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SIX DEGREE OF FREEDOM
MANUAL CONTROLS
STUDY REPORT

PREPARED FOR:

NASA
LYNDON B JOHNSON SPACE CENTER
R & T PROCUREMENT BRANCH

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1. EXECUTIVE SUMMARY

1.1 Introduction:

Numerous potential applications exist in current NASA space programs for the use of multiple degree of freedom manual controls. In addition, a number of such controls have been utilized in space and numerous configurations have been evaluated in mock-ups and simulations. Multiple degree of freedom manual controls have been evaluated in other applications, notably side arm controls for helicopters, flight controls for aircraft, remote controls for nuclear or under sea environments and manual control of robotic equipment.

This study was initiated specifically to determine the feasibility of using six degree of freedom manual controls in space in an on-orbit environment. While several six degree of freedom controls have been tested in a laboratory environment, no production unit has been built and no co-ordinated six degree of freedom controller has been used in a working application with the exception of replica controls used to control robot arms.

The selection of six degrees of freedom as a design goal was based on the fact that six degrees are sufficient to define the location and orientation of a rigid body in space. A six degree of freedom controller is therefore adequate to control a space craft in on orbit manouvers or to position the end effector of a manipulator. If the six degrees are controlled by a single device, the operator will have a free hand to operate other controls or switches, to perform other work or to wipe his brow.

1.2 Potential Applications:

While the stated objective of this study program was to investigate the feasibility of using a six degree of freedom hand control for on orbit manouvering of a space craft, the implied requirement was to analize the use of six degree of freedom controls for general space applications.

Several applications are immediately apparent and were considered in designing the prototype unit.

1.2.1 SRMS System:

The shuttle remote manipulator system (SRMS) is currently cofigured for operation with two three degree of freedom controls, the translational hand control (THC) and the rotational hand control (RHC). The operator is required, in addition to controlling the position and attitude of the end effector, to monitor various parameters, operate panel mounted switches for mode selection and payload related functions, to operate the controls of the CCTV cameras, etc. Clearly, the provision of a workabel six degree of freedom controller would be an advantage in freeing one hand to perform these functions.

1.2.2 Open and Closed Cherry Pickers

The open and closed cherry pickers are maneuverable work stations positioned and pilotted from the end of the RMS arm. In the current configuration, two three degree of freedom controllers are used; however, this requires the astronaut to use both hands to position himself. A six degree of freedom controller would release one hand for other tasks.

In addition, when operating within the closed cherry picker the astronaut will work with two dextrous manipulators. Hence two six degree of freedom controllers are essential in this application.

1.2.3 Manned Remote Work Station

The manned remote work station is a further development of the closed cherry picker where the basic unit is freed from SRMS and has its own propulsive system. The astronaut will require both six degree of freedom flight control, and two six degrees of freedom controllers for the manipulators.

1.2.4 Manned Maneuvering Unit

The Manned Maneuvering Unit is a free flying work station again pilotted by means of two three degree of freedom controls in its present configuration. A six degree of freedom controller would enable the astronaut to use one hand for handling tools, operating other controls or operation switches or latches.

In addition, many other potential applications exist for multiple axis hand controls operating remote manipulators in space or in other harsh environments.

1.3 General Approach:

The study contract was accomplished in three ways. A state of the art survey was carried out in which, many centres of research and design in the area of manual controls were visited. The results of this survey are summarized in Section 1 of this report. In parallel to the state of the art survey, a literature search was carried out as described in Section 2. Finally, a breadboard configuration was constructed to analyze geometry and pivot point location. As a final step a prototype unit was constructed to permit further tests and concept verification.

Testing of the prototype is planned but is beyond the scope of this project. The prototype unit is scheduled for evaluation with the LASS simulator of the cherry picker at Grumman Aerospace and later, at JSC. In addition, plans are under way to test the prototype unit at Martin Marietta using the MMU simulator.

1.4 Design Constraints:

The following requirements were imposed on the prototype design as a result of task analysis and a review of the literature and the state of the art survey.

1.4.1 Fundamental Requirements:

The study was constrained to the analysis of a single point, six degree of freedom controller. Other options such as control by a matrix of push buttons, control by six independent levers etc. were included in the literature search but not considered as candidates for the final design. Certainly, for many applications alternative approaches are preferable; however, the aim of this study was to provide co-ordinated control of motion permitting the operator the option of commanding motion in a single axis without cross-coupling or of commanding combined motion in several axes.

1.4.2 Environment:

The prototype configuration was designed to be suitable for use by a suited astronaut. In particular, the heavy protective glove and the relaxed hand position required for comfort in space were accomodated in the design of the handgrip. The design was configured to be compact and rugged using components that could be designed or purchased to space standards. The problem of zero gravity testing will be addressed in the test program.

1.4.3 Mode of Control

The hand controller should be capable of control, or adaption to control, in different modes of operation. For spacecraft flight control, the controller should be capable of controlling pulsed acceleration in all six axes, or resolved rate control in the three rotational axes with pulsed acceleration in all six axes, or resolved rate control in the three rotational axes with pulsed acceleration in the three translational axes. For operation of dextrous manipulators resolved rate control would be a prime requirement with the possibility of locking out the translation axes into an isometric or force stick control mode thereby providing a 'point and push' mode of control.

1.5 Conclusions

As a result of this study, nothing was found to indicate that six degrees of freedom single point control is not feasible. A prototype device has been developed reflecting the knowledge gained in a review of the literature and through discussions with knowledgeable workers in the field. Evaluation of the prototype is continuing but is beyond the scope of this contract.

2.0 STATE OF THE ART SURVEY

2.1 INTRODUCTION

This report is to summarize the results of a State of the Art survey carried out under Contract to NASA (Contract No. NAS 9-15939). The survey is referenced in Sections 3.1 and 3.2 of the Statement of Work. The survey is supported by a literature search which is the subject of a separate report.

The fundamental purpose of the State of the Art survey was to determine the effectiveness and acceptability of any existing six degree of freedom controllers. In addition, the study included: a general review of hand controller design with knowledgeable and experienced designers and users; a review of possible applications in space and an assessment of related equipment such as space suits, protective gloves, hand holds and foot restraints; and a review of related human factors, anthropometric data and human modelling considerations.

The survey was well supported at all the facilities visited. In every case, knowledgeable and experienced people talked freely of their knowledge of manual controls. While there is a very limited amount of current research on six degree of freedom hand controls, most knowledgeable people felt that the concept is feasible and, in many cases, useful.

This report is presented in several sections. A chronological summary of the visits made is followed by a summary of the opinions and arguments that arose. Finally, a summary of opinion is presented.

2.2 SUMMARY OF VISITS

Visits were made in four separate trips. The first trip was to the Los Angeles area, the second to San Francisco, the third down the Eastern Seaboard including Boston, New York and Philadelphia and the fourth was to NASA/Marshall in Alabama. In addition, a review was held at JSC in Houston subsequent to the preliminary review meeting for the contract.

2.2.1 Johnson Space Center - 3, 4 October 1979

As part of an initial contract review meeting, there was discussion of the requirements and applications for a six degree of freedom controller. NASA were somewhat vague about specific requirements except to say that the controller must be suitable for on-orbit operation by a 5-95th percentile constrained astronaut. The immediate requirement would be to replace the two controllers, the THC and RHC, of the remote manipulator system by a single unit. The requirement is for flight control; however, control of the manipulator end effector is considered equivalent to flight control. Other possible applications include the Manned Remote Work Station, the Manned Manoeuvering Unit and the Cherry Picker. In general, a concept evaluation is required rather than a design for a specific application.

Following the contract review meeting a number of discussions and visits were made to review relevant work at JSC. Visits were made to the aft station mock-up, the shuttle simulator, the aft crew station engineering simulation and to the hand controller evaluation facility.

Mike Thomas conducted the tours and arranged the visits. He also demonstrated the equipment available in the hand controller evaluation facility. The facility consists of a flexible mounting arrangement on which to position controllers under evaluation, a CRT display and supporting software to generate tracking tasks and to assist in data analysis.

One interesting point which arose at the aft station mock-up was that, in docking the RMS arm, a tenth scale replica controller, which was available and could be switched in as the command device, provided more accurate control than the THC, RHC combination. The replica controller did not include force feel or force feedback.

Lew Harvey described tests of an exoskeletal controller used to control SAM, a nuclear station remote manipulator. The work was done as part of a Nuclear Test Program carried out at the NASA Test Station in Jackass Flats, Nevada. The people involved were:

- Richard Davidson then Chairman, Manipulators Working Group
- Edwin Johnson, now at National Bureau of Standards

Bill Langdoc reviewed the hand controller programs which he knew of. These included the Lincoln Wand, an unsupported stick held over a sensitive plate such that motions of the stick were resolved in six degrees of freedom. The work was done at MIT in the late sixties. (Attempts to locate the Wand or its developers at MIT proved unsuccessful and this remains an outstanding item to be reviewed.)

Bill also mentioned the Boeing Vertol 4DOF controller for the heavy lift system, (see report of visit to Boeing Vertol), and 6DOF manipulator controllers both exoskeletal (hard suit) and isometric (Measurement Systems) which had been evaluated at Marshall Space Flight Centre. He also mentioned that U.S. Matrix had developed a cheap multi-degree of freedom controller for TV adjustment.

In discussing possible controller applications, Bill mentioned that the manned remote work station will be equiped with two dextrous manipulators, each of which will require simultaneous control on arrival at a task area. Another controller(s) would be required for spaceflight and ideally this should be achieved with the same controller(s) as for the manipulators.

Lou Livingston described the Hand Controller Evaluation facility and some of the work done there. He described evaluation of the MIT 6 DOF isometric controller. The main problem mentioned was the lack of feedback to indicate full scale input with the result that operators over controlled and became fatigued. Lou felt that the isometric concept worked only in the case of simple system dynamics. He had experienced acceptable results in the case of telescope altitude control; however, in general, the controller is improved by the addition of displacement.

Lou mentioned the F16 experiments with isometric and displacement sticks and the fact that the addition of displacement improved results. He also mentioned that he felt that excellent control could be achieved using a replica controller in the case of the RMS.

J. Kennedy discussed the evaluation of the MIT isometric controller and felt that the evaluation was insufficient and inconclusive. He also mentioned that a matrix of pushbuttons had been considered as a manipulator control device and that, in his opinion, the concept would work well. He said that he would try to locate the MIT controller and, if possible, provide it for test.

Dale Nussman discussed various general concepts and reviewed development of the RMS controllers. He emphasized the importance of hand or arm reference devices and felt that a well designed 6 DOF controller would have useful applications. He also showed the hand controller literature file where numerous references were recorded.

Finally, J. Jackson provided data concerning hand size requirements, in addition to NASA anthropomorphic data listings. He discussed the F16 tests comparing deflection and isometric controllers and provided the names of the following contacts:

Dr. Butch Hustler, General Dynamics, Fort Worth

Dr. Joe McDaniels, Wright Patterson

2.2.2 Jet Propulsion Laboratories, Pasadena, California

JPL proved to be one of the most productive visits. Dr. Antal Bejczy, who co-ordinated the visit and who co-ordinates much of the hand controller work at JPL, organized an interesting and productive session.

PERSONS SEEN:

Dr. Antal Bejczy, Visit Organizer
Mr. Steve Szirmay - Director
Mr. Ron Dotson
Mr. Thurston Brooks
Mr. Robin Zawacki
Mr. Frank Mathur
Mr. Carl Ruoff
Mr. Mathis Handlykken

The visit commenced with a film show demonstrating JPL and MIT manipulation work to date. This was useful as an introduction since all hardware shown was later seen in the labs.

After completion of the films we were taken to the Control Development Labs to review various different systems as follows:

2.2.2.1 Hard Suit Arm - A sample 'hard' space suit arm has been instrumented and equipped with a handgrip, and all outputs couple via software to a powered slave arm of identical configuration.

The 'master' arm is supported at the shoulder so that the operator can sit with his arm inside it, gripping the hand grip below the wrist. Any movement of the master by the operator is reproduced in the slave. The hand can be made to grip or relax anything via a trigger on the master handgrip. The trigger is sequential, i.e. one operation causes the hand to close, the next to open, the next to close and so on.

Articulation of the master and slave is achieved with seven rotating joints. The system will cover any possible hand movements. However, the master was somewhat tiring to operate and one was always aware of the intermediate rotations of the various sections in order, for example, to achieve a simple flexing of the elbow. However, fine hand and wrist movements could be readily achieved.

In order to achieve full travel of the slave arm it is necessary to achieve the same movement of the master since the control mode is 1 to 1 positional. Hence, the envelope required by the operator must allow him complete freedom to move his own hand to any position. This makes the system very limited in its application to space craft.

Also, of course, the concept is suitable for manipulator control and not space craft control.

2.2.2.2 SRMS Experimental End Effector and Control System - The system has been produced for evaluation exercises to be carried out at J.S.C. in the SRMS 1g manipulator mock-up in place of the current wire snare end effector. The end effector consists of a system of four claws equipped with optical proximity sensing. The payload attachment consists of a four plate target to align with the optical sensors on the end effector and four grapple points for the claws to lock onto.

The display system consists of a cross formation of LEDS with a single angled line of LEDS. This line indicates proximity of the end effector to the target, the displayed line getting shorter as the end effector closes on the target. The cross works in a similar fashion, the line lengths reducing towards the centre as the end effector closes. Angular misalignment is indicated by differing line lengths on either side of the centre.

In addition, a green light illuminates when the end effector is sufficiently aligned for capture to take place. Control of the system will be achieved by the standard SRMS control systems.

Again, the system was concerned only with manipulator applications although the location and proximity sensing could be applicable to space crafts docking manoeuvers or, for example, when in a small maintenance MMV for grappling onto a work station in larger space structures.

2.2.2.3 Voice Command System - This system was used to demonstrate and to evaluate the feasibility of achieving operation of a manipulator by direct voice command. The system capability was limited to 40 command words.

In order to be recognized by the computer, a learning process had to be gone through for each new operator. In the case of an unfamiliar accent, several iterations were required before 100% command was possible.

A typical command sequence would be to give the commands in a series of simple instructions followed by an 'execute'. Whilst such a command system may be applicable to some tasks it is obviously limited when direct command of a manipulator or space craft is required.

However, such systems are still in their infancy and should not be dismissed lightly as there is significant serious development work being done in a number of centers.

2.2.2.4 Mobile Remote Manipulator - Unfortunately, the device was not operable at the time of the visit. The actual manipulator is built into a vehicle about the size of a 2/3 scale jeep with steerable front wheels. The manipulator arm is mounted on a rotating turret, is fully articulate and uses a simple claw type end effector equipped with optical proximity distance sensing of a similar design to that used in SRMS claw type end effector. The manipulator arm and vehicle were hydraulic power systems which are currently being improved, hence the non-operability.

The original control box consisted of a pedestal mounted panel with two typical radio control joysticks each with 3 degrees of freedom and a set of individual joint/vehicle movement controls. A rate trim system was also provided to vary rate authority of the controls.

The CRT displays were driven by remote TV cameras mounted at the rear of the vehicle and also a visual representation of the information from the end effector proximity sensors. The display consisted of a simple arm mounted 'U' shaped claw with extending lines from the tips displaying proximity etc, similar to the LED display for the SRMS end effector.

The only operational item was the end effector display. By moving a target around the fixed end effector it was possible to demonstrate the effectiveness of the display system.

2.2.2.5 Touch Sensing - The system used a matrix of contact points and a conductive plastic overlay to sense any pressure applied to the plastic and to display where such pressure took place on a CRTV matrix display. The system did have some electronic faults but the film shown earlier adequately demonstrated its effectiveness in sensing for instance the position of a finger on the matrix area.

The application of the system to some sort of touch control device for space craft and manipulator control should be studied. Also, NASA is considering its application to manipulator end effectors as a 'feel' sensing element for operator feedback.

2.2.2.6 'Slip Ball' Sensor - This consisted of a dimpled ball set in a cup with a central sensing probe. Any rolling motion of the ball was detected by the probe and transferred to a contact system capable of determining the direction of ball rotation. The mechanism is basically simple but has obvious reliability problems.

It is being considered mainly as a device to be mounted onto end effectors etc, to sense direction of any relative motion between claws and payloads. Its application as a Control Device has also been considered.

The main advantage of the device is that it is unlimited in travel.

2.2.2.7 Six Degree of Freedom Development Hand Controller - This device is still under construction and is JPL's first attempt at a full 6 D.O.F. controller. Its purpose is to evaluate the feasibility and determine guidelines for remote manipulation control. They are not considering any application such as space craft control.

The device is intended as an experimental evaluation tool and hence is not a final or practical design.

The hand grip is designed to cover paths within a 1 foot cube, although, because translation in two axes is achieved via a polar movement, the actual hand grip envelope is wedge shaped. The hand grip assembly contains the roll and yaw axes while the pitch is achieved by rotation of the hand grip assembly mounting shaft. The controller is used in such a manner that this shaft is horizontal at 90° to its forward direction of the operator.

'Y' axis movement is achieved by axial movements of this shaft only when in the horizontal mid position. X and Z axis are polar mountings and as a consequence all translations apart from mid position Y translation, is achieved with a combination of the three 'machine' axes. The mechanisms are precision built, using a wire drive system but nevertheless noticeable friction exists when attempting a straight X, Y or Z translation.

All six axes have both a position output device and a force feel feedback motor. The basic controller mechanism is designed to be as mechanically transparent as possible with no self centering feel, notches etc, so that when de-activated the handle moves freely within the end stops in all axes.

The interface between the hand controller and the remote manipulator is a computer which will be capable of being programmed to achieve any combination of force feel characteristics, center position notching, dead bands, soft stops etc, utilizing the position sensors and feedback motors. In addition, any amount of feedback from the remote manipulator will be applied to the hand grip, giving direct end effector feel to the operator. Thus for experimental work the system will be extremely flexible.

It is obvious that the results of this study will be valuable and the very co-operative attitude of the JPL staff will make it possible to exchange information.

2.2.3 <u>Rockwell International, Downey, Califronia</u> 13 November 1979

PERSONS SEEN: Mr. Jack Bell - Director Advanced Systems
Mr. Dean Carlson
Ms. Marianne McCafferty
Mr. Tom Healy
Mr. Marvin Sanger
Mr. Bob Olesen
Mr. Lea Krupp (part time)

A great deal of interest was shown by Rockwell in our visit although in terms of information gained the results were limited. There was some concern that someone may be considering a change to the Space Shuttle and we were able at least to dispel that concern!

Rockwell have never investigated the use of 6 D.O.F. hand controllers The view was expressed that there was a preference to keep to a two handed system separating rotation and translation for ease of operation, and the fact that such devices existed for the Space Shuttle, developed from Apollo models, meant that no 6 D.O.F. work had been attempted.

A general discussion on the pros and cons of 6 D.O.F. single hand controllers ensued from which it was learnt that space craft tended to be handled in different ways for rotation and translation.

At this point the meeting was joined by Leo Krupp, a test pilot who had been involved in simulation flying of Apollo and LEM and more recently on the Space Shuttle. He confirmed that in his experience he had only used two handed systems and that the normal method of manoeuvering was to try to complete rotational movement and then to translate, i.e. two sequential sets of three degrees rather than an integrated combination of all six axes. He expressed great interest in the idea of a single handed approach, but suggested that the ability to 'lock out' some of the degrees of freedom should be considered.

He also went into details of how the Shuttle R.H.C. and T.H.C. are used in on-orbit manoeuvering and the distinct difference between rotating and translating. The orbiter R.H.C. gives proportional rate movements in roll, pitch and yaw for travel of the control up to the soft stop. Beyond the soft stop into the hard stop 'raw' acceleration is maintained until the control is returned to the soft stop at which point the rate of rotation is constant at the value obtained at the end of acceleration. Returning the control towards the centre reduces the rate of rotation at the same slope as before. Releasing the control, or returning it to mid position causes thrusters to fire to reduce the rate of rotation to zero, the attitude then existing being maintained by the on-board computer.

The orbiter T.H.C. is a stepped switch device. When moved in any direction thrusters fire to accelerate the craft in the desired direction, such acceleration being maintained until the control is returned to the mid position. The orbiter then continues at the new commanded velocity.

The two different control modes would appear to be the preferred mode of control and are to some extent a result of the dynamics to be controlled. In rotation it is possible for three states to exist, i.e. 1) Zero rotational velocity relative to any fixed point in space and hence zero rotational kinetic energy, 2) rotation at a constant angular velocity, hence steady rotational kinetic energy and 3) Rotational acceleration or increasing rotational kinetic energy. These correspond to the three RHC positions, i.e. mid position, breakout to soft stop and soft stop to hard stop. When considering translation within the bounds of foreseeable useage there are only two possible states, i.e. constant velocity (constant kinetic energy) and acceleration (increasing kinetic energy), and these correspond to the current T.H.C. pattern, i.e. mid position: zero input; and any control position out of mid position: acceleration. A zero energy state could only be conceived in deep space. A 'false' zero reference, e.g. a given orbit could not be used as a reference zero because any zero command would return the ship to that orbit.)

When asked what typical operation he could recommend in order to assess control capability he stated that docking with another craft is perhaps the most critical manoeuver since both rotation in all axes and closing velocities to achieve a 'hard' capture, are critical.

Other specific points to come out of the general discussion were:

a) If used for atmospheric flight there should be a translation lock out facility.

b) Critical to guard against inadvertent inputs caused by body movements.

c) Weight and volume are always highly critical.

d) For space craft handling the THC is used in a pulse mode by most pilots.

Following more general discussions the meeting closed with Jack Bell of Rockwell expressing a wish to be kept informed of our developments if possible and also assuring us of their future co-operation if required.

2.2.4 Hughes Aircraft, El Segando, California 14 November, 1979

PERSONS SEEN: Dr. Larry Scanlan
Mr. George Corrick

Larry Scanlan was very co-operative but stated that Hughes had not carried out any recent hand controller development work. The most extensive work was that resulting in the publication of Hughes Report P68-57 which we have in the form of the USAF Wright-Patterson Report, AFFDL-TR-68-72. The person responsible for this work was Mr. Don Bauerschmidt, now working for Rockwell Autonetics Division in Annaheim whom he recommended we visit.

Although Hughes have retained some hand controller hardware, much of it was in-accessible due to their recent move from Culver City. However, he was able to find a 2 degree side-arm device of high quality. As they become more organized in the El Segundo Establishment all hardware will be categorized and stored in a hardware 'library'. Dr. Scanlan was sure that both the controller and any others which come to light, could be made available to us thru the official channels.

Whilst Dr. Scanlan was searching for hardware George Corrick conducted us to the library computer terminal and carried out a literature search for us, producing several useful documents.

Enroute to Hughes Irvine we followed Larry Scanlan's suggestion and visited Don Bauerschmidt at Rockwell Autonetics in Annaheim. He also stated that he had never been involved in any 6 D.O.F. development.

2.2.5 Megateck Corporation, San Diego California 15 November, 1979

The intention was to visit Mr. John Roese at the Naval Undersea Centre. However, the area of interest is now being handled by Megatech with John Roese as a consultant. Unfortunately, we were not able to meet John Roese but did see Dr. Verne Hildebrand of Megatech, the "Megavision" Program Manager.

The "Megavision" stereoscopic viewing system was demonstrated using video tapes and a TV set coupled to the viewing system. The viewer wears a pair of glasses coupled to a small belt unit which in turn is coupled to the Megavision Controller with a small cable of up to 50 ft in length. The controller is coupled to the viewing TV and synchronizes left and right views with the DLZT ceramic electronic shutters in the glasses.

The display shows alternating left and right eye views which, when viewed without glasses appears as a double image. With glasses on the picture appears as a verygood stereoscopic display with very good depth.

At the present time the system is compatible with the North American 60 frames per second TV systems. Hence each eye sees 30 frames per second. We were warned that we may see a slight flicker before viewing the demonstration. I did notice this to start with but found the effect vanishing when concentrating on the film subject.

The current spectacle design is based on a 2 1/2" lens diameter but there is no physical limitation to prevent 'wrap around' lenses being produced.

Megatek also produce graphic display systems of high quality and a system was demonstrated to us. It is an advanced system, easy to use, and backed up with available software packages. In combination with the Megavision viewing system it is capable of producing stereoscopic imagery. It can also be interfaced with the VAX computer There could be a possible application for simulated spacecraft manoeuvering visual displays for final evaluation of the 6 D.O.F. controller.

2.2.6 Lockheed Missiles, Moffett Field, California 25 February, 1980

PERSONS SEEN: Mr. Tom Fisher (organizer of tour)
Mr. Henry Streb
Mr. Tom Sticzynski

The visit to Lockheed was interesting primarily from the point of view of reviewing current design of equipment to support work in space. In addition, Henry Streb had past experience in the design of hand controls.

The work being done in Tom Fisher's group was directed at support and maintenance equipment for the Large Scale Telescope (LST). The design of foot restraints, handhold and tether devices, wrenches (all maintenance is accomplished using a single wrench, a concept that would be revolutionary in Detroit) and insertion and disconnect devices for cables and electronic packages. The devices were of practical interest to this study since they indicated the conditions under which astronauts will work and the types of tasks to be performed.

Hank Streb expressed interest in the concept of a six degree of freedom hand controller although he doubted that it would be necessary or optimal. Hank, a designer, felt that a design concept should be generated based on a particular application and then evaluated. He thought that good design evolved from evaluation of hardware rather than from theoretical or abstract approaches. His experience is related to the design and evaluation of a two axis controller for the Dyna-Soar project.

Hank felt that the force levels on most existing controllers were too low and stated firmly that a wrist pivot was preferable to a palm pivot for pitch inputs. One of the significant features of the Dyna Soar controller was a lag such that the controller would activate the system only if a sustained input were generated. The system operated in a bang-bang mode although force gradients were included and considered important. A similar approach is used in a classified project at Lockheed Sunnyvale.

The following people were recommended as sources of information on hand controls:

Col. Ed Whitsett	- NASA - JSC (MMU)
Mr. Gibson	- NASA - JSC (Extra Vehicular Systems)
Dr. John Billingham	- NASA Ames
Mr. Frank Cepollina	- NASA Goddard

After a tour of the LST mock-up facility, we were directed to the remote pilotless vehicle group. The RPV group were interested in controllers but did not have an application since no manual control is required in their design.

The RPV group recommended a discussion with Mr. Al Williams and Dr. Stuart Parsons of the human factors group. Williams and Parsons made a few general comments on hand control design but most of their comments concerned their recent report on the design of control panels for nuclear power simulators. In general, they were reticent and concerned about the legal implications of firm statements.

2.2.7 NASA/AMES, Moffett Field, California 26 February, 1980

The visit to NASA/AMES was arranged and organized in a very efficient manner by Dr. David Nagel. The first session was a meeting with Dr. Brent Clark and Dr. John Stuart. General approaches to hand control design were discussed and both Dr. Clark and Dr. Stuart thought that a 6 DOF concept was feasible.

Dr. Renwick Curry, the next person visited, was currently investigating the effects of turbulence on pilot performance. He had no specifc interest in hand controllers and as a result, only a general discussion was held.

A discussion was then held with members of the simulator design group, Mr. Larry Russell, Mr. Sam Wilson, Mr. Rodger Hayes, and Mr. Bob Gin. Discussion contered on load units for flight controls and on motion systems. Sam Wilson conducted a tour of the simulator facility which included the new large amplitude motion system. The tour included a pass through a storage room with numerous hand controller designs which had been tested. Various concepts from one to four degrees of freedom were found. One model, which was of particular interest, was a two degree of freedom joy stick, similar to a THC, surrounded by a single degree of freedom wobble plate. This concept clearly permitted the operator to isolate translation and rotational motions as well as to carry out co-ordinated motions. In further discussion, the possibility of mounting a two axis wobble plate around a THC with three translation axes plus twist to achieve six axis control evolved. This concept should be further explored.

The final visit at NASA/AMES was to the laboratory of Mr. Vic Vykukal and his assistant Mr. Bruce Weber. A model of the hard suit, identical to that seen at JLP was available for assessment. The exoskeletal approach has various obvious advantages, principally, the ease with which co-ordinated movements can be controlled since the model is an exact replica of the controller. A significant drawback, inherent in the replica approach, is the fact that the model and replica must be aligned at switch on and the model must not exceed the velocity, acceleration constraints of the replica. There was no force feedback in the system.

The possibility of modifying the mode of control, for example, using the arm of the suit to generate rate or, perhaps, indexed position commands was reviewed. In this way, the arm could be switched off without a realignment problem; however, the advantage of 'natural' resolution of axes is lost. This discussion led to the idea of building a controller attachment for a space suit so that an astronaut could manipulate the controller with a bare hand, inside the suit. Such a unit could attach to the sleeve of the suit to replace the normal glove and would thus avoid the problem of having the astronaut trying to manipulate a controller with a heavily gloved hand. In any case, the idea of instrumenting the arm of a space suit and using arm movements as control inputs does have potential application.

In this laboratory, there was also an evacuated chamber to permit testing of gloves under the anticipated working conditions. Several gloves were tested and even the lightest resisted hand movement and greatly reduced tactile feel. In addition, in extra-vehicular work, an additional radiation shield would be required with these gloves which would further reduce flexibility.

Vic was slightly skeptical of the applicability of a 6 DOF controller. He felt that a good design depended on a firm definition of the task. In addition he felt that since the controller would be used in the future, design should not be limited to the currently acceptable space techniques. For example, he suggested that at that time hydraulic devices may be acceptable and useful. He also suggested the consideration of other than manual techniques, for example, the use of signal from nerves or the neuro-muscular system.

Mr. Ronald Hess described some of his work modelling the human operator. He had developed a transfer function for the human operator which was basically a derivative element. He had further established modes of control adapted automatically by operators based on the dynamics of the task. In some cases he showed that optimal control required bang-bang operation of the controller. This was verified experimentally by plotting the power spectra of control movements. In those cases where bang-bang mode was indicated, the power spectrum showed two distinct peaks corresponding to positive and negative inputs.

References: Report AIAA 79-4066, "A Rationale For Human Operator Pulsive Control Behaviour".

Report AIAA 79-1784, "A Structural Model of the Adaptive Human Pilot".

2.2.8 U.S. Army Aeromechanics Lab, Moffett Field, California, 27 Feb. 1980

A number of people both at NASA/AMES and Lockheed had suggested that we talk to Mr. Dave Key with respect to his involvement with helicopter controls. A discussion with Mr. Key, Mr. Robert Wright and Mr. Edwin Aiken, however, was not very productive. They appeared interested in our comments, particularly with respect to isometric controls, but did not provide information concerning their application except for general comments on design approaches.

2.2.9 Martin Marietta, Denver, Colorado 28 Feb. 1980

Persons Seen: Mr. W. Lowry
Mr. L. Ducharme
Mr. R. Skidmore

Mr. Lowry and Mr. Ducharme gave a brief review of company structure and interests. They explained that Martin Marietta had considered entering the hand controller market as a supplier but had rejected the idea. They are, however, interested users of hand controllers. At one point Mr. Ducharme asked pointedly, "Why should we tell you what we have done?". After an explanation of the terms of our contract, they were very co-operative.

Most of the visit centered on a tour of the Manned Manouvering Unit Simulator which was being prepared for test. We were shown the simulator as well as photographs of previous tests, many concerning the evaluation of controls for the Martin Marietta manipulator system. It was clear that Mr. Skidmore had carried out evaluations of various configurations of controller and had delt with fundamental simulator design problems. The manned manouvering unit, itself, was being set up for a tile inspection task on space shuttle and the controls consisted of THC on-off devices.

We were shown a six degree of freedom indexed position controller which had been evaluated for use with the manipulator. The device included force feedback which Mr. Skidmore considered important. Mr. Skidmore was firmly in favour of position control for manipulators. The controller was floor mounted with a pivot close to the floor for longitudinal and lateral movements. A telescoping effect permitted at least twelve inches of vertical displacement. The rotational movements were palm centered although it was noted that a wrist pivot had been evaluated in previous designs. An indexing switch was included so that control authority could be initiated at any position, i.e. there was no defined relationship between absolute position of the manipulator and the absolute position of the control. This design approach has been validated by test and by comparison to other modes. Unfortunately, the controller was not powered during our visit so that we were unable to assess its capabilities ourselves.

Of the visits made in this survey, Martin Marietta is the best source of hands on operating experience with six degree of freedom controllers in space applications.

2.2.10 Massachussets Institute of Technology 11 March, 1980
Cambridge, Mass.

Persons Seen: Dr. Tom Sheridan
Mr. Dana Yoeger
Dr. Mike Rosen

The visit to MIT began with a general discussion with Dr. Tom Sheridan concerning feasibility and applicationof six degree of freedom controllers with the concept of 'transparency' discussed at length. Tom and Dana Yoeger then reviewed their knowledge of previous developments of hand controllers at MIT and, in particular, some of the problems experienced in the design and testing of the "Superman" program, a current design program concerned with the control of undersea manipulators. The control approach tested was that of a replica controller with attention focussed on problems of visual feedback and, in particular, control in the presence of significant transport delays which resulted from an acoustic communication link.

We were shown a mock-up of the arm and the replica controller which had been refurbished recently. Tests were being carried out to evaluate problems due to limited visual feedback. The system is the same one that was used in previous evaluations by Tom Sheridan and Thurston Brooks and which is featured in a film. The system does not include force feedback and when the manipulator encounters an object which prevents motion, it remains in position until the master is returned to an achievable position.

A short discussion was held with Dr. Mike Rosen who described his success at helping a patient with severe tremors to control his arm movements through the use of viscous dampers. This approach is applicable in the case where the inner nervous system loop has been damaged.

2.2.11 Stark Draper Laboratory, Cambridge, Mass 11 March, 1980

Person Seen: Dr. Dan Whitney

The visit to Draper Lab was short but very interesting. Dr. Whitney described the development of the resolved rate concept for manipulator control. He had been responsible for the development of the MIT isometric controller and has extensive experience in the design and evaluation of manipulator controls.

A major current interest is a mechanical device which permits motion in all axes except the push direction. This device has been instrumented using strain gauges and is used to provide automatic alignment of components in precision assembly. Dr. Whitney suggested that a similar concept could be used to resolve forces in a hand controller.

One interesting device observed in the facility was a six degree of freedom controller which was isometric in translation but free to move and provide position commands in rotation. This concept was well thought out and implemented. Many of the objections to the six isometric axes are overcome. Dr. Whitney said that the model had been built following evaluation of the isometric controller but had never been evaluated. The model, the only one made, was not completely operational at the time of our visit and needed minor mechanical repairs; however, it is sufficiently well built to permit evaluation of the concept which appears to be workable. In this device all axes pass through a common palm pivot.

Dr. Whitney favoured position control for use with manipulators.

2.2.12 <u>Grumman Aerospace, Bethpage, New York</u> 12 March, 1980

Persons Seen: Mr. John Hussey
Mr. Allen Nathan
Mr. Stanley Cortzel
Mr. Marty Pollack

Grumman Aerospace proved to be an interested potential user of controllers and a source of information concerning working conditions and current design of shuttle based work stations.

Grumman have constructed a large structure for manned remote work station simulation. The device consists of a large yaw ring, a roll ring, an X-Y drive with a chain driven Z axis. Outrigger supports enable the simulation of a man working bent forward supported by the ankles.

The open cherry picker (OCP) was described, which later will be enclosed to permit shirt sleeve operation (Closed Cherry Picker - CCP). The OCP will be attached to the end of the SRMS arm. By control of the existing SRMS control system and/or hand controllers on the OCP, a suited astronaut will be able to maneuver himself to the work area. The OCP has a grapple device to lock onto the work area thereby providing a stable platform for the astronaut to have direct visual and tactual access to his task.

In the more sophisticated version, i.e. the CCP, a capsule would be provided to enable the astronaut to work in a shirt-sleeve environment via two short and stiff manipulator arms (2 meters in length).

Grumman are evaluationg both proportional and on-off control, and are concerned about dynamic interactions among the manipulator, the cherry picker and the shuttle. Grumman's concept seems to fit a man amplification arroach, possibly bilateral, tending toward an exoskeletal force reflecting device.

The comment was made that suited astronauts prefer to work at face level. The requirement for an arm or hand restraint clamp was discussed. Grumman will require a COARSE/VERNIER mode selection due to a wide variability in manipulator velocities. The MRWS operator will always be monitored from the aft crew station.

2.2.13 Measurement Systems, Norwalk, Conn. 12 March, 1980

Persons Seen: Mr. Morton Mehr
Mr. Bob Goroski

Measurement Systems are continuing to produce and improve their basic product line which includes a variety of configurations of isometric and deflection controllers and joy sticks. We were not shown any device with more than three degrees of freedom although MSI have supplied a nominal six degree of freedom isometric controller to NASA Marshall which, we believe, consists of a four degree isometric handle with a two degree isometric thumb control. We had the opportunity to evaluate a number of the standard MSI controllers using their demonstration unit which presents a simple tracking task on a CRT and provides results in terms of time and percent of time on target. Track balls, small joy sticks and one displacement controller were tested.

Mr. Mehr felt that the six DOF concept could be feasible but that extensive development and evaluation would be required. He suggested that at least three alternate designs should be breadboarded and tested.

2.2.14 Boeing Vertol, Philadelphia, Pa. 13 March, 1980

Persons Seen: Mr. Tom O'Brien
Mr. Lynn Friesner
Mr. Archie Sherbert
Mr. Ken Landis

The discussion at Boeing Vertol was interesting since it included designers and test pilots with experience in the evaluation of hand controllers. Discussion started with the TAGS controller and carried on to the four axis,ball-on-stick heavy lift helicopter controller. The similarity between an aft facing SRMS operator and the aft facing heavy lift operator was pointed out. No unusual problems were encountered due to the orientation of the operator.

Mr. Sherbert made the comment that the mass of a controller should be comparable to the mass of the part of the body used to operate it. For example, a pencil should be comparable in mass to a finger, a hand controller to a hand etc. These comments were made with specific reference to the short term stability inputs required in the control of the CH47.

There was a general comment that almost all aerospace switches are too stiff and result in cross-coupling if mounted on a hand controller.

Mr. Friesner felt that any trimming or indexing should modify the forces on the control so that the new zero trim position would be apparent to the operator.

Mr. Sherbert has observed a consistant dither input invariably made by pilots when there is backlash or heavy breakout forces in a controller. He has observed that experienced pilots generate this pulse input at 40 pulses per minute with novice pilots tending to even higher rates.

There was general agreement that a controller should physically model the task as is the case with the heavy lift helicopter controller. At one time a stick grip with a thumbwheel was tested with poor acceptance by pilots. Forces and damping should reflect the task.

Boeing evaluated a two axis isometric controller to lateral and longitudinal control. The controller worked well at low speed and in hover.

In the use of the heavy lift controller, Boeing identified three operating regimes which they refer to as beep, creep, leap. Boeing use non-linear and assymetric forces with the force levels for inward rotation of the hand higher than those for outward rotation. They have recorded force-displacement curves to demonstrate this effect using various operators.

The heavy lift helicopter controller includes an arm rest which is considered essential both for comfort and as a hand reference. The arm rest should be as close as possible to the controller. For fingertip control, the hand should be supported.

2.2.15 U.S. Army Human Engineering Laboratories — 14 March, 1980
Aberdeen Proving Grounds, Maryland

Persons Seen: Mr. Clarence Fry
Mr. John Waugh
Mr. Thomas Frezel
Mr. Murray Foster
Mr. John Barnes
Mr. John Rollins
Mr. Gordon Herald

Mr.Clarence Fry described the organizational structure at HEL. Then Mr. John Waugh described tests of a helicopter control system designed at HEL and evaluated in their GAT-2H simulator of a small helicopter. The purpose of the controller was to permit an injured pilot to fly using only one hand. The configuration was similar to an aircraft control wheel consisting of a central column holding a pair of hand grips arranged similar to a control wheel. The grips control pitch by rotating in the pitch plane about an axis in the centre of the hand. Roll is achieved by a parallelogram movement about the palm pivot. Pulling back on the column increases torque with pedal input required for stabilization.

The unit was tested and received favourable comments from pilots, however, control was inferior to that achieved with conventional cyclic and collective.

The control deflections are approximately 30° in rotation and roughly 10 in. in translation. An evaluation of an isometric control is planned.

2.2.6 NASA - Marshall, Huntsville, Ala. 8 April, 1980

Persons Seen: Mr. Ed Guerin
Mr. Dave Cramblit
Mr. Frank Vinz
Mr. Bill Perry
Mr. Ed Noel
Mr. Linnis Thomas
Mr. Jerry Hethcoat

The visit to NASA Marshall was interesting from the point of view of gaining information on the control system planned for the Remote Manoeuvering Unit and of seeing various mock-ups of the Shuttle Aft Crew Station which were used to evaluate hand controllers and displays for docking and remote manoeuvering tasks.

Docking simulators observed included a docking apparatus mounted on a six degree of freedom synergistic motion system, two servo driven optical displays and a realistic air bearing supported, pneumatic thruster driven full scale simulation of the remote manoeuring unit. Camera images from several camera angles were available on CRT displays including one stereoscopic display used to provide depth of field for docking manoeuvers.

The MIT six degree of freedom isometric controller was available and had been evaluated. The general comments were that controllability was very poor in spite of the apparent simplicity of design and attractiveness of the concept. The device was considered unacceptable. A Measurement Systems controller was ready for evaluation. This consisted of four isometric degrees of freedom on the handle with two additional degrees of freedom activated by a thumb control.

The applications at NASA Marshall all involve on-off control of thrusters although the possibility of using a proportional controller to control pulse rate is considered feasible.

We had an opportunity to attempt to dock the full scale simulation using two finger tip joy sticks and the steroscopic display.

2.2.7 National Aeronautical Establishment
National Research Council of Canada
Uplands Airport
Ottawa.

26 March 1981

Persons Seen: Dr. Mac Sinclair
Mr. A. D. Wood

A brief discussion was held with Dr. Mac Sinclair and Mr. A. D. Wood of NAE who have been working on the evaluation of three degree of freedom isometric controls as side arm controls for helicopters. This work was done in conjunction with the U.S. Army Aeromechanics Lab (see Para. 2.2.8).

2.2.8 Annual Manual Controls Conference

As a result of papers presented at the Annual Conference on Manual Control in Los Angeles some further contacts were made:

Mr. J. P. Gaillard of Laboratore SPARTACUS University of Paris, has done some investigation with a six degree of freedom controller very similar in configuration to the breadboard model described in this report.

Mr. John Garin of Oak Ridge National Laboratory has evaluated a six degree of freedom controller for nuclear fuel handling applications. This work was done in conjunction with Mr. R. Skidmore of Martin Marietta and the configuration was the indexed position device observed at Martin Marietta. Mr. Garin has compiled a bibliography on the subject which he said was similar to the one contained in this report although it was done two years ago.

2.2.9 Polhemus Navigation, Burlington Vermont July 1981

During a visit to Polhemus Navigation to review position sensors for helmet position sensors, a film was shown which was recorded at MIT. A stick, fitted with magnetic emitters was used as a pointer. Magnetic sensors were used to detect position and altitude of the pointer which could be moved freely in space. Using the pointer and a voice recognition system, an operator was able to locate, change, erase, a position, etc, coloured geometric shapes on a large display.

The position transducers used are magnetic and are probably not suitable for use in space. The use of helmet or eye position as a control input provides an interesting alternative to a hand controller.

GENERAL COMMENTS AND SUMMARY

Overall, the state of the art survey demonstrated that there have been few recent or current developments in the area of multi-axis controllers. In the case of six degree, single point controllers, the work of Dr. Antal Beczy at JPL, an evaluation by Ed Guerin at NASA Marshall of six degree of isometric controllers and our own work at CAE, is the extent of current development, although, probably the most advanced existing design of a six degree single point controller is the combined displacement in rotation, isometric translation device of Dr. Dan Whitney of Draper Labs. Martin Marietta, too, have done excellent work in the development and evaluation of their indexed position control.

There is more activity in the area of master slave and exoskeletel devices including Dr. Tom Sheridan's work at MIT with undersea manipulators, the hard suit being evaluated and JPL, NASA Ames and NASA Marshall. In the commercial sector and in the nuclear power industry, there remains a body of literature to be reviewed. This has not been done as yet, since, master slave devices are secondary to this study, although, there was a general feeling that replica controllers, particularly with force feedback provided the best form of control for manipulators.

The common argument in favour of replica controllers was that of 'transparency' of the controller, that is, the feeling by the operator that he is manoeuvering the manipulator and not the controller. There was unanimous agreement that a single point controller, too, must be matched to the task in terms of orientation and force characteristics to be effective. This is especially true for multiple axis controllers.

From the space applications observed, nearly all systems for extra vehicular activity, and flying space craft will utilize on-off thrusters so that a bang-bang or perhaps two-step controller is the most likely requirement. The notable exception is the SRMS system.

The argument of isometric versus displacement controllers recurred at each visit. Generally, displacement controllers are favoured from the point of view of functionality and operator acceptance although the relative compactness and elegance of implementation of the isometric devices is recognized. It is clear that the dynamics of the task affect the acceptability of an isometric device. The problem of operator fatigue due to the lack of an indication of full scale input was commonly discussed as a disadvantage of isometric devices together with the inherent difficulty in making inputs in pure axes.

Other modes of control were considered with several people expressing the opinion that six independent, 'back hoe' type controls would be effective. The possibility of voice commands was discussed and, with the current trend to computerized voice recognition systems, this may prove an effective technique in the future. Mr. Skidmore, at Martin Marietta, also proposed a foot operated controller and suggested that the foot was under- rated in terms of manipulation.

The concept of six degree of freedom control was considered feasible by all; however, a number of people doubted that it was the optimal approach if an operator were concentrating solely on the control of a manipulator. Everyone agreed that effectiveness would depend on careful matching of the controller movements and forces to the task and on the effectiveness of the displays providing feedback information.

REFERENCES STILL TO BE CONTACTED

Mr. Gibson	JSC Eva Crew Systems
Dr. John Billingham	NASA/AMES
Mr. Frank Cepollina	Manager, Satellite Development NASA/Goddard
Mr. Tom Niewald	Lockheed RPV Group
Sam Meerhauf	Technikon
Mr. Greg Star	University of New Mexico
Hamilton Standard	Referred to at Grumman as a source of information
Martin Orlando	Fly-by-wire Control of CH53
Lear-Siegler	Possibly continuing hand controller work
Dr. Bob Wright	Canadian, formerly of North American Rockwell, then Hummarro. Evaluated 6 DOF Controller in conjunction with Deep Submerged Research Vehicle
Wiegand Wire	Position Transducer
Essex Corporation	Man-Machine Interface work
URS Matrix	Man-Machine Interface work
Richard Davidson Edwin Johnson	Evaluated exoskeletal controller for Nuclear Test Program. Work was done at now defunct NASA Test Station in Jack Ass Flats, Nevada. Edwin Johnson is now at National Bureau of Standards.
Dr. Butch Hostler 817-732-4811	General Dynamics, Fort Worth and involved in evaluation of F11e Isometric Controller.
Dr. Joe McDaniels 513-775-3325	Wright Patterson AFB involved in evaluation of F11e Isometric Controller.
MacDouglas or Brown	Franklin Research
Del Tesar	University of Florida

3.1. INTRODUCTION

3.1.1 Manual Controls

Conventional flight controls of the joystick or wheel and column type have dominated cockpit designs from the early days of manned flight, and are still standard in aircraft.
Typically, these devices are connected directly or with power assist to specific control surfaces or devices and control the movements of the vehicle.

Flight controls have been the subject of many studies and the interaction between pilot and controls is well documented. The USAF B-8A grip and the DC-10 control wheel are fine examples. Control systems have evolved to reduce the physical effort of piloting and to generate tactile feedback signals by presenting control loading forces to the pilot's hand. This feedback is an essential factor for stability in the pilot-vehicle system and a major component of the dynamic man-machine interface.

Advances in aerospace technology and vehicular performance, closely linked with developments in electronics and control systems, have made it both possible and mandatory that a new generation of flight controls be initiated.

Fly-by-wire and fly-by-computer technology have eliminated the need for direct linkage to the flight surfaces and have given rise to the concept of direct flight path control and task - (manoeuvre) oriented pilot inputs.

The sidearm controller was one of the first designs to emerge, reflecting the need of the cockpit designer for freedom to locate the primary flight controls away from the center of the cockpit. This need is even greater in spacecraft where the contour-seated astronaut presents special difficulties in terms of manual access to and operating envelope of primary flight controls. Furthermore, spacecraft flight demands independent control in all six degrees of freedom as well as simultaneous commands in two or more. Remote manipulators, still another newly developing technology, have similar command requirements.

It is essential that the pilot or operator be able to predict the results of his manual inputs at all times with an absolute minimum of mental effort or added workload.

The controller should be transparent in that the operator should feel that he is achieving the task, not merely moving a joy stickor control. This transparency is enhanced if there is a spatial correspondence between the controller and task, that is an upward movement of the controller corresponds to an upward motion in the task, and if there are no spurious inputs or discontinuities either in the force characteristics of the controller or its output.

3.1.2 Purpose and Scope of Search

The literature search described in this paper was carried out as one part of a study to examine the feasibility of using a six degree of freedom hand controller to control a spacecraft. The study program includes, in addition to the literature search, a review of current work in the area of multi-axis controllers, achieved by visits to relevant research and design centres, and the development and evaluation of prototype configurations. The focus of the literature search is specific; however, since little work has been done in the area of interest, the search includes directly related areas, other approaches to manual control, other applications of manual controllers and related studies of the human neuro-muscular system.

The literature search, then, is intended to provide not only definition of accomplishments achieved to date in the area of interest, but to provide references and resource material to support a conceptual development program. The search is not intended to be exhaustive, except in the specific area of interest, but rather to select the most useful and applicable available literature in related areas. All material found describing multi-axis manual controllers in space applications is included in this report, but, in the case of articles in a related area such as studies of human hand-eye co-ordination, the available material was reviewed and listed only if considered pertinent.

3.1.3 Criteria of Search

Earlier, similar efforts by the authors failed to disclose reliable single source of information covering the field of multi-axis control devices. Furthermore, no specific titles or sections dedicated to manual control seem to exist in any of the listings and abstract journals checked.

Hence, a broad search was made to cover potential sources and development areas such as vehicular control systems, behavioural sciences, man-machine systems and cybernetics. Titles found in this manner were assessed for relevance and checked against the expertise of the authors and nature of the source, if known, before a particular article or reference was obtained or retrieved for reviewing.

The criteria of relevance were based on areas of interest tentatively established for the conceptual development phase of the project, grouped as follows:

- Human Engineering Criteria
  - Compatibility with arm and hand biomechanics
  - Operability, cross-coupling
  - Accuracy, manual resolution
  - Physical effort, fatigue generation
- Man-Machine Systems Criteria
  - Applicability to Task
  - Performance Criteria
  - Performance measurement methods
  - Pilot acceptance data
  - Failure modes and effects
  - Command and Force Harmony

- Engineering Design Criteria
  - Cost, weight, size
  - Reliability, Maintainability
  - Crash-Worthiness
  - Redundancy

Furthermore, information was deemed relevant if the title or abstract indicated:

- Similarity to study or development objectives
- Applied research, development or evaluation work or data on a similar man-machine system.
- Design or evaluation data related to devices or components potentially applicable to the 6 DOF concept.
- Flight test data, simulator evaluation and performance measurement methods, pilot acceptance analysis, etc., of manual controllers.
- Annotated bibliographies listing sources of further information related to man-in-loop control and factors affecting manned system performance.

3.2. OBJECTIVES

The following objectives and desired end items have been defined for the search:

To find information to cover areas of interest. This included:

- Establishing a set of key word descriptions and access codes.
- Selecting the information systems and libraries to be used.

To collect library material and categories to aid future retrievals.

Analyze Contents of references in terms of:

- Areas in which development work has been done.
- Current state of the art in controllers and vehicular systems.
- Devices with 3-6 degrees of freedom, engineering and test data.
- Devices, components, system details applicable to a six DOF design.
- General man-vehicle system concepts.
- System description, analytical and test results.
- Human performance factors
- Performance evaluation methods
- Pilot acceptance of existing devices

Draw conclusions and generate guidelines to:

- Support the conceptual development effort.
- Reinforce State-of-the-Art survey.
- Recommend further work in literature search.

3.3 AREAS OF SEARCH

3.3.1 Selection of Potential Topics

The criteria defined for hand controller functions and related topics were transformed into descriptors recognizable by librarians and information systems. These were numerous and diverse, as the tabulation of key words shows.

The descriptors were further adjusted as each library or service made recommendations as to the exact words to be used in defining the areas of the search. This was time-consuming but the broad base used in the search ensured that a good cross-section of topics was obtained and that no significant areas of development work were neglected. Data pertinent to controllers with less than six degrees of freedom were also retrieved.

3.3.2 Selection of Information Sources

Both direct search methods and computerized information retrieval were used. Direct search was carried out in specialized libraries, such as the Aeronautical Library of the National Research Council of Canada, Ottawa, and the technical library of the Ecole Polytechnique in Montreal. Computer search were requested in these libraries and those of McGill and Concordia Universities of Montreal, in addition to a manual search.

Computer searches were carried out by various people, thus reducing bias when entering key words. Furthermore, operators were allowed to alter key words or to try synonomous terms if the initial run yielded a data base too wide or too restricted.

Abstracting services and journals were also scanned for references and for evidence of trends or new activities in the manual control field.

3.3.3 Keywords and Descriptors

Key words were used to describe the desired search topics in specific terms. Key words shown in the abstracts and computer printouts were used to assess the value and relevance of the report prior to retrieval of the physical article.

3.3.4 Maturity of Effort

The design of multi-freedom controllers represents a developing technology with a wide spectrum of applications and requirements. Efforts will be made to continue the gathering of information during the life of the study, as new sources and data may be revealed..

3.4. RESULTS OF SEARCH

The literature search was carried out using the following sources:

The NRC Main Library
Ottawa

The NRC Aerodynamics Library
Ottawa

McGill University
Science and Engineering Library
Montreal

Concordia University
Science and Engineering Library
Montreal

Ecole Polytechnique
Library
Montreal

The Star Index

The search was completed using three methods: manual, off-the-shelf searches, a time-consuming but very accurate method with an estimated 100% hit rate of relevant articles; computer searches including Engineering Index and NTIS data bases, a faster but less accurate method with an estimated 30% hit rate; and manual reviews of bibliographies and indexes such as STAR, a tedious but fairly accurate method with an estimated 65% hit rate.

3.5 COMPLETENESS

The success of this literature search can be described according to three separate criteria: First, the completeness of the search itself in terms of how thorough was the search and how much available information was missed; second, the suitability of an existing design to perform the six degree of freedom space vehicle control task specified; and third, the development of a set of reliable reference information for use in prototype design.

In terms of completeness, at least in the area of multi-axis manual controllers, the authors are confident that the bulk of significant work in North America has been included. This is partly due to the fact that there is little current work in the field, most of the significant work having been done some five to ten years ago. In addition, during the state of the state of the art survey, numerous knowledgeable researchers in the field were asked for references and the resulting list of references was limited. Sources outside the North American continent were not reviewed in as much detail and it is possible that European or Asian sources of information have been overlooked.

In terms of existing designs, several six degree of freedom controllers have been designed which may be suitable for space craft control. Of these the most suitable are:

a) An isometric six axis controller developed at MIT and currently being evaluated at Marshall Space Centre. Problems have been encountered due to cross-coupling and operator fatigue.

b) A controller developed by Dan Whitney of Stark Draper Labs which includes three rotational displacement axes and three isometric force axes. This design has not been evaluated; however, a working model is in existence which appears to be the best available six degree of freedom controller.

c) A six axis, floor mounted displacement unit used; at Martin Marietta in conjunction with manned manoeuvering unit studies. This unit was evaluated both in resolved rate and indexed position modes.

d) An experimental six degree of freedom evaluation device currently being evaluated by Dr. Antal Bejczy at JPL.

e) A hard suit replica controller evaluated at NASA/AMES and at JPL.

In terms of the development of a resource data bank, the search has been productive. The problem of designing a manual controller is related to a wide spectrum of fields both in terms of hardware design and the human interface. The sources listed in this paper provide a selective review of directly related literature. In addition to the above controllers, a prototype unit has been constructed and will be tested by CAE as part of this project

3.6. ANALYSIS OF RESULTS AND CONCLUSIONS

3.6.1 General

The net results of this search turned out to be very similar to those of a 1972 search, both in volume and in content (062). There is a lot of interest in the general area but very few determined efforts to define a design philosophy for multi-axis controllers or to build working units and test these under representative conditions. In sharp contrast is the consistently active and well-reported research area of describing and modelling the human operator in continuous control systems, which developed the optimal pilot model and established several fundamental relationships at the man-machine system level (086, 139, 141, 226, 239, 272, 303, 320, 322)

Manual controller design and evaluation is usually included as a minor task in the area of vehicle handling characteristics. The reports dedicate much space to system aspects, but deal with the controller in a paragraph or two. This is evident in the large number of reports whose titles and announced contents seem to indicate high relevance but contributed little to the present study. (008, 245, 326) Yet the very fact that vehicle handling characteristics a measure of success in the man-machine interface design, and controllers are evaluated together indicates the importance of controller characteristics and mechanical properties.

3.6.2 Pilot Acceptance

In the absence of a definitive design philosophy, the best source of information would be pilot opinion and performance/preference ratings derived from full flight simulation or actual flight evaluation. However, such reports are few. (269, 297, 299, 351, 352, 355, 243.)

3.6.3 Theoretical Studies

Theoretical studies of man-in-loop requirements and reports on laboratory-based experiments are more plentiful and some were found to contain useful data. However, in general, the studies are limited to one or two degrees of freedom, and test conditions are less than representative. Frequently, results are arbitrarily extrapolated to the real world. Such conclusions must be accepted with due qualification and great caution. (178, 205, 072, 217, 323).

3.6.4 Related Fields

Developments in fields related to controller design and incidental studies show a significant increase since 1970 - 72, as the following samples indicate:

Dynamic environment and anthropometry (002, 051, 054, 055, 065, 070, 071, 093, 107, 213, 335, 343, 345)

Human Engineering Personal equipment and Computer aided cockpit design (047, 189, 204, 214, 337)

Force feel feedback systems (060, 086, 089, 090, 168, 210, 363)

Man machine system synthesis and modelling (034, 030, 076, 139, 206, 216, 251, 263, 282, 304, 330, 361).

Biomechanical skills and performance (035, 043, 056, 077, 083, 098, 152, 193, 208, 339, 341, 365).

These peripheral efforts indicate that multi-axis manual control presents a many-faceted problem to which there is no single universal solution.

3.6.5 Basic Questions

No final answers have been found in the literature to some fundamental questions related to multi-axis manual control. Others have been investigated in part only, hence the answers are only partially valid and reliable. The following discussion presents the general philosophy derived from direct statements and interpretation of results found in the references.

3.6.5.1 Are six degrees of freedom too many to control with one arm and hand?

No proof is offered, affirmative or negative. It is a biological fact that the human hand and arm complex uses some 47 axes in dextrous manipulation, and the neuromotor control centers handle bilateral activities simultaneously with walking and talking. Thus, limitations must lie in restrictive controller and control system properties, inadequate or badly presented information and lack of control harmony. Qualitatively, the needs and requirements are well understood; the control task must become a means of accomplishing objectives, not a task in itself. (352). Bejczy says the controller should be transparent to its operator, or that it should not in any way restrict the input commands except as dictated by a scheduled force feel system reflecting the controller system conditions to the operator. The authors concur (24A) that command harmony, biomechanical compatibility and high engineering qualities in the controller are essential to pilot acceptance and performance. These parameters of successful man-machine integration also ensure quick and reliable detection of failures and loss of control, whereas a non-harmonious controller is a dangerous source of error.

3.6.5.2 Do mechanical properties and stick feel affect pilot/system performance?

The affirmative and unequivocal statement by Krüger (004) is supported by a large body of reports on research and development work on joysticks, grip shapes, sidearm and center stick configurations, stick forces, breakouts and gradients, ranges of motion, damping and other characteristics. The necessity and usefulness of proprioceptive feedback is accepted, but there is wide disagreement as to the nature, pattern and balance (harmony) of stick forces to be used. This, of course, is partially due to the individual requirement of each manually controlled system and each control task.

The principal issues most relevant to the present development task are:

- Sidestick vs center stick
- Deflection vs force stick and basic geometry
- Basic force feel requirements appropriate to the zero-g environment.

The feasibility and acceptability of the sidearm controller may now be considered proven. (018, 062, 182, 186, 187, 192, 243, 244, 262, 269, 271, 272, 282, 321, 325).

The isometric or force stick offers engineering advantages and reappears in the literature, frequently, as a means of mechanizing the side-arm controller. Its proponents claim that since force is the principal parameter of proprioception, (178, 341) and since pilot comments are mostly centered on stick forces vs system response, deflection is not necessary for aircraft controls (072). Many of such statements are based on laboratory experiments with non-representative equipment as observed by Krüger and others. Some claim definite superiority for pressure (force) controls, especially with increasing task complexity (075, 178). Flight tests with isometric sticks have been disappointing, but this is blamed on lack of proper understanding and application of this type of controller (341). A tendency to generate crosstalk between axes, poor stick feel and hand fatigue are reported most often as drawbacks or areas of further work to be done. (075, 178, 198, 193).

The force controller is, essentially, a deflection controller with infinitely steep spring gradients. Stick deflection maintained against spring tension causes hand fatigue and crosstalk.

In summary, the superiority of isometric sticks for spacecraft application is by no means proven.

Forces appearing on the control stick, both active and reactive (resisting movement) have been the focus of interest since the early days of systematic flight control design. (196, 261, 276) More recently, artificial feel systems have been defined and developed which essentially turn the flight controls into a feedback source, similar to the flight instruments and other sensory information available to the pilot (004, 010, 011, 060, 114, 115, 146, 198).

The principal concern is the prevention of overcontrol or overstressing the vehicle. Since stick force dynamically leads stick deflection, stick forces provide a predictive capability similar to quickening of displays (060, 062, 363) and provide a significant step towards head-up piloting. Even passive force systems can generate a "solid feel" which spells pilot acceptance (352) and positive stability, while negative stick stability, backlash and Coulomb friction degrade control accuracy and increase pilot workload (010).

The principal recurrent problem in each manual control system design is to define the forces appearing on the control grip at any instant, the rate of change of these forces and the driver parameters of scheduling the stick forces. Ideally, a high-speed servo system driven by an intelligent device, such as the flight control computer, could be programmed to deliver active force feel feedback and advisory signals (060, 363), but the engineering cost and complexity are prohibitive in some cases.

Unfortunately, much of the available literature refers to atmospheric flight of maneuvering aircraft or helicopters. The relative lack of reports in the general literature on similar work pertaining ot on-orbit space operation is surprising.

3.6.5.3 Is Six-Axis Control Necessary?

Whitsett (352) says yes, prompted by MMU experience in Skylab. It may also safely be said that the control-configured aircraft and direct flight path control will eventually require command inputs in six degrees of freedom. The literature fails to show this conclusively. This must be at least partly due to the engineering complexity of such a device holding back experimental work. Alternatives are tried, such as 2 x 3 degrees of freedom and foot controls. The former occupies both hands and continuous control is interrupted every time an additional manual actively is required such as adjustment of TV cameras. Foot control is generally slow, and inaccurate, as shown by the Skylab experience.

Integrated controls are advocated for U.S. Army helicopters (351) where a wounded pilot could save his crew if he could fly the helicopter with a single hand. Some of the ongoing research efforts will undoubtedly show the necessity and desirability of integrated, multi-axis controllers (334, 315, 305).

3.6.5.4 Is a Six-Axis Device Feasible?

The literature is inconclusive. The State-of-the-Art survey found three models, and several four DOF devices. No definitive design philosophy could be found on such topics as the cascading order of axes, or the segments of the arm and hand to be used as command sources.

3.6.5.5 How Does the Controller Fit into the Man-Machine System?

The picture is by no means complete but several research efforts and trends were identified in the fundamental areas of man-machine integration, namely the concept of inner/outer control loops, objective measurement of workload, and the concept of the internal model.

If a complex machine process is to be controlled manually, the command task should be presented to the operator such that the workload remains within the limits of his capability at all times and such that he can use his decisionmaking abilities to the full. This means that he should control the outer loops where frequencies and complexity are low, (251) and the machine should perform the inner loop functions. The controller contributes by command/task and command/display harmony where outer loop parameters of the task are matched by controller position or rates which in turn are manifested/predicted by stick force.(069) An earlier attempt at defining this process was called the matched manipulator technique, manipulator meaning controller (157).

Typically, pilot workload levels have been derived from debriefing questionnaires and pilot rating of system controllability. A more objective result can be obtained by measuring the direct and indirect muscular effort extracted from the pilot by electromyography (EMG) and by counting the control reversals (frequency of inputs) during the time frame of a given task. "White knuckles", or unproductive nervous effort is proposed as a measure of workload stress (341), and EMG power spectra as a metric of local muscle fatigue (193), both related to controller characteristics and forces. A flight evaluation related stick sensitivity, lack of command/display harmony or cross coupling tendencies to control reversals and hence workload.

The concept of an internal normative model is relatively new, although its equivalent (body image) has been recognized in physchology and physical medicine for quite some time. The human acquires through experience and cognitive process a fast-running mdel of the system response he is trying to bring about. If the system fails to match this model, he either increases his workload or registers a system failure. Attempts are being made to quantify this model and relate it to tracking tasks.[183]

3.6.6 Classification of Data

The following listing relates the references to the criteria of the search and is intended to serve as a rough index to the data base. Some of the articles not directly relevant to the present effort have been omitted from this index but retained in the computer listings. Articles frequently appear under several headings to show a broad discussion or significant statements/citations or diverse topics.

3.6.6.1 Configuration

Control sticks, sidearm, centrally located.

PAT -004

REF - 008	REF-014	REF -055	REF -062
-067	-068	-181	-182
-184	-185	-186	-187
-188	-190	-190	-193
-194	-195	-243	-244
-255	-256	-262	-269
-271	-295	-296	-297
-298	-305	-321	-325
-326	-341	-356	

Multi-axis devices, integrated controllers.

REF - 015	REF -020	REF -023	REF -034
-037	-068	-076	-193
-245	-246	-257	-269
-284	-294	-295	-296
-297	-305	-316	-326
-327	-351	-355	-356

General controller forms, control/display relationships

REF -018	REF -040	REF -048	REF -114
-118	-147	-240	-241
-270	-280	-305	-311
-324	-329	-334	-349
-364	-369		

3.6.6.2 Anthropometry, Biomechanics, human limits, fatique, clothing, static equipment properties, cockpit design.

PAT -008	PAT -010	PAT -011	PAT -013
REF -019	REF -031	REF -038	REF -048
-049	-051	-056	-065
-067	-070	-071	-077
-083	-084	-085	-093
-096	-098	-103	-121
-152	-155	-163	-179
-189	-193	-197	-213
-261	-276	-311	-336
-341	-343		

3.6.6.3 Dynamic Properties

Forces, force feel, force harmony linearity, optimization, feedback.

PAT -006	PAT-013		
REF -003	REF -004	REF -008	REF -010
-011	-021	-022	-025
-041	-052	-060	-062
-086	-090	-094	-195
-197	-199	-210	-219
-244	-248	-291	-292
-253	-254	-259	-260
-262	-303	-306	-317
-321	-340	-349	-352
-353	-356	-358	-363
-370			

Dynamic environment, command/task harmony, cross-coupling, zero-g effects.

REF -002	REF -030	REF -054	REF -055
-059	-123	-210	-318
-351	-352	-366	-368

Force sticks and Deflection sticks.

PAT -007			
REF -027	REF -034	REF -060	REF -072
-075	-176	-178	-205
-218	-243	-263	-291
-341			

Control Authority, stick gain, linearity, stability.

REF -008	REF -262	REF -271	REF -323
-352	-363		

3.6.6.4 Man-in-loop system aspects control tasks, modes, system synthesis.

REF -004	REF -024	REF -038	REF -046
-064	-125	-204	-206
-207	-208	-216	-220
-221	-224	-231	-263
-266	-282	-315	-316
-319 (?)	-320	-323	-326
-330	-334	-352	-357
-364			

Handling qualities, controller evaluation, pilot-vehicle integration pilot acceptance.

REF -017	REF -023	REF -024	REF -115
-139	-194	-231	-243
-269	-293	-295	-297
-298	-311	-355	-363

Performance evaluation, optimization, workload.

REF -004	REF -013	REF - 053	REF -143
-216	-237	-251	-259
-270	-300	-330	
-335	-338	-344	-346
-358			

Human control behaviour and skills, modelling, analysis, research.

REF -004	REF -007	REF -021	REF -035
-043	-090	-199	-208
-225	-230	-267	-272
-287	-295	-301	-302
-303	-307	-320	-324
-360	-361		

3.6.6.5 Engineering and design data, general specifications and bibliographies.

PAT -001	PAT -002	PAT -009	REF -045
REF -047	REF -091	REF -150	REF -209
-211	-212	-2421	-243
-277	-284	-289	-293
-294	-297	-298	321
-322	-326	-327	-351
-363	-363		

3.7. CONCLUSION

A literature search was completed to support a feasibility study on the use of a six degree of freedom hand control for on orbit use in space applications. The bulk of published information relevant to this logic is referenced in this paper together with a synopsis of expert opinion. The comments and analysis are intended to reflect, without bias or interpretation, the current trends and developments among experts in the field.

4. BREADBOARD DESIGN

4.1 INTRODUCTION

A breadboard six degree of freedom hand controller was built to serve as a laboratory tool for fundamental evaluation. The device was intended only to provide qualitative assessment of such basic parameters as pivot locations, hand grip design and inherent tendancies to cross-couple motions. The design goal was to have an easily adjustable configuration, suitable for the evaluation of basic principles but not necessarily compact or suitable for implementation in a space environment. The device was spring centered with breakouts to indicate null in all axes. Position transducers provided readouts on all axes positions.

4.2 CONFIGURATION

The basic design configuration was based on all axes passing through a single pivot located at the centre of the handgrip although adjustability was provided to relocate the axes for rotational movements. In particular, the yaw pivot could be displaced to correspond to the wrist joint rather than the centre of the hand. The configuration is shown schematically in Figure 4.1 and engineering sketches are included in Appendix A.

The device consisted of a handgrip mounted in a gimballed cage which, in turn, was mounted on a three dimensional translational base.

4.3 BREADBOARD TESTS

Limited testing was carried out using the breadboard model. Most of the testing was done to evaluate the comfort and acceptability of handgrip configurations. In addition, the use of a wrist pivot for yaw motions was compared to a pivot at the hand centre. The hand centered pivot was selected due to its greater comfort, reduced tendancy to crosscouple lateral and yaw motions and ease of manufacture.

The breadboard model can be used to evaluate suitable force-position characteristics and to compare symmetric, linear forces to force profiles tailored to the apparent forces felt by the hand. The gradient for negotive yaw, for example, should probably be less than that for positive yaw since an inward rotation of the hand is a more natural movement than an outward rotation.

The breadboard model will also be used to evaluate any proposed changes to the prototype since, although the basic configuration is different in that the gimbals are located outside the handgrip whereas the gimbals of the prototype are internal, equivalent motions can be generated.

5. PROTOTYPE MODEL

5.1 Introduction

The design of the prototype model was based on results obtained using the breadboard model, from an analysis of the literature and of the state-of-the-art survey and on basic mechanical design principles. Contrary to the philosophy of the breadboard, a major design constraint was that the device be suitable in size, envelope, weight and mechanical characteristics to be manufactured to space standards and used either in a spacecraft or externally in space. The handgrip must be suitable for use with the protective glove used in space and the design should be suitable for use in a zero-g environment.

Further, the design was developed such that the translational axes could be locked out and used in an isometric mode. The controller can be configured either for use as a displacement controller in all six axes or on a "point and push" mode with the three rotational axes responding to position inputs and the three translational axes purely isometric. The final selection of mode will be based on operational tests.

The controller itself has little adjustability although breakouts, force gradients and travels can be changed by replacement of parts. Using an electronic interface associated with the controller, however, electrical characteristics can be modified. Gradients, breakouts and saturation points can be adjusted independently in each direction in each axis. The output can be used in an on-off or pulsed mode.

5.2 Configuration

The prototype model is shown in Figure 5.1. Engineering sketches are included in Appendix B.

The handgrip is shaped to fit the relaxed position of the hand in a pressurized glove. It was found in Sky Lab experiments, that only closed or gripping action of the hand was tiring to maintain. The proposed grip permits operation without gripping or squeezing, provides orientation by means of the raised reference grip which can also be used for auxilliary switches and provides sufficient space for internal mounting of the rotational mechanisms and transducers.

6.0 SPECIFICATION

At the conception of this project, the end result was intended to be a specification for a six degree of freedom hand controller to meet a selected application. At present, no immediate application has been identified so that a detailed specification is not a reasonable requirement; however, a number of potential applications have been defined, (RMS, Cherry Picker, MMU, on orbit control, teleoperator) and there is some commonality in the handling quality requirements. In addition, some guidelines have been established based on matching the controller to the human hand and arm.

The definition of a specification will be aided by tests which are planned to evaluate the prototype model developed under this study. This series of tests should provide data to aid in the selection of mode, travels and handling qualities. The importance of these tests should be emphasized since previous studies have resulted in prototype models which were potentially useful but did not receive adequate test and evaluation.

In this section, a general discussion of hand control/requirements is presented. Environmental, quality control, material, reliability and other general requirements are not discussed in detail since these depend on the particular application and environment. The prototype model contains no components or techniques which could not be implemented to space standards and potential requirements for high reliability, severe environments and use with gloved hands were considered in the design process.

No position transducers are used in the controller and displacement is measured indirectly by using force transducers to detect deflection of load springs. This approach was used to permit conversion to an isometric configuration. One problem in this approach is the generation of unwanted disturbance signals due to vibration or external accelerations, but this problem can be overcome through the use of adequate filtering and isgnal processing techniques.

The prototype includes breakouts, gradient and hand stops in each axis. It is designed in a configuration which could realistically be produced to space standards. It is also designed for ease of mounting in mock-ups or simulators and includes a signal conditioning box located near the controller permitting the interface stations to be located remotely.

One advantage of the "point and push" mode of control is that the operating envelope of the device is essentially fixed and limited to the outside dimensions of the device itself.

6.1 Configuration

As a result of this study, some recommendations can be made concerning configuration. These recommendations are embodied in the design of the prototype and will be verified by additional testing. Other configurations were considered and rejected based on tests with the breadboard model or on a review of existing configurations of hand controls.

For mechanical simplicity, compactness and ease of operation, a single pivot at the geometric centre of the handgrip is preferable. The handgrip should be spring centered in all axes. A breakout force should be included in each axis to provide null definition and to prevent unwanted inputs and cross-coupling. The magnitude of the breakout force and gradient should be matched to the specific task, a process which requires experimentation and optimization. Viscous damping improves handling quality and should be matched to the task.

For space applications, the handgrip should be large enough to fit a partially closed, gloved hand comfortably. It requires a sustained effort to grip a small object in a pressurized suit in a space environment.

A fully isometric six degree of freedom controller is not considered a feasible device; hence, the controller should be either fully displacement or displacement in rotation and isometric in translation. The combined type has not yet been evaluated; however, tests on the prototype model should determine the relative advantages of each approach.

The basic configuration should be suitable for use in an on-off mode in all axes. In this case, a breakout, displacement and hard stop is required in each axis. Isometric implementation of an on-off mode is not a realistic proposal.

In each axis the displacement should be the minimum required to provide the resolution required by the specific task. Force-displacement characteristics, aside from breakouts and hardstops, should be linear; however, the electrical output curve should be matched to the perceived input, that is, for an inward rotation of the hand with symmetric force characteristics, a deflection may not feel equivalent to an outward deflection of an identical amount The electrical output should be specified to fit perceived displacement rather than for linearity.

The operating envelope of the device should be reduced as much as possible. For a mixed isometric/displacement device, the operating envelope is limited basically to outside dimensions of the controller. Translational travel must be added directly to the envelope.

In many manipulator tasks force feedback is extremely useful. Ideally an active, force reflecting hand controller should be used; however, it is unlikely that such a device could be mechanized in any reasonable envelope. Alternative devices should be considered using vibration or other devices to indicate applied force or to warn of approaching force limits. The design of such a technique is, of course, complicated in the case of a gloved hand. True force feedback can only be implemented on the displacement mode.

6.2 Transducers

The use of force transducers to provide outputs has several advantages. It permits the controller to be adapted to isometric or displacement modes without complicated changes. In addition, in a final configuration, strain gauges with redundancy and temperature compensation can be mounted in a compact way without requiring complicated linkages or mechanical parts.

6.3 Mechanical Design

The design of the prototype unit has demonstrated the feasibility of mounting control mechanisation within the handgrip. This approach is easily achieved in the case of an isometric controller and can be implemented in displacement defices. This approach should be specified as a baseline approach or design goal.

7.0 POSSIBLE FUTURE APPLICATIONS

As stated previously in the report the use of a six degree of freedom hand controller in the Shuttle Remote Manipulator System would greatly ease the operator's problems by permitting one handed control of the arm. The ease with which a re-fit could be accomplished is described in the following sections.

7.1 Additional Development

As a separate privately funded exercise CAE has continued development work on the 6 DOF controller to the point where basic operational modes have been established, enabling an assessement of realistic basic volumes and weights.

Operationally the device is a displacement rotational controller in roll, pitch, and yaw and a combination of minimum travel/force in the three translational axes. Breakout forces exist in all size axes to reduce unintentional cross-coupling.

By the use of electronic filtering and switching it is possible to obtain outputs proportional to displacement in rotation and to force in translation, or to set up an on/off switching mode in all axes, or any combination of these two extremes. Therefore the device can be adapted for a range of applications from sample on/off (bang-bang) thruster control for basic spaceflight, proportional rotational control plus on/off thruster control in translation for more sophisticated spaceflight systems, to fully proportional rate control for manipulator operation.

No firm outline dimensions have been determined beyond the basic four inch diameter spherical handgrip. However, it has been established that all mechanics related to yaw, X, Y, and Z axes can be accommodated within a space equal to, or less than, the upper section of the existing RHC. Also all associated electronics could be accommodated in the lower section. Thus a six-degree of freedom controller adapted to the specific requirements of SRMS could be built to be physically interchangeable with the RHC.

7.2 Introduction into the SRMS

A basic comparison of the two systems is shown in Figure 7.2.1. The system would operate from the $\pm$ 12 VDC power line, thus eliminating the 1500 Hz oscillator.

Additional controls such as the capture/release switch, coarse/vernier switch and the rate hold switch, which are currently mounted on the RHC Handgrip have not as yet been considered in detail. However, by using a 6 DOF controller the option would then exist to either mount them on the handgrip extension (see Figures 7.1.2) or elsewhere for operation with the left hand.

7.3 Simplified System for Ground Based Evaluation

A simple means of achieving direct interchangeability with ground based SRMS facilities is shown in Figure 7.3.1.

7.4 Shuttle Installation

The installation within the Shuttle is illustrated in Figure 7.4.1.

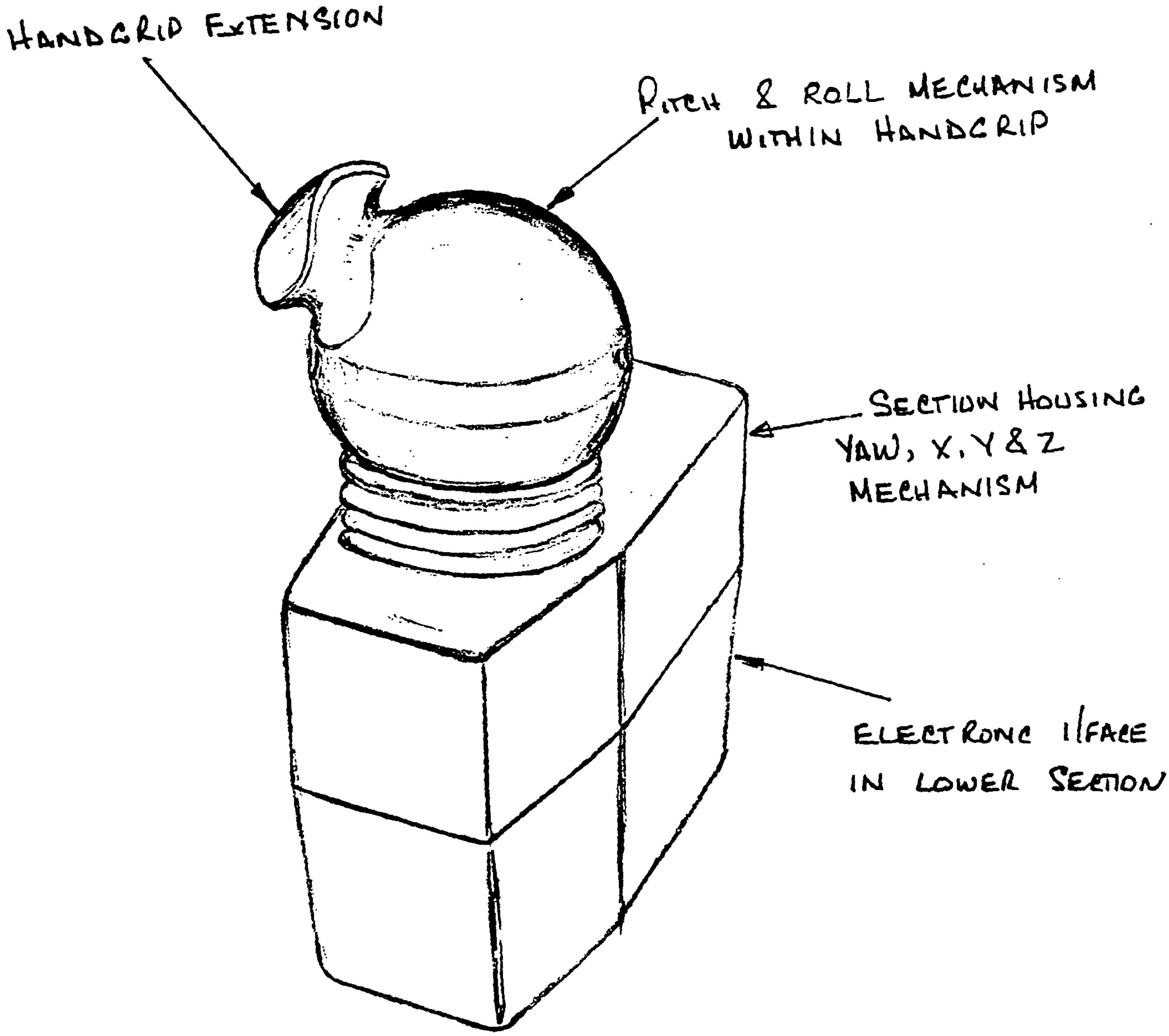
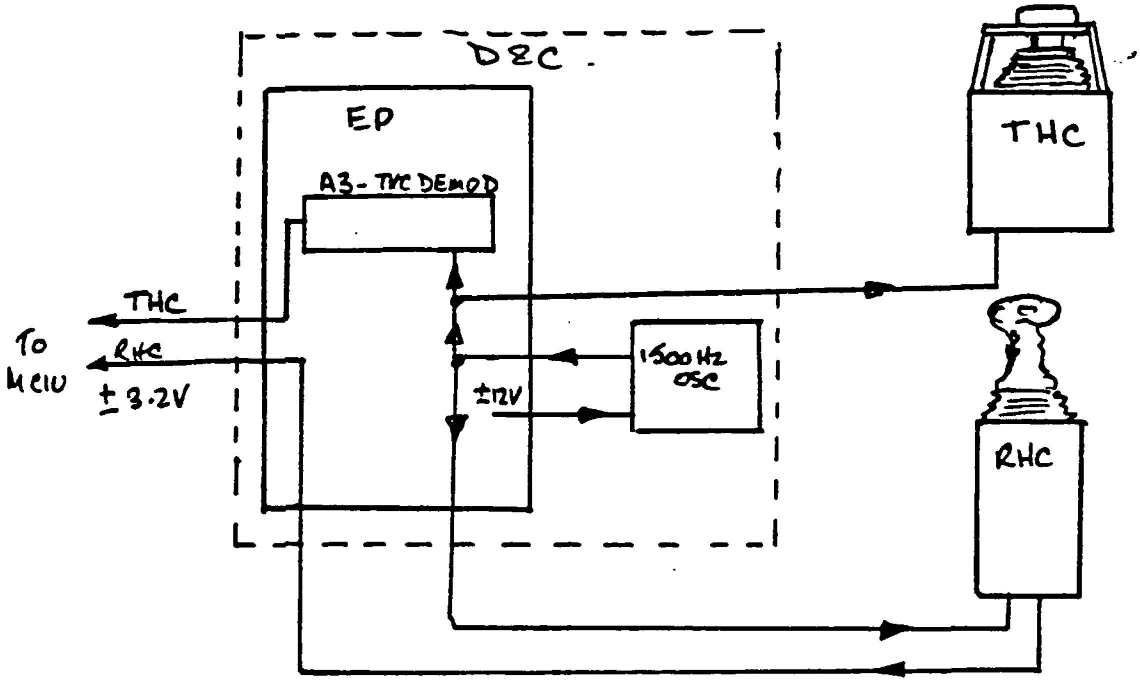
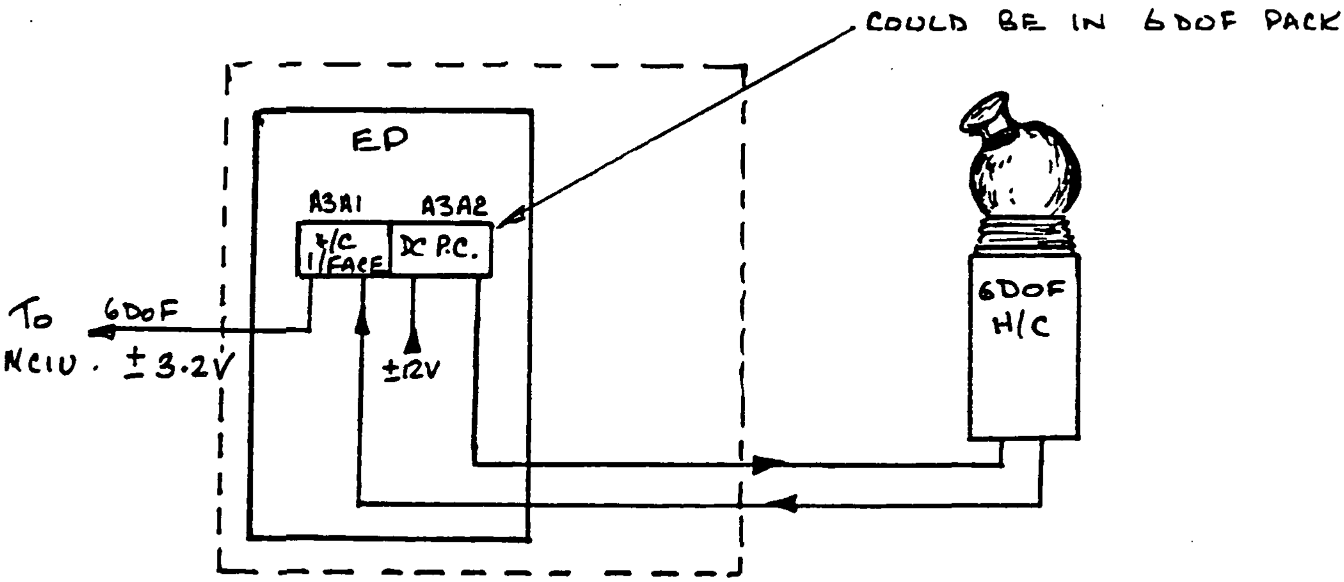


FIGURE 7.1.2. 6 DOF. CONTROLLER IN SRMS RHC PACKAGE



PRESENT HAND CONTROLLER SYSTEM



REVISED 6 D.O.F. HC SYSTEM.

FIGURE. 7.2.1.

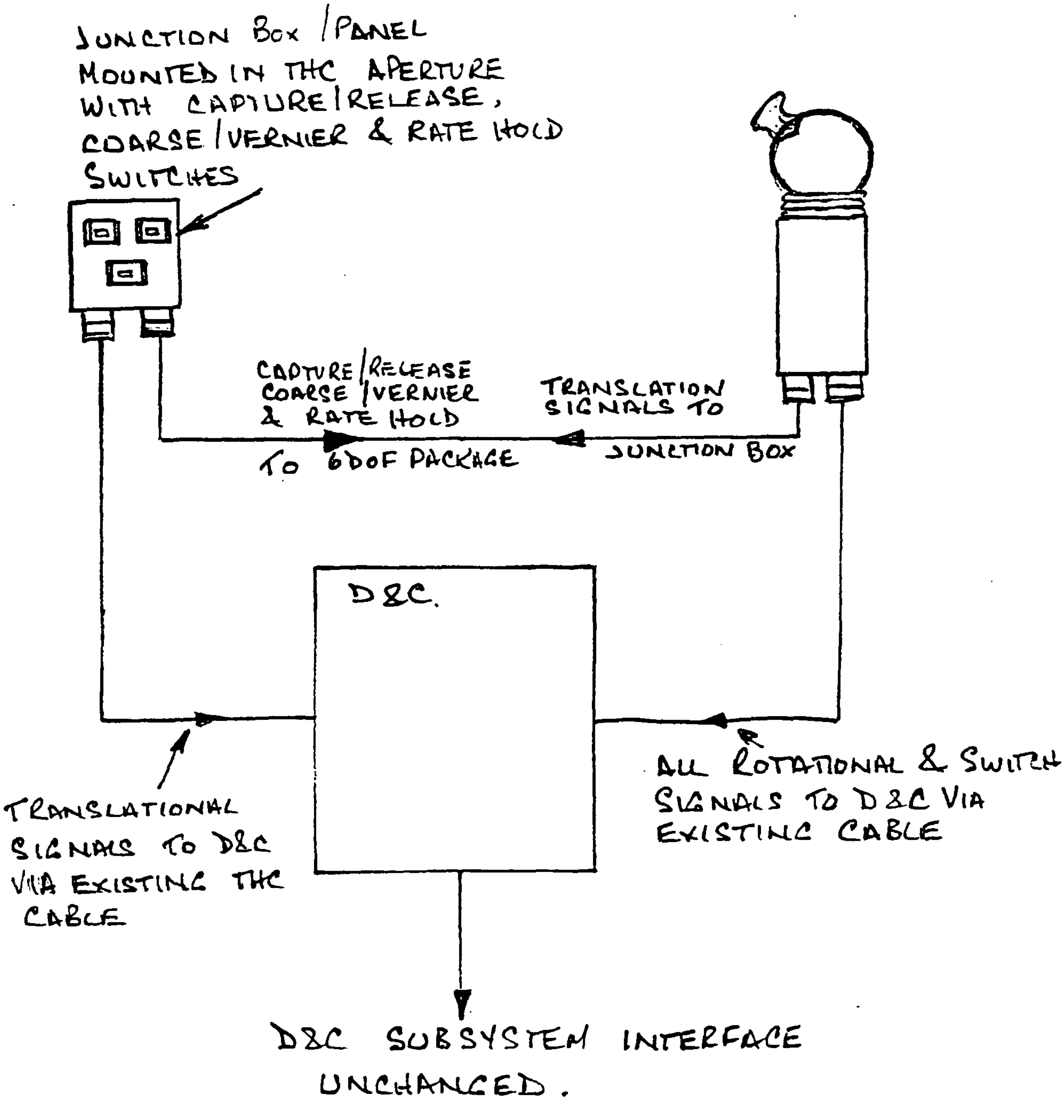


FIGURE 7.3.1. SYSTEM FOR GROUND BASED TRIALS WITH SRMS

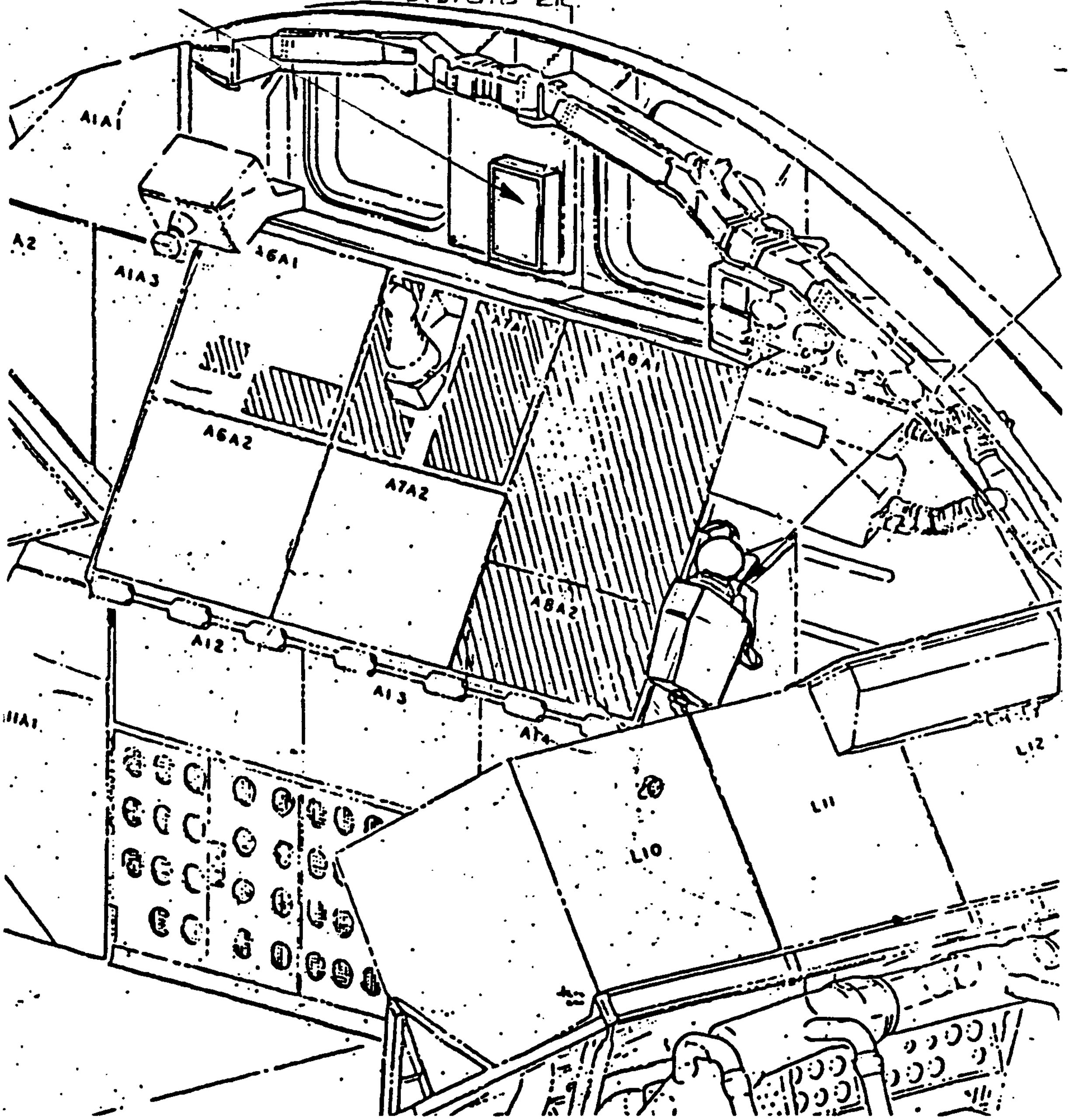


FIGURE 7.4.1. SHUTTLE AFT STATION SHOWING 6 DOF H/C INSTALLATION. NOTE THAT A LOCAL HAND REST/REFERENCE WOULD ALSO BE REQUIRED.