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DESIGN AND DEVELOPMENT OF A SIX DEGREE OF FREEDOM HAND CONTROLLER

M. L. King
Group Leader
SRMS

G. M. McKinnon
Manager
Research and Development

A. Lippay
Human Factors
Engineering

CAE ELECTRONICS LTD.

ABSTRACT

The design objectives of a six degree of freedom manual controller are discussed with emphasis on a space environment. Details covered in the discussion include problems associated with a zero g environment, the need to accommodate both 'shirt sleeve' and space suited astronauts, the combination of both manipulator operation and space craft flight control in a single device, and to accommodate restraints in space.

The lack of positive direction provided by a State-of-the-Art survey is discussed briefly as an introduction into the development work currently under way.

The initial work, consisting of a variable configuration device designed as a development tool in which rotational axes can be moved relative to one another, is described and its limitations discussed.

From work with the development tool two additional devices were developed for concept testing. Each device combines the need for good quality with its ability to achieve a wide range of adjustments.

The future work to be carried out towards an actual design proposal is described. The work so far indicates a trend to a particular type of handgrip for the space environment. When considering wider applications this type of grip may not recieve operator acceptance. Methods of mechanizing the same concept into more conventional forms are therefore discussed briefly.

The final section covers possible applications and the advantages which such a device could provide. Possible applications include the Shuttle Transportation System, its associated remote manipulators and appendages, and on-orbit or extended orbit space-craft.

INTRODUCTION

Co-ordinated manual control of multiple interactive devices is a common requirement. For a specific application, the ideal configuration of a controller depends on several factors: the relative importance of combined interdependent actions as opposed to sequential independent actions; the precision required; the working environment; other simultaneous tasks required of the operator. As a result, when one surveys available manual controls one finds myriad apparently unrelated devices, be it a steering wheel for a car, a control column for an aircraft or a set of levers for a back hoe operator. This paper blithely ignores the historical emphasis on a specific device for a specific application and addresses a more general problem, essentially responding to the question, "Can a six degree of freedom manual controller be designed to fit a general class of control problems?"

While the potential for general application was considered from the start, the design was guided by the requirements of certain specific tasks which imposed severe constraints. The stated objective was to provide single point control of six degrees of freedom on orbit in space, a non-dynamic zero 'g' environment. The tasks for such control indlude flight control of a craft carrying the operator and controller, control of manipulators attached to that craft, and the teleoperation of unmanned craft from a parent vehicle. An additional requirement is the operation of a large manipulator such as SRMS from a manned work station positioned at its outboard end.

The space application imposed two immediate design constraints: the controller must be suitable for use in a weightless environment; and it must be capable of being configured for operation with a heavily gloved hand. The protective glove worn by an astronaut performing extra vehicular activities severely limits manual dexterity and tactile feel. Further, the controller configuration has to be suitable for proportional control in all axes although an on-off or pulsed acceleration mode is required in some or all axes to achieve motion control of a spacecraft by the use of thrusters. Additional requirements of compactness, light weight and rugged mechanical design are generally beneficial in any application.

Ideally, the controller should enable the operator to command motions in any axis without crosscoupling while not inhibiting co-ordinated motion in any combination of axes.

The reason for the selection of six degrees of freedom is obvious in the case of motion control since six degrees are sufficient to determine the attitude and position of a rigid body. If co-ordinated, single hand control of six degrees of freedom is achievable, the order can be reduced by elimination of those axes for which motion is constrained. On orbit manoeuvers in space constitute a six degree of freedom control problem.

The chosen design should be adaptable to include additional controls to operate, for example, end effectors of manipulators.

Initial design activities included a literature search and a state-of-the-art survey which included discussions with many experts. The discussions, while lively and stimulating, produced a wide spectrum of opinion with few points of common agreement. There was general agreement, however, that a six degree of freedom controller was feasible and that a key factor in design is to ensure that the controller be compatible with the normative or mental model that an operator creates of his task. This implies that there should be spatial correspondence between the controller and the task, that is, up in the controller should correspond to up in the operators frame of reference and the forces applied to the controller should reflect the requirements of the task.

DESIGN CONSIDERATIONS

Various control modes and techniques were considered. The design selected evolved from selection of approaches which have been proven in practice. The selection process was subjective since it is difficult to compare results from previous studies due to the wide variation of applications, test conditions, quality of devices tested and personnel involved. The justification for some fundamental decisions is given here.

The first decision required was to select the mode, or modes of control required. Obvious candidates from a manipulation standpoint, were to use a replica controller or, alternatively, resolved rate control.

A replica control strategy involves using a scale model of the task in such a manner that manipulations of the model result in similar motions of the controlled device. In the case of a remote manipulator, this mode of control can provide excellent results. Problems arise from scaling, however, especially in the case of a large arm. A useable replica controller for the SRMS arm, for example, was not feasible since to model the 50 foot arm in the space available in the shuttle aft crew station would demand a large scale reduction requiring extreme precision in the master and with the effect that minor motions, nervousness or even the pulse of the operator result in significant control inputs. A twentieth scale replica controller has been used to provide excellent control of the RMS arm particularly in the case of the precise positioning required for docking the arm. A replica model has been implemented effectively using a one to one scale model for the hard suit arm which has been implemented and tested at several NASA laboratories including AMES and JPL. The replica approach has the advantage of providing excellent spatial correspondence and is adaptable to the use of force feedback. In some cases indexed position control has been used to aleviate the scaling requirements. However, this is achieved at the expense of spatial correspondence.

In the case of flight control of spacecraft, the concept of a replica type controller conflicts with the requirement for large unconstrained motions in all axes, and the requirement for a common fixed point of reference for the controller and the object being controlled.

For these reasons, the fact that the replica mode is task specific, and the excessive envelope requirements, the replica controller was rejected.

Two further alternatives were reviewed and rejected at this stage. One proposal was to use a proven, existing three or four axis controller with mode selection buttons so that one controller axis could be selected to control more than one axis in the task. This approach, while reducing the required mechanical complexity, and the design time for flight hardware, imposes constraints on co-ordinated motions and inhibits spatial correspondence. A second alternative, that of mounting a ring around a three axis translational controller in such a way that the ring could be rotated in the three rotational degrees of freedom, again made it possible to utilize existing hardware. However, the simplicity of single point control is lost.

The choice of six axis single point joy stick was considered the most general approach. While ingenuity would be required to achieve a feasible mechanical implementation, the resulting device could be used to implement resolved rate (or acceleration) or indexed position modes and did not impose any critical constraints in terms of hand position or spatial correspondence.

A second decision required was to select between isometric or force inputs and deflection inputs. Isometric controllers are rugged and easy to configure mechanically; however, they do not provide force feel or tactile feedback so that the operator can generate unwanted inputs and has a tendancy to overcontrol, especially when under stress. These shortcomings can be overcome with operator training and the relative merits of isometric versus displacement controls, as a general philosophy, are still a matter for debate.

For the six axes controller, the use of six isometric axes was rejected on the basis of evaluation of such a device built and tested at MIT. (See Figure 1) As a basic approach it was decided to use deflection in all six axes; however, the translational axes were designed so that the position input was measured indirectly as the force to deflect a spring. In this configuration, the translational deflections could be limited or locked out resulting in a device which uses deflection in the rotational axes and force for translation. The controller then, can be used either as a six axis deflection controller or in a "point and push" mode. The "point and push" mode has the advantage of simplicity in mechanical design while retaining good spatial correspondence features. Based on prototype evaluation, a selection will be made between the two modes.

The six degree controller was designed to provide adjustable force feel characteristics in all deflection axes. Force feedback was considered to be too difficult to implement at this stage. Force feedback or force cueing is, however, extremely important in many manipulator tasks and the possibilities of incorporating either force feedback or some form of force cueing is considered a high priority. True force feedback is achievable only in the case of replica or indexed position type of control; however, some form of force cueing in the resolved rate mode would be advantageous to provide information to indicate interference with stationary objects, external forces or high levels or applied force.

Based on the preceeding considerations two functionally similar, but physically different, devices were designed and built as described below.

BREADBOARD MODEL

A simple geometric breadboard model of a six degree of freedom controller was constructed to be used in evaluation. The model was designed to be adjustable in geometry, in particular permitting the six degrees to be about a single co-ordinate origin while allowing the yaw pivot to be displaced so that the yaw axis could be set either to the centre of the hand or to the wrist pivot point. The unit included light centering and breakout forces and position transducers; however, the inertia forces were large compared to the force feel characteristics. The unit is shown in Figure 2.

The breadboard unit was constructed with the handgrip placed inside the pivot points with the intention that, in later models, the rotational axes could be placed inside the handgrip to provide equivalent motions.

The breadboard model could also be used with a variety of handgrips.

Tests using the breadboard model were carried out to compare a wrist yaw pivot to a single point of origin in the hand centre. The null position of the hand was also evaluated and a novel handgrip evaluated which permits use with a gloved hand. The breadboard will be used in continuing evaluations.

PROTOTYPE MODEL

A prototype model as shown in Figure 3, was designed based on the results of the breadboard evaluation to provide six degrees of freedom about a single pilot located at the centre of the hand grip. The mechanisms for rotational motion and the rotational transducers are mounted inside the handgrip. The handgrip support is mounted on a three axis linear position device. Breakouts, gradients and hard stop positions are adjustable in each axis.

A design of the handgrip was based on several factors. First, to accommodate operation with a gloved hand, a substantial grip was required which conformed to a comfortable hand position. A raised portion was included to provide orientation. The use of a substantial handgrip permitted the rotational mechanisms and transducers to be packaged internally.

The handgrip mechanism, with its three rotational degrees of freedom was mounted on a three degree of freedom translation base. Two alternate configurations have been built, one allowing displacement inputs and the other isometric.

In the mechanical displacement configuration, position is sensed indirectly by means of a force transducer which detects the force applied to a linear spring. Since the breakout forces, force gradients and travels are adjustable, this configuration can also be used as an isometric device. One problem, typical of isometric controls, is that, in the presence of vibration, spurious control inputs can be generated due to the inertia and mechanical dynamics of the controller. This effect can be eliminated in practice through the use of mechanical breakouts, electrical thresholds and careful consideration of controller structure and mounting configuration.

A second configuration in which the translational axes are purely isometric was also constructed. The configuration is mechanically simple and rugged and permits good feel characteristics in the rotational Detents or breakouts can be included in the translational axes to crosscoupling if necessary; the "point and push" mode of control w investigated for a variety of applications.

TESTS

The prototype hand controller was designed to be flexible and adjustable both in terms of force feel and mode of control. Hardware interfaces have been designed which include adjustable threshold, independent gradient adjustment in each direction in each axis and adjustable saturation level.

To date, only 'non task related' tests have been carried out which have demonstrated the capability of generating single axis inputs as well as co-ordinated inputs in up to six axes.

In the immediate future more extensive laboratory testing is planned followed by the evaluation of the controller in various practical applications. The first of these will be as a control device for the Open Cherry Picker (OPC). Suited astronauts will use the controller to 'fly' the Large Amplitude Space Simulator (LASS) six degree of freedom cherry picker simulator. Following these tests the controller will be evaluated in the Hand Controller Development Facility at the Johnson Space Center (JSC). This facility provides simulated spacecraft flight control and can accept a wide variety of control devices for evaluating. Subject to availability it is also planned to carry out evaluation with the Manipulator Development Facility (MDF), also at JSC. This is a full scale working mock-up of the Shuttle Remote Manipulator System (SRMS) which is used for both development work and astronaut crew training. (Currently the system uses two separate hand controllers, one for rotation and the other for translation.)

CONCLUSIONS

A six degree of freedom prototype hand controller has been designed based on a review of existing designs and an assessment of current technology. The unit is flexible in that displacement control can be compared to isometric control in the translational axes. The final assessment depends on rigorous testing using various modes of control in various realistic applications. By assessing the results of these tests it is anticipated that some fundamental principles concerning the use of six degree of freedom controllers can be established.

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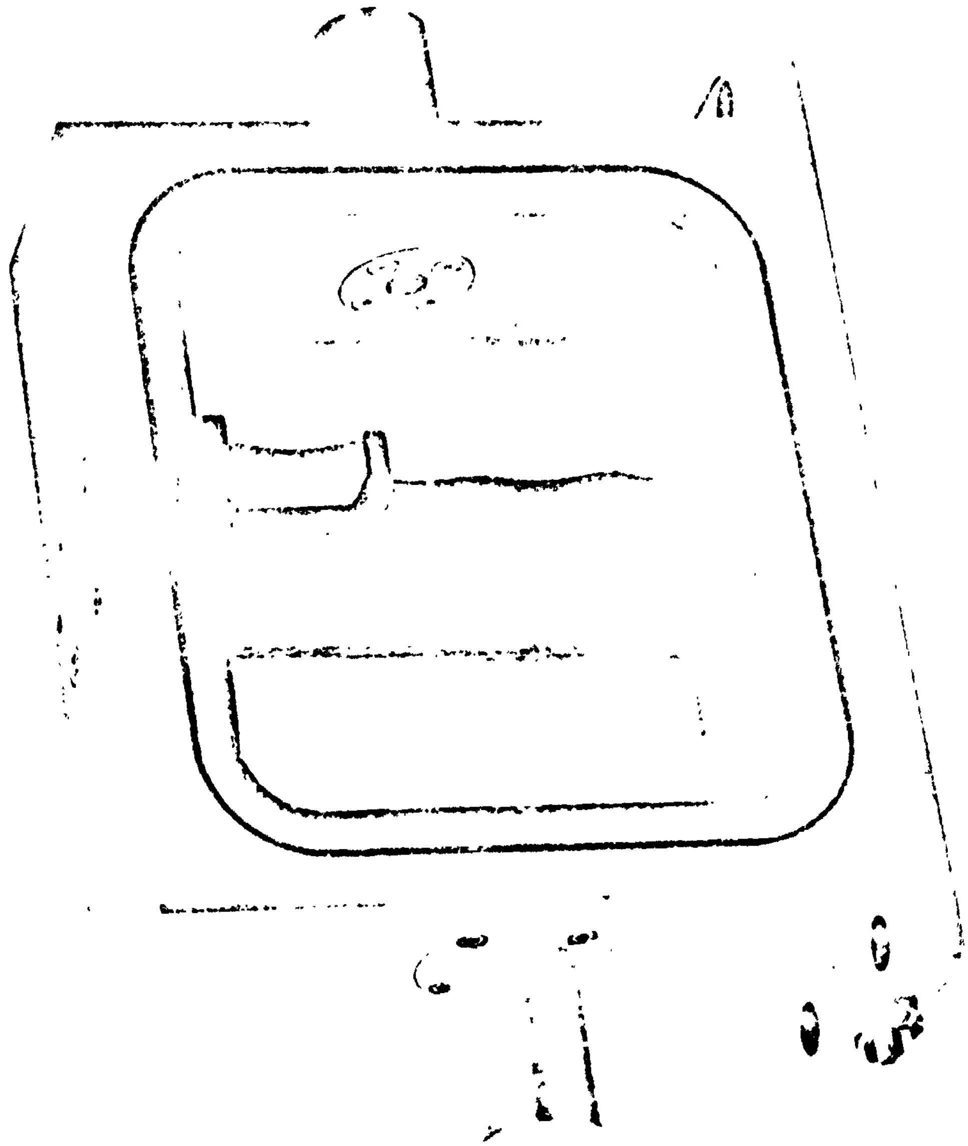

FIGURE 1 - MIT MK II ISOMETRIC HAND CONTROLLER

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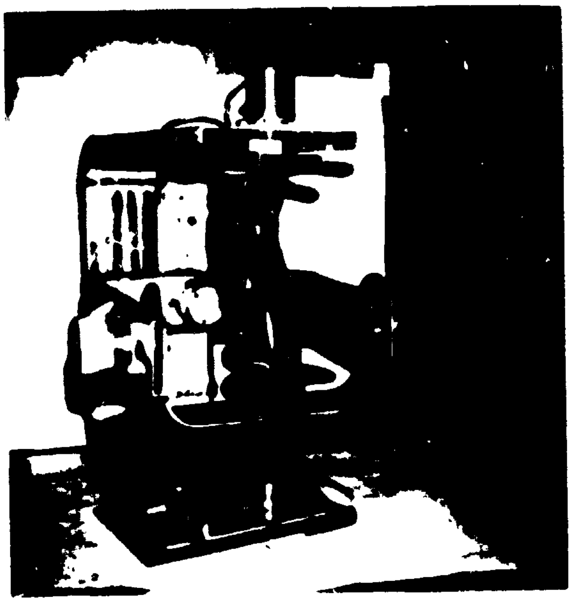
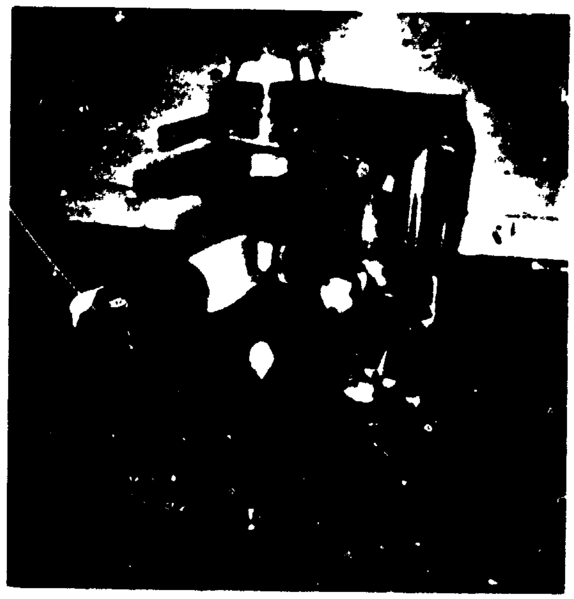


'BREADBOARD WITH CONVENTIONAL HANDGRIP

BREADBOARD WITH NEW STYLE HANDGRIP



FIGURF 2 - BREADBOARD HAND-CONTROLLER

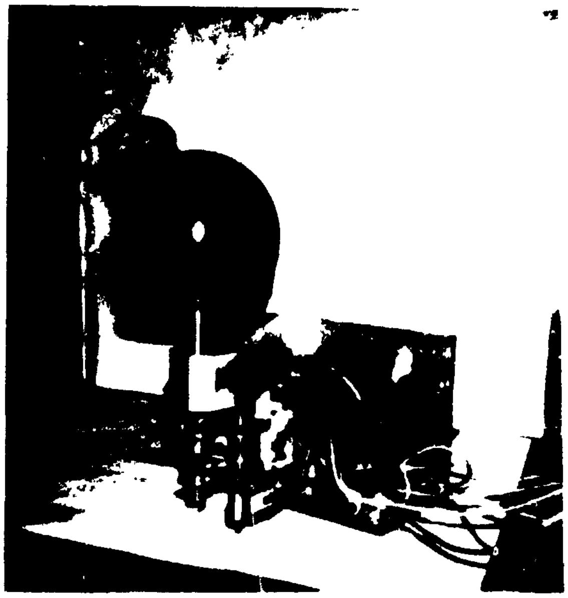


FIGURE 3 - PROTOTYPE HAND CONTROLLER