COMPUTER SIMULATION OF ON-ORBIT MANNED MANEUVERING UNIT OPERATIONS

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ABSTRACT

Simulation of spacecraft on-orbit operations is discussed in reference to Martin Marietta's Space Operations Simulation laboratory's use of computer software models to drive a six-degree-of-freedom moving base carriage and two target gimbal systems. In particular, key simulation issues and related computer software models associated with providing real-time, man-in-the-loop simulations of the Manned Maneuvering Unit (MMU) are addressed with special attention given to how effectively these models and motion systems simulate the MMU's actual on-orbit operations.

THE WEIGHTLESS EFFECTS of the space environment require the development of entirely new devices for locomotion. Since the access to space is very limited, it is necessary to design, build, and test these new devices within the physical constraints of earth using simulators. The simulation method that is discussed in this paper is the technique of using computer software models to drive a Moving Base Carriage (MBC) that is capable of providing simultaneous six-degree-of-freedom motions. This method, utilized at Martin Marietta's Space Operations Simulation (SOS) laboratory, provides the ability to simulate the operation of manned spacecraft, provides the pilot with proper three-dimensional visual cues, and allows training of on-orbit operations. The most effective use of this capability has been in designing, testing, and operational training of the Manned Maneuvering Unit (MMU).

To properly evaluate the operation of a spacecraft and provide the pilot with the necessary training to operate it with confidence, accurate modelling of both the functional operation of the spacecraft and the physical laws that govern its operation are necessary. Due to limitations in the ability to model all aspects of a spacecraft and the space environment, limitations in finances to program these models, and limitations in the amount of computer code that can be executed in a finite amount of time, it is not feasible to model each variable that might affect a spacecraft's operation. Therefore, modelling is limited to those variables that are likely to have a significant effect on the spacecraft's operation. Once the modelling is complete, it is necessary to evaluate the level of simulation system fidelity, as compared to actual on-orbit operations, and to determine where the simulation needs improvement.

The purpose of this paper is to discuss significant MMU simulation issues, the related models that were developed in response to these issues and how effectively these models simulate the MMU's actual on-orbit operations.

MANNED MANEUVERING UNIT

The MMU was designed for untethered astronaut extra-vehicular activity (Figure 1). It is a self-contained vehicle, comprised of electrical power systems, propulsion components, controls, and displays necessary for on-orbit flight operations. The MMU utilizes pressurized gaseous nitrogen, expelled through 24 fixed thrusters, to achieve six-degree-

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of-freedom maneuverability. Attitude and directional motion commands are input through two hand controllers. The left hand controller is used for translational commands (X, Y, and Z) and the right hand controller is used for rotational commands (Roll, Pitch, and Yaw). The hand controllers generate electrical signals that are processed by two independant control electronics assemblies, which then send thruster firing commands to the appropriate thrusters. The unit is fully redundant such that no single credible failure can prevent a safe return.

A button on the rotational hand controller allows initiation of Automatic Attitude Hold (AAH), which uses three rate integrating gyros to maintain the MMU inertial attitude in any combination of rotational axes. To provide mission flexibility, two standard control modes are available: Normal mode, which is used for all operations of the MMU alone; and Satellite Stabilization mode, which is used for operations when the MMU is attached to a satellite or other massive payload. Satellite Stabilization mode uses an alternate thruster select logic to compensate for the induced large moments of inertias and the center-of-mass offset, to provide increased rotational control authority, and to minimize plume impingement of the payload.

SIMULATION SYSTEM

HARDWARE - The simulation system is driven by a Gould 32/9750 computer, that contains software models necessary to simulate spacecraft operations. The output of these software models provide input to a General Electric Series Six digital servo system. This system controls DC servo motors that provide motion to the simulation hardware. Sensors on this hardware return information to the servo system to verify their position and rate. The entire system is classed as a second-ordered, hybrid control system (see Figure 2).

The primary piece of simulation hardware is the man-rated, six-degree-of-freedom MBC (Figure 3) that moves within a cartesian coordinate system. This device provides translational motion and rotational motion, along and about the three axes simultaneously. In addition to the MBC, a Single-Axis Gimbal (SAG) and a Three-Axis Gimbal (TAG) (Figure 4) are used. These gimbals allow the pilot to approach and attempt docks to rotating targets. The SAG provides one-degree-of-freedom motion in rotation for large full-scale target mockups, whereas the TAG provides three-degrees-of-freedom motion in rotation for small full-scale and partial-scale target mockups. Because the SAG and TAG are not capable of translational motions, these motions are compensated for by the MBC.

For MMU simulations, an MMU mockup is attached to the gimbal head of the MBC (Figure 3). The only functional hardware present on this mockup are those interfaces necessary for the pilot to provide input to the system, such as handcontrollers and switches, or to receive system information, such as gauges and lights.

SOFTWARE - Software models are responsible for all aspects of the simulation system. These models simulate MMU electronics, MMU propulsion systems and the physical laws of space that govern the MMU's operation, and control of the simulation system and data recording. The control of the simulation system and data recording will not be discussed in this paper. The simulation of the MMU electronics, propulsion systems, and physical laws of space that govern the MMU's operation were divided into the following four general software modules:

<u>MMU Electrical Control and Switching (ECS)</u> - Monitors all MMU switches, detects changes in switch settings, controls switch malfunctions as initiated by the simulation run coordinator, and passes this information to other modules.

<u>MMU Control Electronics Assembly (CEA)</u> - Accepts handcontroller inputs (X, Y, Z, Roll, Pitch, and Yaw), MMU configuration and control modes, modelled gyro rates, and MMU CEA malfunctions as initiated by the simulation run coordinator. The output from this module specifies which of the MMU's twenty-four thrusters should be fired.

<u>MMU Propulsion</u> - Models the propulsion system, thruster firing times, manifold and regulator pressures, propellant use as a function of thruster firing time, and MMU

propulsion malfunctions as initiated by the simulation run coordinator. Output from this module specifies fuel consumption and which thrusters were actually fired.

MMU Dynamics - Models dynamic performance of flight hardware in zero-g environment. Includes associated center-of-mass offsets, forces, moments, orbital mechanics, flexible body dynamics, MMU plume impingement effects, vehicle/target relative motion, and two-body contact dynamics. Output from this module is returned to the CEA module to provide gyro rate information and to the digital servo system to provide position commands for the servo mechanisms.

Modelling all aspects of the simulation through software allows for complete flexibilty to modify any part of the simulation system. This provides the ability to simulate the operation of the MMU either in orbit or free space, start the simulation with any set of initial conditions desired, select the appropriate models, and insert up to three simultaneous malfunctions from a list of over two hundred possible choices.

SIMULATION ISSUES

In order to develop a valid simulation, it is necessary to assess a wide variety of issues. The first step is to identify which issues will not produce a noticeable effect on the simulation. For example, the SOS lab does not simulate atmospheric effects, the effects of gravity between the earth and sun or between the earth and moon, the effects of the non-spherical shape of the earth, and the effects of non-circular orbits. The next step is to determine which issues, of those that do produce a noticeable effect on the simulation, can be simulated to a high degree of fidelity within the scope of the present simulation system. In the MMU simulation, these include the ECS, CEA, propulsion system, forces, moments, orbital mechanics, and vehicle/target relative motion. Those issues that remain cannot be simulated to the degree of fidelity desired. This is due to either simulation system limitations or lack of sufficient knowledge of the issue. The remainder of this paper discusses some of these simulation issues and the on-orbit experiences related to them.

CENTER-OF-MASS OFFSET - Center-of-mass offset refers to a condition where the center-of-mass and center-of-thrust are not co-located. This results in translational commands inducing rotational motions.

Since the position of the MMU thrusters are fixed, center-of-thrust is simple to locate and remains unchanged. However, the center-of-mass is dependant on the relative positions of MMU system components; specifically, the MMU, target attachment devices, the pilot's spacesuit, and the pilot's body. The exact position of the center-of-mass changes, because the pilot tends to float inside the spacesuit and is likely to move his arms and legs. Since the center-of-mass offset is dynamic, it is not possible to accurately simulate its variable effect on the operation of the MMU. However, it is believed that small variances in center-of-mass offset should not cause significant differences between the simulation and flight hardware operation. Therefore, the anticipated position of the pilot during the majority of the flight is defined and used for all simulation operations.

One instance where this inaccuracy was detectable occurred during mission 41C when astronaut James Van Hoften flew the MMU with his legs forward instead of straight down, as had been assumed for simulation training.

FLEXIBLE BODY DYNAMICS - Flexible Body Dynamics (FBD) is the process in which various parts of a body oscillate at different frequencies due to a "forcing function" vibration. On the MMU, the primary oscillating components are the main body, the two arms, and a docking device (when attached). The primary forcing function is driven by thruster firing activity.

During STS mission 51A astronaut Dale Gardner used the MMU with the Apogee Kick Motor Capture Device (ACD), known as the "stinger", attached to the MMU arms to rendezvous and dock with a satellite. During this mission he reported significant sluggishness in the lateral command response while operating with AAH active and in Satellite Stabilization control mode. He also perceived a higher level of thruster activity in

AAH and a higher than expected propellant usage, than during the simulated training missions.

Due to this on-orbit experience, a variety of simple MMU FBD models were designed and tested to study their effect on the AAH system, including one model that closely resembled the on-orbit configuration of Dale Gardner. The data produced by these series of analyses indicated that FBD of the entire MMU system negatively affects the AAH control system by causing a higher level of thruster activity. This in turn is likely to produce an increase in propellant consumption as compared to a totally rigid configuration. As a result, a simple FBD model has been added to the simulation. To reduce this effect with the flight hardware, it was recommended that the AAH switching lines on the flight hardware be widened or removed, and that the MMU not be flown in AAH in Satellite Stabilization mode while not attached to a satellite.*

*John A. Cuseo, Charles A. Dallas, and David L. Van Duzen, MMU Control System Analysis With Flexible Body Modelling (Martin Marietta Aerospace, December 13, 1985), pp. 1-32.

PLUME IMPINGEMENT - Plume impingement refers to the effect of MMU gas plumes on nearby objects. The simulation issue is to reproduce accurately the affect that the expelled gas will have on the target. As gas is expelled from the MMU thrusters to control its position and attitude, the molecules that impinge upon the target will impart forces that will alter its present motion. Therefore, it is necessary to train the pilots to minimize plume impingement so that they will be able to safely and successfully rendezvous with a target on orbit.

During mission 41C, unexpected plume impingement effects occurred when astronaut George Nelson approached the Solar Maximum satellite. There were approximately 18 cases of MMU thruster plumes contacting the satellite surface, causing the satellite to start tumbling. This experience resulted in the subsequent modelling of plume impingement effects of the MMU.

The plume impingement effects were modelled by ignoring the minor variances in the exterior surface of the target and assuming it to be whatever basic geometric shape it most closely resembled. The plume effect for each thruster oriented towards the target was calculated and summed to produce a net effect. Because of the large number of calculations required to obtain the forces and moments impinging on the target at any given time, all data points for a variety of distances and rotational orientations were calculated off-line prior to the simulation and stored in a data table. During the simulation, the computer calculated the relative position and orientation of the target to the MMU and extracted the three forces and three moments from the table that most closely matched the present conditions.

This method provided a first order approximation of the actual conditions that would exist on orbit, because it was not possible to determine the actual translational orientations, rotational orientations, and rates of the pilot and target that would exist on orbit during the rendezvous. It was also not possible to store a large enough table of data points that would allow for minute changes in position and orientation. In addition, the actual commands that would be used on orbit would be the result of a wide variety of factors that are unpredictable. This rough approximation was acceptable because it was only important for the pilot to be aware of the problems that would be caused if large amounts of gas were used near the target, not for the pilot to train for impingement of a specific target. This modelling was used in training astronauts Joe Allen and Dale Gardner to rendezvous and capture the Hughes Westar and Palapa-B satellites during Mission 51A. Because of their training, both astronauts reported only minor plume impingement effects on orbit.

CONTACT DYNAMICS - Contact dynamics between two bodies in space is an important issue. If a force is applied to an object in the earth environment, the object may or may not move, depending on other forces acting upon it. If a force is applied to an object in space, the object moves in a manner directly related to the magnitude and direction of the force applied. Therefore, it is necessary to simulate this effect so that the pilot can become accustomed to the effects of contact dynamics. The two important areas of the contact dynamics issue are contact between the craft and target during capture, and contact while working on a spacecraft, such as repairing a satellite.

When the MMU is used to capture a target, it is possible to provide a relatively accurate model of the contact dynamics that exist. This is because the simulation system takes into account the relative shapes, positions, orientations, and rates of the two objects involved.

Contact between the pilot's body and another object is difficult to simulate, because the human is an unpredictable and autonomous system. Therefore, it is necessary to obtain real-time data that describes the direction and magnitude of the forces being applied to the object. Presently, the only feasible method of determining this data is to place load cell arrays on all the surfaces of the target that will be involved. The load cell arrays provide a direct input of the magnitude and direction of the forces involved. This data can then be used to simulate the induced rates caused by the interaction and, in turn, affect the resultant motions of both the MMU and target. In a real-time simulation system, it is possible to model the relative motions between the pilot and target accurately with this method. This is an additional capability that is planned for implementation to the simulation system at a later date.

FRAME RATE - Frame rate refers to how often the digital computer executes the necessary software models. This time period is critical when the simulation is operating in real-time, because it is necessary to execute the software as often as possible to simulate an anolog system. If the frame rate is too large, the hardware devices move in noticable steps.

The frame rate of the SOS lab simulator is 40 milliseconds (1/25 second). Although this frame rate has been sufficient, there have been a couple of instances where a higher resolution would have been desirable. An example, was when astronaut Bruce McCandless indicated that thruster firing activity during STS mission 41B was much faster than he had ever experienced in the simulator. This high level thruster activity was caused by AAH responding to rotational rates induced by translational commands. Through analyses, it was determined that the discrepency was due to the fact that the simulation frame rate was slower than the analog flight hardware. Since the simulator operates in discrete increments, it updates these rotational rates only once each frame. Therefore, it is likely that as the rotational rates build up, they will approach the AAH switching line (the point at which AAH will begin to correct for rotational rates or angles) in one frame and pass beyond it by the next frame. The simulation model will then command correcting rates, which will build up and take the rotational rates back across the switching line during one frame. This lagging response time can result in larger correctional moments and a slower AAH cycle time.

On the analog MMU, correcting rates are commanded as soon as rotational rates pass the AAH switching line. As soon as the rates pass back across the switching line, the correcting rates are terminated. Because of this quick response time, the appropriate thrusters will cycle on and off at a frequency of about 5 Hz until the rotational rates are corrected.

AAH RATE - The MMU AAH thruster logic utilizes thruster pulsing and continuous thruster firing, as necessary, to correct for unwanted rotational rates. The pulsing aspect of the logic operates in terms of 8 millisecond pulses, three times a second. Because the SOS lab simulation operates at 40 milliseconds, it was necessary to devise a method where the net forces produced by a specific command would be equal. Because impulse expended is the parameter that determines delta velocity, or in the above case, rotational rate, the net effect will be the same as long as the impulse is the same. The solution is found by using the relation between impulse, force, and time; $I = F \cdot t$. If $t = 0.008$ sec. and $F = 1.7$ lb. (7.56 N) (which is the nominal MMU force for one thruster), $I = 0.0136$ lb.-sec. (0.0605 N-sec.). By setting $t = 0.040$ sec. (the simulation frame rate) and keeping I constant, it can be calculated that the equivalent 40 millisecond force level is F = 0.34 lb. (1.51 N). By executing the AAH pulsing logic three times each frame and using this force value, the resultant effect in MMU motion will be the same as on orbit, even though the simulator is operating at a frame rate much slower than that of AAH.

VISUAL CUES - Close proximity operations between the MMU and a target require full three-dimensional visual cues; therefore, it is necessary to provide the pilot with full-scale mockups of the targets and the ability to move about them. The associated problem is that the MBC operates in a relatively confined area. The information gathered through both direct and peripheral viewing of the room provides the pilot with information that would not exist on orbit.

In an effort to reduce the effect of any visual room cues during simulations, the axes of the target can be rotated so as to not align with any room edges. This procedure was used during training for the Skylab mission and for Cargo Bay mockup operations. In both of these examples, the astronauts trained within full-scale mockups; thus, they received visual cues from the mockups and not from the room.

Another visual cue issue arose during STS mission 51A training. This training involved learning how to capture a satellite in which the axis of spin is close to, but not exactly, aligned along the axis of capture. This spin effect, known as coning, results in the pilot trying to dock with a point that is actually moving in a circle, in reference to himself.

When the addition of the coning effect to the SOS simulation system was first recommended, it was realized that the TAG would not be able to withstand the high inertias that would be induced by the satellite mockup. Since only the relative motions of the pilot and target were necessary for training, the visual coning effect of the satellite was imparted on the MBC. Concerns arose that these MBC motions would result in pilot disorientation or sickness. The results of the training simulations using this method demonstrated that the MBC motions did not cause any discomfort or disorientation. Subjective pilot comments indicated that the visual cues were more predominant than the motions of the MBC. Another concern was that the pilots would visually notice, from room cues, that the MBC and not the satellite mockup was coning. The pilots reported that they were unaware of this because of the high workload involved in performing the task.

SUMMARY

A simulation system that provides both developmental analysis data and operational training requires a high degree of simulation fidelity. Through comments of astronauts who have flown the MMU on orbit, it has been determined that many of the MMU simulation issues have been modelled to an appropriate degree of fidelity. These include center-of-mass offset, plume impingement, contact dynamics, AAH rate, and visual cues. On the other hand, the frame rate and flexible body dynamics issues have not yet been modelled to the desired degree of fidelity.

The use of the SOS laboratory's simulation system has indicated that a high fidelity, real-time, man-in-the-loop simulation is feasible and effective. As demonstrated with the MMU, the simulation provided a reliable means of training personnel to effectively and safely operate on orbit.

NOMENCLATURE

AAH - Automatic Attitude Hold
ACD - Apogee Kick Motor Capture Device
CEA - Control Electronics Assembly
ECS - Electrical Control and Switching
FBD - Flexible Body Dynamics
MBC - Moving Base Carriage
MMU - Manned Maneuvering Unit

SAG - Single Axis Gimbal
SOS - Space Operations Simulation
STS - Space Transportation System
TAG - Three Axis Gimbal

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