting of two degrees of freedom in which the foot is rotated in a vertical plane in the toes up and down direction, and is rotated laterally from side to side
as depicted in figure 2. In anthropometric terms these motions correspond to ankle flexion and extension, and to foot inversion and eversion. Although not normally employed in current control systems, foot inversion-eversion motions are involved most evidently anytime a person stands unaided on one foot or performs on ice or roller skates. Of course, ankle flexion and extension are used extensively to operate accelerator pedals of automobiles and rudder pedals of airplanes. For purposes of this discussion, these two distinct ankle motions will be referred to as foot pitch \((F_\theta)\), and foot roll \((F_\phi)\), inasmuch as they correspond to motions about the axes most closely aligned to those referred to in figure 1 as the operator’s pitch and roll axes.

**Knee rotation.** - The particular motion to be considered here is referred to in anthropometric terms as knee medial and lateral rotation. Here the foot is twisted in the horizontal plane by movement of the lower leg about the knee. There has been no general utilization of this motion as a controlling action. For this discussion this motion will be referred to as foot yaw \((F_\psi)\).

**Hip rotation.** - The motion considered here actually is a compounded action of the hip, knee and ankle which results in the foot being displaced up and down. The muscle groups used primarily for actuation of this motion, however, are associated with the hip flexion. The braking action for an automobile is one of the most prevalent applications of this body motion. For discussion, this motion will be referred to as foot travel \((F_z)\).

There are, of course, several other distinct actions of the lower extremities which could be considered as candidate motions, but they do not appear to be as likely as those described here. The motions of the upper extremities as employed in controlling systems are quite apparent because of the extensive utilization of hand-arm control in most everyday applications. Because of this familiarity there is no need for further discussion of these at this point.
In order for the pilot operator to perform a given controlling task effectively, the control motion input should bear some logical relation with the resulting motion generated by the system. In the case of the most ideal situation where the maneuvering unit is capable of producing motion in all six degrees of freedom, the control system must involve six discrete control inputs which can be made either independently or simultaneously with a minimum of interaction and redundancy. In practice, it may be reasonable, desirable or necessary to eliminate one or more of these control functions to provide a usable device of somewhat lesser mobility due to weight, development costs, system simplicity or some other considerations.

In the case of the Astronaut Maneuvering Unit developed for Gemini, as depicted in figure 3, lateral translation capability was not provided. The remaining five control functions were performed by using both hands, the right for attitude about all three axes and the left for fore-aft and up-down translation. In the case of the FCMU for AAP Experiment T020, as depicted in figure 1, both lateral and fore-aft translations have not been provided, and the resulting capability is considered to be the minimum that can be used to achieve any reasonable degree of success. Here, of course, all control inputs are made by use of some of the foot motions discussed previously.

A list of some alternate control logic concepts employing the feet as well as the hands is given in table I. In making this selection a basic assumption has been made that the right-hand body member is used for attitude inputs when only one member is required for a particular control function. This, of course, is consistent with most control function layouts used in spacecraft systems.
The first concept listed is that of the T020 FCMU which is based on the natural balancing reflexes employed when a person is standing. Using this logic, rotating both feet either toes up or down, \((L+R)θ\), as in leaning forward or backward causes the system to pitch (see figure 1 for definitions of pitch, roll, and yaw). The arrangement of the thrusters used to produce this response motion will be discussed subsequently. Pressing one foot down and the other up, \((L-R)F_z\), produces system roll as in leaning the body from side to side. The logic for yaw control corresponds to the toe-up---heel-down action, \((L-R)F_θ\), used in performing a military right or left face maneuver. Up-and-down translation produced by foot travel, \((L+R)F_z\), corresponds to the muscle action employed in standing up and squatting down. Note that this concept employs only foot pitch and foot travel motions and uses left and right feet in combination for any given control input.

Although the FCMU logic appears to be a rather straightforward copying of conditioned human reflexes, experience in simulation facilities used to study the handling qualities and maneuvering capabilities for AAP Experiment T020 has resulted in some interesting observations. The first is that there is not a carryover of the reflex responses from our normal environment to the simulated space situation and that a definite conditioning or learning process is required, albeit relatively short. There was some objection to the somewhat ambiguous situation as encountered in the balance reflex actions of having to use both feet to perform a given control input. Secondly, most of the subjects, primarily those who are current pilots, stated a preference for the opposite sense or direction of all control inputs. However, experience using both control directions showed that either can be handled relatively easy.
Aside from these comments concerning the control logic of the basic FCMU, the simulation experience indicates that the thrusting capability along only one axis permitted fairly reasonable translations. However, under some conditions, particularly when in a relatively limited space or close to an object, difficulties were encountered in controlling velocities in the lateral and fore-aft translational directions. This can be overcome, of course, by adding thrusters acting in these two directions. Inasmuch as the feet are well "occupied" controlling the other four degrees of freedom using the basic FCMU concept, it appears desirable to delegate the control responsibility for these added capabilities to the hands rather than to the feet. The logical choice appears to be the left hand to control either or both axes, leaving the right hand free to assist in either carrying objects or in grasping the target vehicle to anchor the system during the docking maneuver. This is the second concept given in table I.

The third candidate arrangement uses the feet exclusively for all six control functions and disassociates the two feet so that attitude is controlled solely by the right foot and translation by the left. This scheme uses right foot pitch $RF_\theta$ to command pitch attitude, right foot yaw $RF_\psi$ to command yaw attitude, left foot travel $RF_Z$ to command up-and-down, and left foot pitch $LF_\theta$ for fore-and-aft command. For roll command there are two choices of either right foot travel $RF_Z$ or right foot roll $RF_\phi$. From a control logic viewpoint, foot roll would be preferrable; but from a hardware design consideration, foot travel might be simpler to mechanize and operate. For side or lateral translation, either left foot roll $LF_\phi$ or yaw $LF_\psi$ can be used; but from the anthropometric standpoint, it appears preferable to use foot roll.
This scheme has the seemingly desirable features of providing complete hands-free operation, separating attitude and translation control functions to one specific side of the body, and isolating these functions to singular identifiable types of input motion. The feasibility of such an approach has yet to be demonstrated and the practicability of the mechanization may be critically dependent on other system design features.

In the fourth scheme, two of the translation functions are transferred to the left hand as in the case of the second scheme. Because of mechanical complexities of a three-axis controller, it appears desirable not to shift the third or up-down control function to the hand controller. In considering design trade-offs between these latter two schemes, it would appear preferable to build two mirror-image, three axes foot controllers rather than to build one foot controller and one hand controller of a completely different design and location. Of course, the same argument can be put forth for an all-hands control scheme as opposed to the all-foot control. However, strong argument can be stated in favor of the foot control when consideration is given to the fact that the feet otherwise are not utilized to any extent, whereas the hands have great utility and are necessary for tasks other than controlling. A second consideration is that since the hands are needed for other purposes, the work area in front of the operator where he can see to use his hands should be as unrestricted as possible. Location at the feet removes the controller from this critical area.

THRUSTER CONFIGURATION

To this point, the discussion has been directed primarily toward the "input" considerations for the maneuvering system. There are, of course,
several important considerations relative to the "output" or thrusting capabilities of the system that should be reviewed.

In the case of back-mounted maneuvering systems, as with the Gemini unit shown in figure 3, design requirements and compromises have resulted in the thrusters being disposed more or less equidistant around the system center of gravity on the periphery of the frame for the backpack unit. Although this approach results in a fairly compact configuration, there are several problems encountered. First, the geometry of the man and the system is such that the thrusters must be located on relatively short moment arms, thereby requiring higher fuel expenditure for attitude control than in the case where longer moment arms are employed. Furthermore, having the thrusters so close to the torso imposes the likelihood of localized heating on the suit and erratic or uncertain torques on the system as a result of the jet impingment on the body, arms and hands.

Secondly, because the life support system is packaged within the envelope of the maneuvering system, a relatively massive unit is the result. The location of this mass combined with the nominal "sitting" position of the weightless operator causes the principal axes for the moments of inertia to be inclined relative to the torso axes by angles as large as 20 to 30 degrees. This causes fairly large interacting moments to be generated between the yaw and roll control axes by action of the thrusters which are aligned with respect to the reference torso axes parallel and perpendicular with the backbone. This product-of-inertia coupling causes the system to roll whenever a yaw command is given and vise versa. Such action when prevalent to any significant extent is confusing to the pilot and can lead to a tumbling action or prevent recovery from a tumble motion if such is initiated.
If the procedures for storing and donning the maneuvering unit similar to the Gemini system are employed, the unit will be stored external to the spacecraft so that an auxiliary life support system will be required to permit egress of the operator from the spacecraft and check-out of the maneuvering and life support systems of the integrated unit. The operator must then don the unit by backing into it, a rather awkward operation because of the lack of visibility and the encumbrance of the space suit. Subsequent to this, a switchover from the auxiliary life support system to the main system of the backpack unit must be made. The doffing and stowing operation is essentially the reverse of this rather lengthy and tiring sequence of events.

Development of the FCMU from its original concept has been directed toward an approach in which as many of these problems as practical could be avoided in an operational system based on this approach. The arrangement of the thrusters is indicated in the diagram of figure 4 in which the cluster of arrows represent the location and firing directions of the eight individually operated jets. The jet-firing logic to produce acceleration for each of the four control functions is given in the accompanying table.

The thrusters are located near and outboard of the feet so that the fore-aft firing thrusters (jets 3, 4, 7, and 8) used to generate pitch and yaw moments could be a minimum size and so that the jet impingement of these thrusters is avoided. These thrusters also were located perpendicular to the system's principal axis which passes through the feet. With the pitch moment arm essentially fixed at about 36 inches by the geometric relation between the system center of gravity and the position of the feet, the magnitude of the pitching moment is adjusted by sizing the thrust level of these four jets. With the thrust level now set to accommodate pitch, the yawing moment is adjusted.
by selecting the appropriate location of the units outboard of the feet. Preliminary studies have shown that these thrusters can be set at about 1/2-pound each and about 15 inches from the center line.

The vertical thrusters (jets 1, 2, 5, and 6) located at the same position and used to generate vertical translation and roll moments were aligned fore and aft with the center of gravity of the system. These thrusters were provided with adjustment in the lateral plane to permit canting the thrust axes away from the center of gravity to minimize the up-firing jet impingement on the operator and to permit adjustment of the roll moment arm. Inasmuch as these jets were sized for the translation capability at about 2 pounds each, varying the cant angle up to about 25 degrees permits proper sizing of the rolling capability with span between thrusters previously determined by the yawing moment requirements.

Location of the thrusters at the feet immediately adjacent to the foot controllers makes it relatively easy to design a simple mechanical hookup between the thruster valves and the foot pedals and to provide a compact plumbing system. With all maneuvering system components placed between the legs there is no longer a need to integrate with the backpack life support system. This greatly simplifies the operational procedures and eliminates the need for an auxiliary life support system. The donning and doffing operations should be relatively easy because the unit is in view and easily reached with the hands. In practice, the operator may find it convenient to unbuckle the unit and set it out of the way when he gets to his target area where he wants to be relatively unencumbered; or, on the other hand, the operator may find it convenient to clamp the maneuvering unit to the target and use the unit's restraint system to hold him in proper working position.
With this arrangement of thrusters, there is some degree of interaction between some control functions. Because the pitching moment is produced by a single set of thrusters rather than pairs equally disposed about the center of gravity, the pitch control command is accompanied by a fore-aft translation input. Similarly, when the vertical thrusters are canted outboard, a roll control command generates a lateral velocity. Generally, the magnitude of these interacting inputs are relatively small; however, the consequences of inputs are significant in some instances because of the lack of primary control in the fore-aft and sideward directions.

The arrangement of additional thrusters required to overcome these deficiencies is indicated in figure 5. Here two sets of three thrusters are located waist high at the system center of gravity. Fore-aft translational forces are produced by jets 14-17 and 15-18 fired as simultaneous pairs. The design approach here is to have these thrusters attached to extensions of the saddle arrangement so as to provide a unitized system. With all the thrusters firing away from the body, little difficulty should be experienced with jet impingement problems. Furthermore, the location of the thruster triads in the area of the hips makes the operation of these particular jets directly by either one or both hands quite attractive.

As noted previously, sizing requirements for the control moments and translation thrust are met in the basic FCMU configuration by a combination of adjustments of thrust level, location and alignment. This interrelation is dictated by the duplicity in use of the thrusters in which each thruster is used to supply two separate control functions. In the event of a thruster failure, however, a fairly complicated control problem would arise because of the resulting large coupling moments.
The next arrangement of thrusters, as depicted in figure 5, is intended to reduce the control problems resulting from thruster failure by eliminating the duplicity in thruster firings as required in the original scheme. Here an additional quadrant of thrusters (jets 9, 10, 11, and 12) has been added beneath the feet and aligned in the fore-aft and side-to-side directions. These are used to produce the pitching moment (jets 11 and 12) and the rolling moment (jets 9 and 10). This arrangement now permits jets 3 and 8, and likewise 4 and 7, to be paired together for producing the yawing moments and jet pairs 1-5 and 2-6 for vertical translation. If failure occurs, only control of the corresponding axis is lost and no additional cross coupling or interaction is encountered. An additional bonus of this arrangement is that adjustments to the various control moments or forces can be made independently by sizing the pertinent thrusters without affecting the other controls.

The fourth arrangement of thrusters is given in figure 7 which depicts the same system as the previous but with the addition of the two sets of fore-aft and side firing thrusters located waist high at the system center of gravity to give the additional two degrees of translational capability lacking in the previous scheme.

From the systems design standpoint, it should be noted that the three- and four-thruster assemblies of these schemes can be all of the same design and fabrication. Adjustments for differences in thrust levels can be achieved merely by forming different diameter holes for the jet nozzles. (For system operating pressures of 150 pounds per square inch, these hole sizes range in the order of one-thirty-second to one-sixteenth of an inch). Also, in the same light, any one of the thruster pairs is fired only by a single discrete control input. This makes for relatively simple valve actuation design schemes for either of these or the subsequent thruster locations.
CLOSING REMARKS

The purpose of this discussion was to present various approaches to the design of space maneuvering units based on the concept of using the feet for control functions. In general, the various concepts advanced have attitude about all three axes controlled solely by the feet and translation along one or more axes controlled either by the feet or by one foot and one hand. No attempt has been made at this point to determine the optimum configuration which is considered to depend strongly on the particular application. Although full six degrees of freedom control capability is considered in general to be most desirable, other considerations may make it more desirable to eliminate at least the side-to-side translation. In no case, however, should attitude control capability about any axis be deleted.

No consideration has been given to whether or not some form of stabilization or system feedback should be employed to improve or modify the response of the maneuvering unit to pilot control inputs. Such stabilization techniques as rate and attitude feedback in general can be expected to provide some characteristics which are desirable from the pilot's viewpoint. Experience with the basic FCMU and simulations of other maneuvering systems employing no stabilization techniques has indicated that such schemes may not be required. In any event, however, there appears to be no reason why the foot control concepts cannot be employed whether or not system feedback is used.
Table I.- Alternate Concepts for Foot Controlled Maneuvering Unit Logic

Figure 1.- Foot Controlled Maneuvering Unit.
Figure 2.- Systems of axes for defining foot control motions.
Figure 3.- Gemini Hand Controlled Back Mounted Maneuvering Unit.
Figure 4.- Thruster arrangement for basic FCMU.
Figure 5.- Thruster arrangement for the FCMU hand translation control.
Figure 6.- Thruster arrangement for the modified FCMU.
Figure 7.- Thruster arrangement for the modified FCMU hand translation control.
### TABLE I
ALTERNATE CONCEPTS FOR FOOT CONTROLLED MANEUVERING UNIT LOGIC

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<thead>
<tr>
<th>System</th>
<th>Controlled Direction of Movement</th>
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<td>1. Basic FCMU</td>
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<td>2. FCMU with Hand Translation Control</td>
<td>(L+R)Fθ</td>
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<tr>
<td>3. Modified FCMU</td>
<td>RFθ</td>
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<tr>
<td>4. Modified FCMU with Hand Translation</td>
<td>RFθ</td>
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Figure 2. - Systems of axes for defining foot control motions.
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Figure 4. - Thruster arrangement for basic FCMU.

<table>
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<tr>
<th>Control</th>
<th>Direction</th>
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<td>Vertical Translation</td>
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Control Direction Thruster Jets

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All other controls as given in figure 3.

Figure 5.- Thruster arrangement for the FCMU hand translation control.
Figure 6. - Thruster arrangement for the modified FCMU.
All other controls as given in figure 5.

Figure 7. - Thruster arrangement for the modified FCMU hand translation control.