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MULTI-AXIS CONTROL OF TELEMANIPULATORS

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ABSTRACT

This paper describes the development of multi-axis hand controllers for use in telemanipulator systems. Experience in the control of the SRMS arm is reviewed together with subsequent tests involving a number of simulators and configurations, including use as a side-arm flight control for helicopters. The factors affecting operator acceptability are reviewed.

INTRODUCTION

The success of in-orbit operations depends on the use of autonomous and semiautonomous devices to perform construction, maintenance and operational tasks. While there are merits to both fully autonomous and man-in-the-loop (or teleoperated) systems, as well as for pure extravehicular activity (EVA), it is clear that for many tasks, at least in early stages of development, teleoperated systems will be required.

This paper reviews some experience gained in the design of the human-machine interface for teleoperated systems in space. A number of alternative approaches have been proposed and evaluated over the course of the work described, and some basic design principles have evolved which may appear mundane or obvious after the fact, but which nevertheless are critical and often ignored.

One key design objective in the implementation of human-machine interfaces for space is that of standardization. Astronauts should naturally and comfortably interpret their input motions in terms of motions of the manipulator or task. This "transparency" is achieved by careful design to ensure that task coordinates and views are always presented in a clear, unambiguous and logical way, and by ensuring that standardized input devices are used in standardized modes. If conventions are established and systematic modes of control are respected, training time is reduced and effectiveness and performance are improved. The end objective in the design of displays and controls for telemanipulators is to establish a "remote presence" for the operator.

THE SRMS SYSTEM

A number of manual control input devices have been used in space over the years. For the most part these devices were designed as flight controls for the various satellites and modules

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which have flown. The first truly robotic control device was that used on the SRMS or CANADARM system of the Space Shuttle. The control interface in this case consisted of two three-degree-of-freedom devices used in conjunction with a displays and controls panel, CCTV visual feedback from cargo bay and arm-mounted cameras, augmented by limited direct viewing. A Translational Hand Control (THC) allowed the astronaut to control the end point of the arm in the three rectilinear degrees of freedom with the left hand, and a Rotational Hand Control (RHC) was used in the right hand to control rotational degrees of freedom.

The THC was designed specifically for the SRMS application by CAE Electronics, while the RHC was a modified version of the Shuttle flight control produced by Honeywell. The geometry and overall configuration of the RHC was thus predetermined and was not matched to the task. The device does not have the single centre of rotation which is considered by the authors to be an advantage in generalized manipulator control. The RHC differed from the flight control version in several ways:

- The forces and travels were modified to reflect task requirements.
- Auxiliary switches and functions were changed to comply to task requirements. In fact all auxiliary switches were located on the RHC -COARSE/VERNIER, RATE HOLD and CAPTURE RELEASE.
- A switch guard was added to CAPTURE/RELEASE to prevent inadvertent release of a payload.
- Redundant electronics were eliminated in view of the reduced level of criticality.

The THC differed from the RHC in that it incorporated rate-dependent damping through the use of eddy current dampers driven by planatary gears. A hand index ring was added to the THC after initial evaluations of prototype units. The ring provided a reference for position and led to the use of the device as a fingertip control, whereas the RHC with its larger hand grip was clearly a hand control. Force levels and gradients on the THC were low, and the rate dependent damping enhanced the smooth feel of the device. The x and y inputs of the THC were not true translations, but an effort was made to optimize a linkage in the available space to reduce the curvature due to a displaced pivot point.

The SRMS system has proven to be operable but not optimal. With training, astronauts can become proficient in performing required tasks. In general, however, the tasks must be carefully programmed and significant training and practice is required before an astronaut feels comfortable with the system. Even with training, the skill of the astronaut is still a limiting factor on system capability. Tasks requiring coordinated or dextrous motions are difficult to achieve.

While there is no hard data to compare alternatives, the shortcomings of the SRMS design in part can be attributed to the limitations of the RHC and THC described above, but mainly to the unfortunate location of the two hand controls and lack of direct correspondence between the axes of the controls and those of the visual displays.

The SRMS system incorporated no force-reflective feedback aside from indications of motor parameters from each joint. Positional feedback of the end point is strictly visual–either direct viewing or through CCTV. The axes of the presented display depend on the view selected: direct, cargo bay or arm-mounted camera. Control is in the resolved rate mode. In the case of a large-scale arm such as the SRMS, a master slave or indexed position mode is not suitable because of scaling problems.

Figure 1 shows a simulation of the SRMS Displays and Controls System in SIMFAC. The RHC is located to the lower right of the D&C panel and a breadboard model of the THC to the upper left. The CCTV displays are to the right and the direct viewing ports are overhead and immediately above the D&C panel.

MULTI-AXIS STUDY

Following the design of the SRMS system, the authors conducted a study of multi-axis controls (1). The purpose of the study was to determine the feasibility of controlling six degrees of freedom with a single hand control. According to the guidelines laid down for the study, mode changes were to be avoided so that coordinated control was required simultaneously in all axes. No specific application was defined; however, the controller was to be usable either to fly a spacecraft or to "fly" the end point of a manipulator.

The study included a review of the literature, observation of available multi-axis controllers, and discussions with experts. Although a prototype device was not required by the contract, one was assembled. Interestingly, the consensus of opinion at the time amongst the knowledgeable community was that coordinated control in six axes was desirable, but probably not feasible.

A number of six-degree-of-freedom controls were reviewed. The most notable were devices with force feedback operated in the indexed position mode. A prototype laboratory version was developed by R. Skidmore at Martin Marietta and evaluated in various dynamic and graphic simulations. A similar design and evaluation was done at Jet Propulsion Laboratories by A. Bejczy (2). These devices were both unsuitable in design for implementation in a mature control system, but permitted laboratory evaluation of force characteristics, displacements, and interactions with visual feedback. Another approach was developed by D. Whitney at the Draper Laboratory. This was elegantly designed from the mechanical viewpoint, but difficult to use due to the absence of tactile feedback.

This study uncovered no mature or workable concept for a six-degree-of-freedom controller and a lot of skepticism amongst practitioners as to the feasibility of implementing more than four degrees of freedom. A more recent study of hand controls was done by Brooks and Bejczy (3).

DEVELOPMENT PROCESS

At the conclusion of the study, in spite of the climate of skepticism, the authors felt that there was no reason why a well-coordinated, six-degree-of-freedom controller could not be designed. Experiments with a variable-geometry test rig demonstrated that the only way to avoid inherent cross-coupling between axes, achieve the ability to make discrete inputs where required, and still have a direct correlation between control inputs and resulting action was to center all axes at a single point positioned at the geometric center of the cupped hand. In this way, control of the end point related to hand motions. Alignment of controller axes in a logical way to the axes of visual displays was also considered essential.

One initial concern was the issue of isometric (purely force) versus displacement control. An isometric controller is rugged and easily constructed from a mechanical standpoint. Unfortunately, the concept leads to overcontrol, particularly in stressful situations, because of the lack of proprioceptive indication of input commands. In some situations operators tend to saturate the controller to the extent that they quickly suffer fatigue. While there may be tasks in which isometric control is adequate and acceptable, in general the addition of displacement with suitable breakout gradients and hard-stop positions improves performance. For this reason, most manual controls designed on the isometric principle have been modified to include compliance.

Initial designs by the authors were based on the use of force transducers to generate input signals. The controls were designed to allow for the inclusion of compliance and adjustable force characteristics, although the device could also be configured for isometric operation in all axes. It was quickly established that some compliance was advantageous. Since there was always significant displacement, the force transducers were replaced by position transducers, thus permitting the use of rugged, compact, noncontact, optical position sensors and eliminating the tendency to generate noise signals due to vibration or shock. In addition, a purely position system made it easier to eliminate cross-coupling between axes when pure motions in a single axis were required.

An intermediate step of isometric translational axes and displacement in rotation, a so-called "point and push" approach, was unsuccessful because of the problems described above in the isometric axes.

In the final analysis, a prototype design was constructed which included significant displacement in all six axes. The prototype unit is shown in figure 2.

PROTOTYPE DESIGN

The design concept was to ensure that all six axes pass through a single point. The mechanical components and transducers for the rotational axes were mounted within a ball. The ball in turn was mounted on a stick which was free to translate in three mutually orthogonal axes. All axes had appropriate breakout forces, gradients and stop-force characteristics generated by passive components. The output of the device was a position signal sensed by optical transducers. No additional rate-dependent damping was included. While rate-dependent damping does enhance the "feel" of the controller, the additional mechanical complexity is probably not justified.

The relationship between breakout forces and gradients is task-dependent. In general, the breakouts should be sufficient that pure inputs can be generated easily in a single axis; however, breakouts do have a negative impact on controllability for small coordinated movements in multiple axes simultaneously.

Various handgrip shapes were investigated, but with the emergence of the coincident axis concept as previously described, there was a fundamental need to provide a face perpendicular to the direction of commanded motion. The other prime requirement was a shape which ensured the correct positioning of the hand relative to the geometric center of the system. The natural solution was a sphere. As development of the mechanism and sensing systems progressed, the ball size was reduced to its present configuration. This approximates to the size of a baseball, and has shown to be comfortable for bare-handed, gloved, and pressure-suited operation.

Several derivatives of the basic design evolved for special applications. A bang-bang device was configured for tests on the MMU simulator. A four-axis (three rotations on a vertical purely rate-dependent damped linear axis) model was evaluated for flight control in helicopters. In some configurations a protuberance was added to provide a tactile cue for orientation. Auxiliary switches were added on this protuberance.

TEST AND EVALUATION

To date a number of tests have been carried out. It is difficult to compare data between tests since different tasks and performance metrics were used. In general, though, subjective ratings and measures of performance were consistent and some basic design principles were established. Tests performed were

Johnson Space Flight Center

Initial tests were performed using the controller to control computer graphic representations of docking tasks.

Subsequent tests were also made using the full-scale mockup of the SRMS arm (MDF). Comparisons were made between the conventional SRMS (two three-degree-of-freedom controllers) configuration and the single six-axis device. NASA human factors personnel, technicians and astronauts participated in the tests.

Martin Marietta

The controller was evaluated with computer graphics representations of docking maneuvers.

Astronaut evaluations of a bang-bang configuration were done on the MMU simulator. Tests were performed for operation in pressurized space suits, as shown in figure 3.

Marshall Space Flight Center

A six-axis controller was used to control a six-axis arm as shown in figure 4. The system has been operated over the past 2 years with a variety of operators and tests.

Grumman

Tests were carried out using two six-degree-of-freedom controllers to control two six-degree-of-freedom dextrous manipulators as shown in figure 5. Comparisons were done with master/slave control in the same environment.

Tests were carried out using the six-degree-of-freedom controller with the LASS simulator for various "cherry picker" tasks.

National Aeronautical Establishment

Four-axis versions of the design were installed and flown in a variable-stability helicopter as shown in figure 6. Evaluations were performed by numerous military and civilian pilots, including test pilots from major airframe manufacturers. Cooper-Harper ratings were recorded for a variety of maneuvers at various levels of control augmentation. Results were comparable to conventional controls. For the most part flight tests were performed by highly experienced pilots.

It should be noted that, in the case of the four-axis version, the use of a relatively conventional handgrip superimposed on the ball was possible while respecting the principle of a single centre. The addition of another translation axis with a similar handgrip would introduce cross coupling.

European Space Agency

A model of the controller has been ordered by ESA for evaluation use in the European Space Program.

DISCUSSION

Tests to date have demonstrated that six-axis control using a single hand is not only feasible but, providing certain design guidelines are respected, preferable to approaches in which axes are distributed amongst separate controllers. Statements to the effect that six degrees of freedom is too much for one hand ignore the fact that the humans have the ability to make complex multi-axis movements with one hand using only "end point" conscious control. The coordinate transformations required are mastered at an early age and the inverse kinematics are resolved with no conscious effort. To operate a system using two separate three-axis controllers requires a conscious effort on the part of the operator, thereby increasing his or her work load. The operator requires considerable training and practice with a 2 x 3 axis system before achieving the same level of control as is immediately possible with the single six-axis device. NASA experience has shown that the weeks of training necessary for the former become less than 30 sec for the latter. While the guidelines have been verified only in specific environments for specific tasks, the authors feel confident in making the following statements:

1. A proportional displacement controller will provide improved performance and in many cases more relaxed control than an isometric device. Performance with isometric devices varies more between individual subjects than that with displacement control.

2. Force gradients and characteristics should be correlated to the task being performed. There may be a justification for standardizing force characteristics and controller configurations for all space-related equipment to ensure commonality and to reduce training requirements.

3. An obvious and consistent orientation between controller axes and those of visual feedback displays is essential. This is an area where standardization between tasks and systems is a key element. A single controller design would be suitable for all applications, provided that basic axis orientation and control mode standards are maintained.

4. The use of force-reflecting feedback has not been evaluated by the authors, although a program is under way to investigate some unique and novel approaches. In general, direct force feedback is useful only in a system with high mechanical fidelity. In the presence of abrupt non-linearities such as stiction or backlash and particularly transport lag force, feedback can in fact be detrimental in excess of 100 msec.

5. For some tasks with some manipulators, a master/slave system can provide equal or superior performance to that of a manual control in resolved-rate mode. Resolved rate is, however, universally applicable and can provide a standardized approach for virtually all manipulator or flight-control tasks.

6. In tasks in which lag exceeds 1 sec, it may be assumed that real-time interactive control in the strict sense is not feasible. Providing physical relationships are stable or static, a reconstructive mode using generated graphics for a "prehearsal" of manipulator movement may be used, stored in memory, then activated. When lags are 100 msec or less, resolved-rate control may be used to directly control the end-effector (position control is inadequate when any substantial excursion may be required). The lag regime between 100 msec and 1 sec causes difficulty because there is a tendency to compensate for delay or system instability (e.g., arm-flexing modes) with more complex drive and "prediction" algorithms. Our experience thus far is that the simplest control algorithm which permits stable response generally provides the best performance.

In conclusion, tests have shown that six-degree-of-freedom controllers can be used naturally and effectively to control tasks requiring dexterity and coordination.

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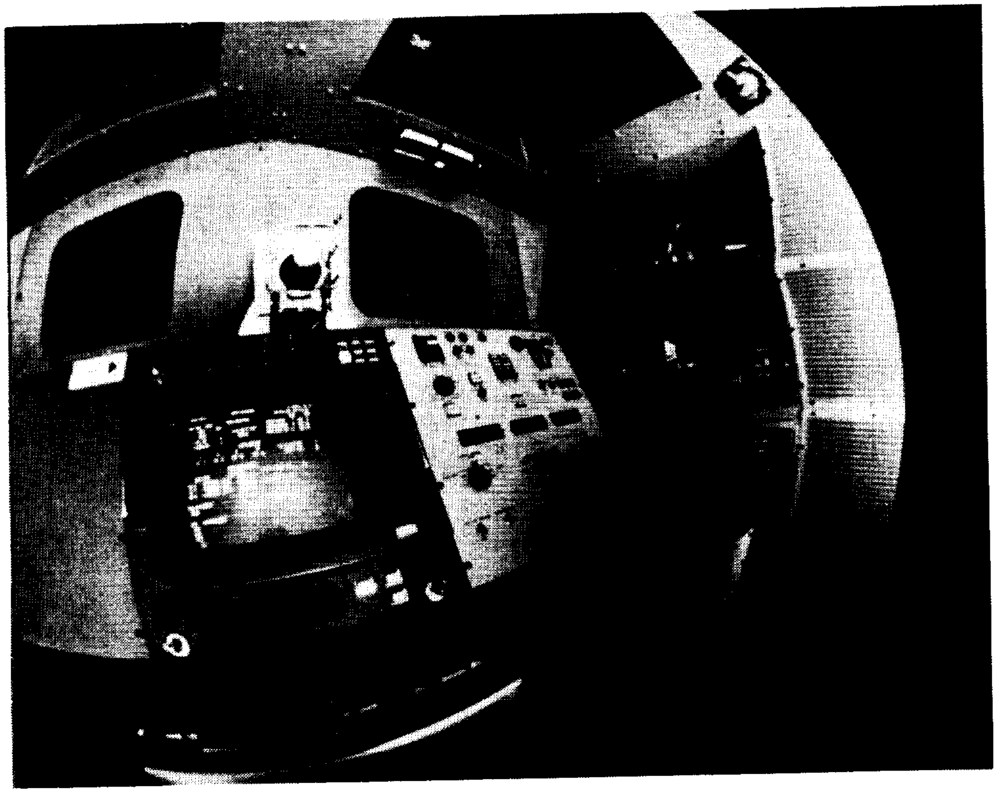

Figure 1.- SIMFAC.

Figure 2.- Six-degree-of-freedom prototype.

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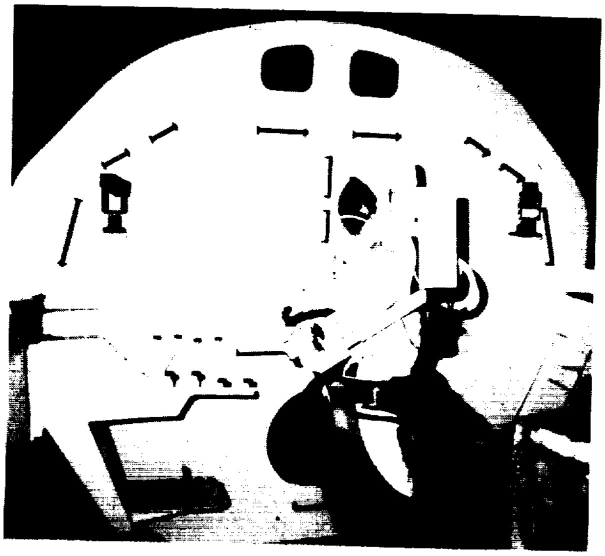

Figure 3.- MMU tests at Martin Marietta.

Figure 4.- Control of robot at Marshall Space Flight Center.

Figure 5.- Simultaneous control of two arms.

Figure 6.- Four-degree-of-freedom controller installed in helicopter.