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MANNED SIMULATIONS OF THE SRMS IN SIMFAC

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INTRODUCTION

SIMFAC is a general-purpose real-time simulation facility currently configured with an Orbiter-like Crew Compartment and a Displays & Controls (D&C) Subsystem to support the engineering development of the Space Shuttle Remote Manipulator (SRMS).

The simulation consists of a software model of the anthropomorphic SRMS manipulator arm including the characteristics of its control system and joint drive modules. Structural flexibility is modelled by presenting the principal modes in six degrees of freedom.

The SRMS control system is normally operated in a Resolved Motion Rate Common mode, commonly known as the Manual Augmented or simply Manual mode. The point of resolution if just inside the tip of the End Effector of the arm, where the head of the Payload Grapple Fixture would fall when in the nominal position for legal capture. A Single mode is also available for selection, whereby the Operator individually commands each joint in turn. In both of these modes a Coarse/Vernier range may be selected, and Rate Hold function may be applied in the Manual mode.

Four coordinate systems may be selected which define the point of resolution and the spatial system response to hand controller inputs. The principal reason for this is to enable the Operator to move the End Effector (and the Payload when attached) in the most direct way possible and reduce the amount of mental transformation required.

Automatic sequences are available to manoeuvre the arm between fixed points. A terminal position and attitude may be determined by pre-programming or by detailed Operator input via a keyboard. The system will move in an optimized path to the terminal point, provided the initial conditions have been fulfilled.

SIMULATION & SCENE GENERATION SUBSYSTEMS

A master/slave computer pair (TI 980B), an Array Processor and floating-point hardware complex execute all computations under a simulator-oriented multi-task operating system (SIMTOS), driving a multi-process interface to which all displays, instruments and other input/output circuitry are connected. An extensive set of peripherals perform data gathering and software development/maintenance tasks.

Displays in SIMFAC are driven by a set of three Varian computers (V73), an array processor and picture generation hardware. An Aft and an Overhead out-the-window scene are presented on two large CRT screens equipped with pancake windows to approximate infinity optics. Two smaller monitors simulate CCTV scenes from six possible camera positions in selected pairs. Of these the camera mounted on the wrist of the arm seems to carry the greatest impact and will be discussed in detail below.

The visual presentation is driven by a serial data link output from the simulation subsystem, delivered every 50 msec, the pictures are refreshed three times between the frame updates. Camera controls enable the Operator to zoom all cameras, and to pan and tilt all except the End Effector (Wrist) Camera.

Cockpit displays and controls resemble the Manipulator Station of the Orbiter. Mode selector switches, digital position/attitude/rate readouts and a comprehensive Caution & Warning annunciator panel are mechanized and driven by the main model outputs.

A Translational (THC) and a Rotational Hand Controller (RHC) are mounted to the left and right of the D&C panel. The THC has one linear and two pivoted axes in a package representing the flight article. It controls the rates of movement in the X, Y and Z freedoms of the point of resolution in the coordinates selected. The RHC has three pivoted axes and controls the attitude (angular) rates about the point of resolution. It also carries the Rate Hold, Capture/Release and Coarse/Vernier auxiliary controls. The THC has rate-dependent damping, both have spring return and breakout forces.

Caution/Warning annunciators include a Master Alarm coupled with an audio tone, and a lighted annunciator panel. The two most frequently activated are the Reach Limit Alarm, indicating that one of the joints is too close to its angular limit, and the Singularity alarm signalling a limited arm geometry such as that of the arm at rest in its latches, fully extended and unable to accommodate an applied load by yielding to excessive forces.

The manual control problem can be appreciated by considering that the design load limit of the arm is a deflection of 25.4 mm (1.0") under a lateral force of 4536 g (10) lbs, with the not-to-exceed limit being 4763 g 15 lbs. Software stops provide protection by refusing to drive a joint into its hard stops and arm movement ceases completely if the Reach Limit alarm does not result in the reversion of the manual inputs.

THE SRMS TASK IN SIMFAC

The principal task of the SRMS Operator is to manoeuvre the arm and its End Effector into a precise position and attitude with respect to the Payload in order to establish a rigid contact with the Grapple Fixture, and thence manoeuvre the Payload into the desired position and attitude with respect to the appropriate coordinate references, with zero residual energy remaining in the total system. In real life, the End Effector must not contact the Payload until the latter has been secured against escape, and must not touch any other part except the grapple fixture. The Payload may initially be moving with respect to the Orbiter or it may be docked and secured in the Cargo Bay of the Orbiter. Relative velocity in excess of 0.061 m/s (0.2 fps) constitutes an illegal capture condition where contact must not be attempted. The arm must arrest the Payload within 608 mm (2.0 feet) after Capture. The positioning accuracy must be such that the maximum size Payload 18.24m long, 4.56 m dia (or 60 feet long x 15 feet diameter) can be placed into the Cargo Bay with an all-around clearance of 76.2 mm (3.0 ins).

In the case of the simulated moving Payload, the Operator must establish stable tracking with the End Effector before attempting to grapple, in approx. 80 secs. from the time the Payload enters the effective reach envelope of the arm. This phase is the most dynamic of the entire control task and will be the principal subject of discussion from here on. The tracking and eventual capture are based almost exclusively on the visual information provided by the CCTV camera carried by the arm. This scene is presented on a small CCTV monitor to the right of the Operator with a reticule applied to the glass envelope. This "gunsight" scene has a significant impact on the Operator; any high rate of movement or oscillatory behaviour generates a high gain condition in the external man-machine loop, increases the workload and may lead to PIO (Operation-Induced Oscillations). Among other things, it encourages capture attempts "on risk", i.e. without the assurance of being within legal limits. Since the camera is simulated as mounted on the wrist, a less than stable platform, arm flexibility effects generate just such visual dynamics, in addition to those produced by the real movement of the Payload with respect to the End Effector. Furthermore, the Operator is not positioned on the same platform, hence he will not receive motion cues to help him compensate for the lively visual scene.

A less dynamic but equally difficult situation ensues when the principal axes of the Payload or the End Effector are displaced from being parallel to those of the Orbiter. The four available coordinate systems recognized by the control algorithm are referenced to the End Effector, the Orbiter, and the Payload, respectively, and the fourth is divided between the Payload for attitudes and the Orbiter for translations. Euler sequences destroy the spatial correspondence between the hand controllers and system response where the coordinate system in use moves with the Payload or End Effector, but the Operator remains "frozen" to the Orbiter. Furthermore, a coordinate system, consistent in the engineering sense, will generate contradictory display increments and cause wrong-sign inputs unless its sign convention is duly adjusted to conform with the aeronautical "positive" and "negative" in terms of switch or stick movements.

In summary, the SRMS command task is somewhat similar to flying a airplane by remote control, rather than that of piloting an aircraft.

OPERATOR TACTICS AND OPTIONS

Successful Operators in the SIMFAC simulations have quickly learned to accommodate the basic system responses and developed individual but similar command techniques. In the capture task they eliminate attitude errors first, in Coarse mode at a safe distance from the Payload, then use long, smooth approaches, maintain tracking. They apply ramped, well-damped command inputs to avoid flexibility effects and to reduce the image displacement rate on the End Effector gunsight scene. One attitude and one translational correction is applied as a pair to avoid roll-pitch cross-coupling and to minimize target displacement on the CCTV scene. Trained Operators maintain a good inner image of the arm geometry and are able to avoid joint angle limits, estimate the total arm performance available and even trade-off rotational vs. translational corrections for a smooth and efficient approach. The SIMFAC hand controller characteristics are said to make a significant difference against earlier models which had no damping and generally poor engineering quality.

Operator options such as Vernier selection which reduces the command authority to 10%, and Rate Hold, are used by all Operators, the former mostly to reduce the liveliness of the gunsight scene and to increase precision as required. The system applies Vernier automatically on Capture, i.e. during the transition between unloaded and loaded arm, and a manual selection reduces the Loaded Vernier velocity to 50%.

WORKLOAD

A peak is reached during the Track and Capture task. Arm flexibility effects appear in the CCTV reticule as elliptical oscillations, easily excited with high visual effects especially at close range. However, they damp out if not further excited and true PIO does not develop. The spare Operator capacity is significantly reduced, the gunsight scene is the focus of intense concentration. The selection of Vernier is easily predictable for most Operators, as a function of range from the Grapple Fixture, since it is determined by their acceptance of activity on the CCTV scene.

Other sources of increased workload include the necessity to make ramped inputs to command precision movements, to perform mental transformations in Payload manoeuvering and the management of the D&C subsystem, especially while operating in the Single mode, controlling each joint individually. Ramped inputs require high concentration over many seconds; well-balanced and damped hand controller characteristics are essential. Coordinate transformations also require high mental effort during the final phases of Payload positioning, since a wrong-sign input will not only disturb a near-perfect deployment condition, but many cause collisions during the berthing task, with the Payload in close proximity with the Orbiter.

Displays and Controls Management involves mode selection and display selection, since all parameters cannot be simultaneously displayed; XYZ position and pitch-yaw-roll attitude must be selected for digital display readout. Mode selection must be followed by an Enter command to be accepted by the system. The Single mode involves not only display selection (associated with the tasks the mode is normally used) but also the selection of each of the six joints followed by the operation of a double-throw switch for positive or negative input.

In summary, the Resolved-Motion Rate Control system provides adequate means to control the manipulator arm by one Operator as specified for the SRMS tasks. Research work at MIT, NASA/JSC, NASA/Ames and NASA/Marshall have been compared with some experimental setups at Martin-Marietta, as well as Honeywell and CAE experience in fly-by-wire applications, and command philosophies such as the replica arm and force-stick controllers have been considered but later rejected in favour of the displacement stick and rate command with resolved-motion augmentation. A six degree-of-freedom controller would have been favoured for a single/command/input point but had to be abandoned for lack of cockpit space and because of higher design risk.

OPERATOR ERRORS AND SOURCES

Up to the time of this writing, the main SIMFAC effort was directed to validate the flexible arm and SRMS subsystems simulation, and to establish basic controllability and operability for the tasks specified. Initial work has been completed to simulate malfunctions and off-nominal conditions to verify procedures and indicate parameter sensitivities. No attempts have been made to simulate side-tasks, Orbiter environment and on-orbit workload. However, comments of Operators have been carefully recorded and analyzed, and their assessment of their own performance was elicited whenever practicable, both in terms of the simulation and the simulated SRMS tasks.

Short of malfunctions, the reference coordinate systems and sign conventions presented the greatest single problem as soon as human operators were inserted in the control loop.

The End-Effector CCTV scene with its reticule is essentially a fly-to display. One of the Alignment Aids (Payload target) resembled the small aircraft symbol usually found on artificial horizons and flight directors. An Operator with long flying experience promptly reverted to the fly-from technique associated with that type of instruments and has had considerable trouble in readjusting his thinking during the demanding Track and Capture task. With a different target he had no difficulty.

Arm geometry causes non-linear responses due to limitations in the individual joint drives, necessary to ensure that the End Effector does not exceed certain velocity limits. Finite joint ranges and arm singularities also cause uncommanded stoppages. While most of these effects can be avoided or accommodated by trained Operators, the visual conditions in SIMFAC do not provide texture, hardware markings, shadows and other assistive side effects.

Visual conditions in the Space Shuttle are expected to vary between extremes, from sunshafting and specular reflections to near-total darkness. Wide variations in illumination will occur with every adjustment of the Orbiter attitude or Payload position. Judgement of depth or X-ranging is expected to be poor in real life as it is in SIMFAC, with its two-dimensional visual displays.

The dynamic aspects of the SIMFAC visual presentation are quite adequate. However, the SRMS task itself produces low-key visual cues with low dynamics, difficult to detect and monitor. A 18.24m (60 ft.) long Payload suspended say 15.2m (50 ft.) away from the Operator may have a very low yaw rate but its end bulkheads move with relatively high speed, and may contain great energy with the maximum Payload mass of 29,484 Kg (65,000 lbs). Furthermore, arm flexibility effects and control system responses are very similar in their visual aspects under certain circumstances near the Cargo Bay, potentially inducing the Operator into erroneous corrective action.

The SIMFAC Displays and Controls Subsystem resembles the Orbiter complement but is not completely representative of it and lacks some of the visual impact of the flight article. The hand controllers are engineering model quality but well engineered and have acceptable force characteristics and feel.

The harmony of manual input to system response is generally good, the controllers providing a one-to-one relationship with the desired Payload or End Effector movement. The displays follow the system responses adequately and present necessary and useful task information. However, the harmony between the command inputs and the display responses is not optimized in that the position and attitude information is referred to the Orbiter, while the command axes may be transferred to the End Effector or Payload. Hence, the same manual input will drive one display window or another, depending on the Euler angles. The Operator then has to compensate with mental transformations and therefore is prone to errors and incorrect inputs. This effect is most noticeable in precision manoeuvres during Berthing and Payload Deployment, when the Operator is "flying the Payload on instruments", i.e. making final adjustments by the digital displays. This observation on SIMFAC resulted in a change of SRMS coordinate systems and displayed values.

The management of displays and controls is a significant side task with some peak workloads occurring in parallel with other high-activity periods.

AREAS FOR FURTHER WORK

Visual improvements are being planned for SIMFAC. Full hidden line removal and additional scene contents are considered. As noted above, the dynamics of the visual scenes are largely satisfactory and carry a high impact.

Orbiter-SRMS interaction, namely reactive forces and the operation of the Orbiter attitude control systems, have not been fully simulated in SIMFAC.

Man-machine integration and rigorous Operator modelling work would be most desirable from the resarch point of view, since these are outside the scope of an industrial development. Multi-axis hand controllers, computer-driven active force feel systems, integrated displays may be needed for future generations of Remote Manipulators. The loop dynamics exhibited by the wrist camera in this simulation in connection with the human visual and neuromotor channels is peculiar to large manipulators and presents a set of interesting modelling tasks in itself.

GENERAL OBSERVATIONS

The simulation as a whole is considered successful, judging from the reaction of Operators to computer glitches and malfunctions. These indicate that the experienced Operator is very much in the simulation picture and is using his best efforts to perform the task.

Learning curve effects are readily visible and repeatable, well documented. The task presented in SIMFAC, that of capturing a free-flying satellite and berthing it into the Cargo Bay is deemed equivalent to the worst case task expected to be attempted in real life.

Quick setup and initialization capability of SIMFAC facilities manned simulation under reasonably consistent conditions.

The observed command strategy and Operator behaviour, as well as individual performances, clearly indicate not only the existence of an "inner model" but the necessity of one even in the static sense, whereby some Operators manage to maintain a picture of arm configuration regardless of arm visibility, and avoid potential joint limits, singularities and collisions.

Some Operators perform equally well in dynamic and precision manoeuvres, others exhibit a distinct preference and success in one or the other. No explanation is offered at this time except the possibility that the force characteristics of the hand controllers may have enhanced competence in some cases by matching the individual neuromotor systems.

The flexibility of the dynamic arm presented a distinct increase of task difficulty compared to the kinematic arm model, but all operators managed to adapt their input rates and control strategies to overcome these effects. It may be noted that both the increased dynamics in the wrist camera scene due to flexibility, and the absence of an alignment aid target, led to attempts to capture with less than proper alignment or at a questionable capture distance.

Simulated malfunctions presented in SIMFAC generated three distinct phases of response in each Operator participating in the tests. At first, a malfunction was immediately considered on the SIMFAC system, i.e. a simulation error. No corrective action was attempted. In the next phase, most Operators blamed themselves, claimed Crew Error and tried to rectify it until they realized that the corrective commands were ineffective. Finally, absolutely everything out of line was suspect, and immediately questioned as to which malfunction is being presented.

From the point of view of man-machine integration, the external loop composed of the Operator, the Wrist Camera display and the behaviour of the End Effector due to flexibility effects and arm geometry present a intricate problem. It is impossible to analyze these relationships on paper and understand the wide range of factors involved, many of which are intangible, such as the aeronautical control conventions ingrained in Operators with piloting experience. SIMFAC has some shortcomings; to be sure; the visual scenes lack texture, reflections and shadows, contrast and similar effects, but the dynamics of the presentation are sufficiently convincing to point out flaws in the man-machine interface and to validate system stability and operability with man in the loop.