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Informal Discussion

Multi-axis Hand Controller for the Shuttle Remote Manipulator System

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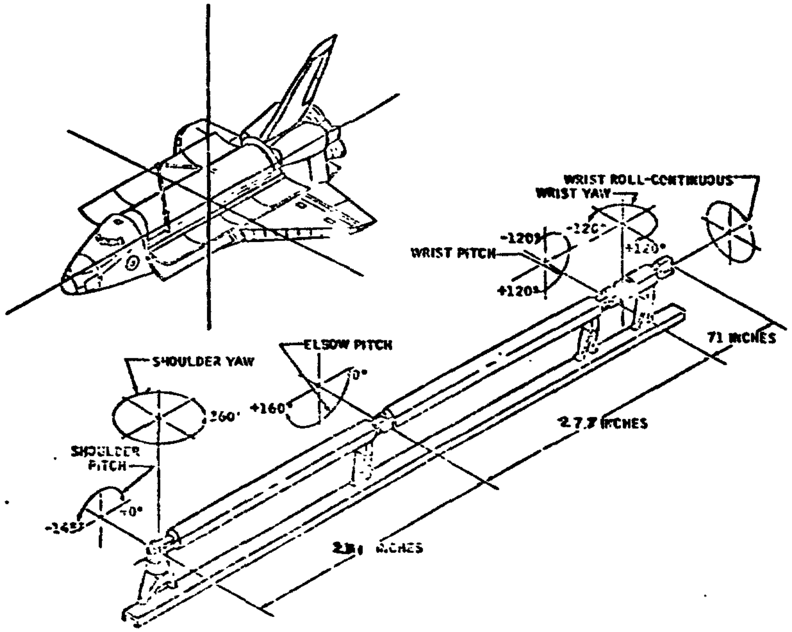

INTRODUCTION

The Shuttle Remote Manipulator System (SRMS), a Canadian contribution to the NASA Space Program, has an articulated arm of 50 ft. length with six motor-driven joints. The basic purpose is to establish physical contact with various space hardware items and maneuver these to the desired position and attitude with respect to the Orbiter, nulling out relative velocities and stabilizing the free-body system by managing residual energies.

The normal operating mode is resolved-motion end-point rate control by man-in-loop command. The translational freedoms are defined so that the End Effector (EEFTR) of the arm will move in planes parallel to the principal translational planes of the Orbiter, at a rate commanded by the displacement of the Translation Hand Controller (THC) in the corresponding freedom and direction. The rotational freedoms are rate-controlled by the Rotation Hand Controller (RHC) about pivot axes parallel to Orbiter roll, pitch and yaw, originating at the EEFTR reference point. Both sets of coordinates may be transposed to the EEFTR or to the mass/geometric center of the Payload, by appropriate software selections and adjustment, following which the freedoms will be defined by the EEFTR or Payload attitude with respect to the Orbiter.

The THC and RHC form a bi-manual controller complex with six individual axes of freedoms, each of which may be displaced individually or in any combination to effect coordinated (vectorial) movement. The system depends on computer augmentation for end-point control and for semi-automatic and fully programmed sequences selectable by the Operator. Joint-by-joint control is available with computer support and by a hard-wired direct manual control system provided to permit the orderly termination of a mission under contingency conditions. The THC and RHC are not utilized in the joint-by-joint mode.

Weight and envelope constraints limit the manipulator arm strength to 10 lbf applied to the EEFTR at right angles. Fully extended, the arm will then deflect 1.0 in. The largest planned Payload has a mass of 65,000 lb in a 60 ft long 15 ft diameter envelope. Structural modes of the loaded arm will permit Payload movement at rates and accelerations similar to those caused by the arm responding to drive inputs. Clearances in the Cargo Bay are in the order of 3.0 ins. Most of the larger Payloads will have complex contours and appendages easily damaged by even a light collision with the arm or the Orbiter. The Orbiter itself will be unable to land if one of its Cargo Bay door hinges is damaged and will burn up on re-entry if one of its ceramic tiles is cracked. All of this indicates that smooth, coordinated and transient-free operation of the SRMS is an essential requirement.

The development effort and manned test results carried out to date to produce a Translation Hand Controller suitable for this task will be the topic of this discussion.

CRITERIA & CONSTRAINTS

It is a well-known fact that each new manual control application has its own characteristic requirements and that the controller must typically be unique and compatible with the particular system and its task, in order to achieve proper functional matching at the man-machine interface. The problem is not so much that of providing the various components that will generate the necessary inputs for the machine, as it is one of packaging them into a device that can be operated as a comfortable hand tool in spatial harmony with the overall system task under all conditions, and that will generate proprioceptive feedback to instill confidence and to enable the human sensory system to be convincingly projected into the task area, with an acceptable workload. Rigorous system identification and elegant mathematics frequently overshadow the importance of the basic physical and handling qualities of the hardware in direct contact with the human neuro-muscular channels, and only the great adaptive capability of the operator enables him to compensate for these imperfections and still predict system response.

Orbiter cockpit layout, size and weight constraints have defined many of the design parameters from the start. The THC envelope was not to exceed 6 x 4 x 4.5 inches. This and limitations in weight and available computational capacity ruled out an active force feel feedback system. (Development of a single-input-point command device was denied as a high schedule and design risk item.) The THC-RHC complex must be operable by 5th percentile female to 95th percentile male Crewmembers. All will be elevated to the same design eye point approximately in line with the center of the aft window. Configuration "G" of a NASA-JSC study of controller locations places the THC near shoulder height and some 11 inches left of the body centerline. This is currently used as a baseline.

Conceptual design specifications required a ± 2.0 ins or arc-ins travel on each axis for adequate manual resolution. From previous experience, a deflection-type action was preferred to a force-stick. Input rate limiting (damping) was to be generated by the THC rather than by electronics further downstream, in order to preserve tactile feedback. Springloaded return to zero was required, so it was decided to initially set the maximum rate-dependant resistance equal to the maximum deflection-dependent forces, the sum never to exceed 10 lbf in view of the weightless operator. The spring system was to be preloaded to provide a breakout step force and identify the null point on each axis. A detent cartridge has been designed but not tested so far. All of the above was based on best estimates of system characteristics and on maximum permissible energy transfer through the arm, since no valid model existed at the time. In order to enhance display dynamics and facilitate predictive control, a quickened command/actual display was proposed, but this became impracticable when the rate meters were deleted from the SRMS panel design.

Rate-dependent damping was seen as the most appropriate passive means of generating input rate feedback, force feel, static and motional stability. Viscous dampers offered acceptable unit size for the force levels, convenient adjustment and freedom from the very objectionable stick-slip characteristics of other friction devices. Viscous damping in manual controllers is by no means new, but some unexpected observations will be related here.

TEST OBJECTIVES & APPROACH

A THC Demonstration Model has been built by CAE Electronics in Montreal to verify that adequate mechanical design and handling qualities can be contained in the envelope specified, and to set the initial force feel variables. Design recommendations would then be made based on manned testing.

The Model was equipped with a T-bar handgrip, vertical at first and rotated to horizontal for the final tests. The Hand Pressure Point (HPP) was defined as the intersection of the stem with the T-bar and all travels and forces were referred to this point. Angular displacements of ± 12 deg or ± 1.0 arc-ins constituted the vertical (Z-axis) and the lateral (Y-axis) freedoms. The X-axis was mechanized as a ± 0.55 in linear displacement, the maximum permitted by the enclosure.

Control laws of the SRMS and a task presentation software were inserted in a real-time digital facility associated with the SRMS modelling and software development effort at CAE. A kinematic model of the arm was lagged by arbitrary time constants of 3.0 sec in all axes to approximate dynamic behaviour of the loaded EEFTR. The task software was designed to drive or position a target, to accept command inputs and move a cursor symbol, EEFTR and to calculate vectorial and partial error (X, Y, Z) and partial rates on line. The resulting tracking task was presented to the Test Operators on a 23 in CRT as two triangular symbols of different color. The target moved vertically, laterally, rotated to represent Orbiter-referenced roll, and varied in size according to its computed distance to the observer, all within the geometry of the Orbiter Cargo Bay.

Positioning, rate-tracking and trajectory-control task modules were developed, totaling more than sixty, designed to elicit single-, two-, or three-axis inputs from the Operator, i.e., exercise the hand controller in any axis or combination desired, from full-scale maximum-rate displacement to minimum amplitude precision adjustments. Quick-stop maneuvers were included to simulate an error in the original estimate of the target position or trajectory. The roll axis was also available but seldom used since the available Apollo ACA and a breadboard RHC model were not representative of the SRMS requirements. Wherever possible, the task simulated events and controller activity expected to be seen in SRMS missions.

Performance data were collected on disc and recorder hard copy, showing the command activity in each axis, the vectorial error and its time integral. No statistical analysis was performed since the basic objectives could be achieved by inspection and debriefing, but full performance analysis will be executed probably following SRMS system integration.

The Operator, the THC Model and the Task Display were enclosed in a darkened cubicle with reasonable isolation from external noise and disturbances. A simple set of blocks was used to elevate their eyes to the center of the CRT serving as the aft window. The THC handgrip and the (inactive) RHC were installed in representative positions according to NASA Configuration G, the latter used as a hand positioner.

RESULTS & CONCLUSIONS

Two Test Operator groups consisted of one 5th percentile female, a medium and a tall male subject each. The females had little or no man-machine experience, the males were familiar with the SRMS and its tasks. Two had had previous practice during the shakedown trials, the other two had extensive control experience in aircraft and flight simulators.

Sixteen tests were conducted with the initial force settings. Eleven tests, essentially repetitions of the above were performed with the dampers disconnected. Five further tests had the T-bar handgrip oriented horizontally and the damping set at 50% of the initial value. Each data run was repeated three times. Operators were immediately debriefed by discussing the command traces and having them explain their strategies, difficulties and general assessment of the task and controller. This method produced meaningful information in quantity and identified patterns of agreement.

Operators reported the visual presentation to be reasonably convincing, and produced consistent and repeatable results, despite the very simplistic symbolic imagery. The dynamics seemed to be more important, as was to be expected. Some visual problems did exist, e.g. poor depth perception at 50-55 ft range, due to the increase/decrease of image size being a step function of the CRT raster line dimensions, but similar difficulties will exist in real life due to optical effects.

Spatial correspondence was good, very few starting errors were noted. The two angular freedoms were used simultaneously by instinct, and were reported to have sufficient travel, good positional feedback and little tendency to unwanted inputs. Rotating the handgrip to horizontal relieved the tensions at the wrist without affecting this assessment, but removal of the damping degraded the perception of the null position. The latter was an observation not encountered before.

The fore-aft (X-axis) travel was found marginally insufficient and the spring forces (2.4 lbf for full scale) created a tendency to drift, especially with the damping removed. Operators tried to establish a finger reference point by touching the casing or the gimbal sleeve with their middle- and index fingers. A two-ring finger fixture will be added as a design improvement. The experienced operators would have preferred a detent-type null identification with damping.

Command traces show typical patterns for male, female, expert and novice Operators almost to the point where individuals could be identified by their command signatures and error performance patterns. The experienced Operator applied coordinated inputs in all required axes and proceeded to reduce the vectorial error in a straight-line fashion even when the target was unexpectedly moved. The female subjects tended towards a bang-bang method with high peaks, especially when making small adjustments with low amplitudes. Cross coupling was more evident than with the males, but the traces identified this as a result of their shoulders being as much as eight inches out of line with the controller, making orthogonal movements difficult. All operators were required to keep their right hand on the RHC as a hand positioner. The undamped controller induced more cross-coupling and bang-bang inputs in all operators.

A consistent coasting approach was developed with the lagged positioning tasks, as a learning effect. The cursor was accelerated vectorially towards the target, then the commands were nulled so as to arrive at a point corresponding to eight feet from the "Payload Grapple Point". Small additional inputs were then used to cover the target, the experienced males using coordinated displacements, the females tending to small spikes. When asked to use a minimum of time, Operators maintained the rates longer, then applied counter-commands to assist in the deceleration. This has not been validated as an acceptable command strategy but harmonious and instinctive use of the THC was again indicated.

Some inter-controller coupling has been noted, mainly due to the wide separation of the THC and RHC, as shown by the case of the small percentile female Operators. This will be further explored as soon as an engineering quality RHC becomes available, but controller force patterns are expected to provide an adequate solution, in the light of the following discussion.

Operators agreed that the handing qualities, and particularly the rate-dependent damping was a key factor in their assessment and use of the controller. The command traces show more coordinated (vectorial) inputs, less cross-coupling and overshoots, and generally less command activity with the damped controller. On-line voice-taped comments and debriefings proved this to be more than the physical restraining effects of the viscous friction; operators commented on the static and motional stability, reported a more confident approach to the estimated inputs required, and consequently produced less hunting and overshoots. They even claimed to derive positional information from the damping resistance, not attainable from spring forces alone, which is surprising in view of the low levels used, but which explains the reduction in drift and improvement in long-term maintained inputs. From the systems point of view, a marked reduction of transients, and better coordination in at least two axes were the most significant results ascribed to the controller handling qualities.

RELEVANT OBSERVATIONS

When assessing controller forces, Operators are not aware of the difference between spring rates and damping as such, but their remarks and command behaviour indicate the effects related to each. Generally, low forces are preferred, especially by the female subjects, but all agree that some damping is necessary for stability and force feel. With the short travels typical of the sidearm controller family, spring rates do not yield adequate information on deflection, and tend to cause drift as the haptic receptors accommodate to the stick pressures. The SRMS requirements, except for the hands-off return to zero, could probably be satisfied with hand controllers having optimized rate-dependent forces and adequate null identification (detent or electronic notch.). Adjustment of such a system is far more convenient than replacing the special springs normally found in hand controllers. Individual operator preferences and wide variations in the task dynamics, Payload mass etc. could be accommodated this way even by a passive system.

The command behaviour of the small-frame lightweight subjects in unity gravity, i.e. a tendency to spiky inputs and bang-bang modes, may well be indicative of future problems with lightly restrained Orbiter Crewmembers in zero gravity. Photo exhibits at NASA-JSC show a Skylab Astronaut holding onto a countertop with one hand, wrapping three fingers of the other around the base of a lollypop-type controller while deflecting it with thumb and index finger against spring tension. The SRMS Operator will be restrained at the feet and probably at the waist, but will need to use both hands, often simultaneously, on a number of controls in a coordinated manner. Force patterns will again yield essential feedback.

When the T-bar handgrip of the THC was rotated from the vertical to the horizontal, the lateral axis suddenly became "too sensitive", although no parameters related to stick gain have been altered. In retrospect, the horizontal grip required arm movement as against wrist deflections, and produced less position feedback than the vertical grip. Operators applied excessive inputs and saw excessive responses. A similar effect in reverse can be observed in flight simulators where the (purposeful) degradation of the motion cues brings complaints about the control forces being too heavy, when in fact the response has been made inadequate. During this period the dampers of the THC have been disconnected and the spring forces could not generate the expected resistance. In the other two axes the Operators used fingertip touch and wrist deflections, and were able to compensate for the lack of damping, but complained of "white knuckles" effort to stabilize the handgrip.

The comments of the Operators reacting to the task presentation and to questioning by the Test Conductor strongly support the concept of an "inner model" whereby an active picture is developed of the task and the system, probably at a high cranial level. This fast-running model responds to all sensory inputs and generates outputs in an outer-loop fashion, involving complex pattern recognition and predictive processes. The system outputs or controlled variables must then display corresponding behaviour as expected, to match the model. The same phenomenon is very much evident in observations involving pilot assessment of flight simulators, various man-machine combinations and the control and acceptance of powered artificial limbs. In the latter case, the concept of "body image" is widely recognized in physical medicine.

It appears that dynamic effects, especially in the short term, are particularly significant in satisfying the expectations of the inner model; pictorial details and accuracy are of secondary importance. (However, motion-visual relationships and phasing are critical, such as in the case of whole-body and vestibular motion cues.) The haptic proprioceptive sensors can derive direct and significant information from the dynamic handling qualities of the hand controller and enhance the integration of man and machine.