JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 29, No. 6, November-December 1992

# Extravehicular Activity Self-Rescue Using a Hand-Held Thruster

Adam R. Brody* and Rick Jacoby†
*Sterling Software, Palo Alto, California 94303*
and
Stephen R. Ellis‡
*NASA Ames Research Center, Moffett Field, California 94035*



**A study was performed in the virtual interactive environment workstation. Simulations were conducted to assess the feasibility and quantify the fuel and time requirements for a stranded crewperson to return to a space station after an accidental separation. A hand-held thruster, similar to the hand-held maneuvering unit from the Gemini program, was used for propulsion. Thirty different separation scenarios were composed of three separation rates, five initial spin rates, and an opportunity to use an attitude hold device in a repeated measures design. Statistically significant results were produced by separation velocity. Fuel, time maximum range, time to maximum range, maximum axial range, and final axial velocity increased with separation rate. A hand-held thruster is a viable alternative for accomplishing a self-rescue. Although one cannot prove a null effect, the fact that an attitude hold capability did not decrease solution time or fuel consumption is important for system designers. This fact, coupled with the success of a hand-held thruster in simulations, suggests that the added expense of more sophisticated solutions requiring a multitude of thrusters—and higher computation and power capabilities—may be unwarranted.**

## Introduction

ALTHOUGH there are no flight data for crew separations in the U.S. space program, neutral buoyancy simulations in the weightless environment training facility (WETF) have revealed that separation incidents will occur periodically. These WETF untethered incidents are considered to be realistic; however, the small numbers have made predictions of flight incidents difficult. A linear extrapolation of these data (three incidents in seven WETF years) corresponds to approximately one incident every 1000 extra vehicular activity (EVA) hours. Although the size and scope of Space Station Freedom and the number of supporting EVAs have been drastically reduced recently, crew safety is considered an important issue.[1] Crew rescue and equipment retrieval is a Space Station Freedom requirement.[2]

A rapid response is critical and unlikely to be achieved by a manned retrieval.[2] This constraint leads toward a robotic or self-rescue solution. A robotic rescue will most likely require either sophisticated ranging and sensor instrumentation that are not present in the current space station design or unproven visual recognition techniques. A trajectory planning tool, known as NAVIE, would be useful for planning such maneuvers.[3,4]

Self-rescue is conceptually the simplest in addition to being the least costly solution to the EVA separation problem; the big questions are: How much instrumentation and how many user aids are required for this capability? Can a crewperson stop his or her tumbling or is an attitude-hold device required? What are the fuel requirements?

The Russians are working on a rescue system whereby a controller inside Mir remotely operates an incapacitated crewperson's manned maneuvering unit (MMU).[5,6] This system, if functional, would be more robust than a self-rescue system since it could rescue an incapacitated crewperson. However, it is vastly more complex, requiring transmitters, responders, and a multitude of fixed thrusters. One of the purposes of this study is to quantify the operational envelope of a simple system to determine if a more robust, more expensive system is required.

Current work in developing an EVA self-rescue technique for the space station is severely hampered by the uncertainty in determining velocity increment (fuel) requirements. Analytical, ideal solutions can be found for rescue from any initial condition of position, velocity, and rotation rates along any combination of the three coordinate axes. However, using this analytical method ignores human factors.

Human participation comes into play in several discrete instances. First, the human will most likely be responsible for the action(s) that cause him or her to become separated from the space station. Second, on separation, the EVA crewperson must be able to ascertain location and orientation with respect to the space station. Third, the stranded astronaut must take the necessary steps to return to the station. This includes positioning and firing the thruster(s).

A number of simulators exist that are capable of simulating EVA or a rescue trajectory. The list is composed of software- and hardware-based devices and includes eivaN, NAVIE, the virtual interactive environment workstation (VIEW), motion-base carriage, the Shuttle engineering simulator (SES), air-bearing floor, neutral buoyancy, the KC-135 microgravity aircraft, and the Space Shuttle.

Each offers unique advantages and disadvantages. For example, eivaN,[7,8] used by Brody and Lomax,[9] models thruster firings analytically and instantaneously and ignores the human factor. However, it is inexpensive, portable, convenient, and correctly models orbital mechanics. Alternatively, NAVIE uses inverse dynamics and a geometric spread sheet to assist a user in planning a rescue mission. Table 1 summarizes the comparison of the various simulation facilities.

None of these simulators completely characterize the orbital environment. Therefore, the long-term research goal is to

Received Aug. 17, 1991; revision received March 10, 1992; accepted for publication March 10, 1992. 

*Aerospace Engineer/Experimental Psychologist, NASA Ames Division, NASA Ames Research Center, MS 262-2. Member AIAA.

†Software Engineer, NASA Ames Division, NASA Ames Research Center, MS 262-2.

‡Head, Advanced Displays and Spatial Perception Laboratory.

**Table 1 Comparison of simulators**

| Simulator | Visuals | Orb mech | Expensive | Other |
|---|---|---|---|---|
| eviaN | Third person view | Yes | No | Limited human factor |
| NAVIE | Third person view | Yes | Free software runs on IRIS computer | Limited human factor, user inputs waypoints instead of thrusts |
| VIEW | Stereo LCD | Yes | Yes | Operator in helmet |
| SOS | Good | Yes | Yes | Limited trans. and rot. range, erroneous gravity cue (blood rushes to head) |
| SES | Projection | Yes | Yes | Very low accessibility |
| Air-bearing floor | Good | No | Yes | Limited to three simultaneous DOF (only one rotational) |
| Neutral buoyancy | Good | No | Yes | Water drag |
| KC-135 | Good | No | Yes | Limited duration and range |
| Space Shuttle | Best | Yes | Extremely | Extremely low accessibility |

perform similar EVA rescue studies on each of them. Mission duration, velocity increment (delta-V or fuel), and other collected data from each could ultimately be compared with on-orbit data from the Space Shuttle. These comparisons would yield "gain" factors for each device. For example, if the median velocity increment value achieved for a particular separation scenario was 4.3 m/s in VIEW and the corresponding value on-orbit was 8.6, one could multiply all velocity increment values collected from VIEW simulations by 2 to arrive at approximate real world values. Obtaining these gain values for each simulator would be very useful for mission planning. (The relationship might be more complicated than linear.)

In addition to the ratio between real and simulator values, knowledge of the variance in experimental data would be useful for mission planners. Cost/benefit analyses could be performed to determine whether the expected benefits (e.g., more accurate data, smaller variance) from a more expensive simulator were worth the added expense. Indicatively, uncertainties in the rendezvous fuel requirements in the Gemini program ranging from 1.52–4.28 times minimum values made estimates of actual fuel consumption impossible.[10]

Although none of the simulators mentioned earlier will help in the determination of the parameters describing the error scenario, their utility as simulation devices will enable studies of the human factors involved with a self-rescue. By providing the simulators with the mass and moments of inertia of an EVA crewperson and the thruster characteristics for a rescue device, researchers will be able to examine human performance in a rescue. Measurements such as onset time until response, time and fuel necessary to cease rotations, and time and fuel required to return to the station may be made for an assortment of failure scenarios. Thrusters may be altered in magnitude, capacity, moment arm, and number to examine the effects these parameters might have on a self-rescue capability. Different control modes such as pulse, displacement proportional, force proportional, and on/off could be compared to determine which works best in terms of fuel, time, safety, or any other desired cost function.

## Background

Brody and Lomax[9] analytically determined the average velocity increment required for self-rescue to be 4.7 m/s for the translation solution and an additional 0.5 m/s to eliminate the rotations. They modeled a separation from a space station from 47 m above its center of mass. The separation velocity was 2 m/s. The mass of the crewmember, including AX-5 spacesuit and portable life support system (PLSS), was 274 kg and the moments of inertia were 34.25 kg-m$^2$ about the longitudinal axis and 108 kg-m$^2$ about the other axes.

This analytical solution did not take the human factor into account sufficiently. The stranded crewperson will not be able to target his or her thrusts optimally for two reasons. First, the sensors, displays, and other instrumentation necessary for informing the astronaut of his or her position and velocity with respect to the space station will not be available. Second, even if this information were available, the likelihood that a tumbling astronaut could accurately point his or her thruster and fire at the appropriate time is essentially impossible. To arrive at a fuel requirement for the rescue mission, the effect of the human factor must be quantified.

### Virtual Environments

The current study was conducted in the virtual interactive environment workstation (VIEW) lab at NASA Ames Research Center. A virtual environment (VE), or virtual reality as it is often called, is described in several sources.[11-20] The VIEW lab in particular is also described in several papers.[21,22] Following is a brief description of VE and the VIEW lab.

Virtual environment is a term that describes the use of several technologies integrated together to create an interactive electronic simulation. It typically entails the use of a computer, a head-mounted stereo display, an electronic glove for interacting with the computer by way of hand gestures, and head and hand trackers for telling the computer where the head and hands are located. Voice input and audio output are often part of a VE.

VEs have their roots in diverse fields, including entertainment (Cinerama)[22] and flight simulators.[23] Recent improvements in graphics workstations and other electronics fields have enabled the development of modern, low-cost VEs. VE techniques are currently being applied to a large variety of areas, including scientific and medical visualization, telerobotics, computer-aided design, architecture, and vehicle simulation.

### View

The VE at NASA Ames Research Center's VIEW lab supports research into teleoperation, scientific visualization, perceptual psychology, and virtual control devices. The current configuration of VIEW hardware consists of an HP 9000/835 host computer and an ISG Technologies graphics computer, both running UNIX. A large library of C functions provides access to the peripherals and support simulation processing. Peripherals attached to the host include a VPL DataGlove, a Polhemus 6 degree-of-freedom tracking source, and two sensors (one for the head and one for the DataGlove), a Convolvotron three-dimensional sound localizer, and a VocaLink voice recognizer. Visual output to the user is provided through a pair of stereo, head-mounted, monochrome liquid crystal displays with wide-angle optics. Audio output is provided through headphones and room speakers that present a combination of synthesized speech (DecTalk) and computer generated tones.[21,22]

Several modifications to the VIEW software were made to simulate EVA rescue. The modifications included creating graphics for the space station, hand-held thruster, and Earth. Control logic for the thruster and attitude hold device, orbital mechanics effects, and data collection capabilities were also added.

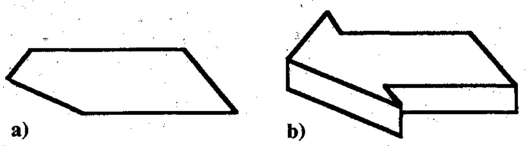


**Fig. 1 Graphics for a) hand and inactive thruster, and b) hand and active thruster.**

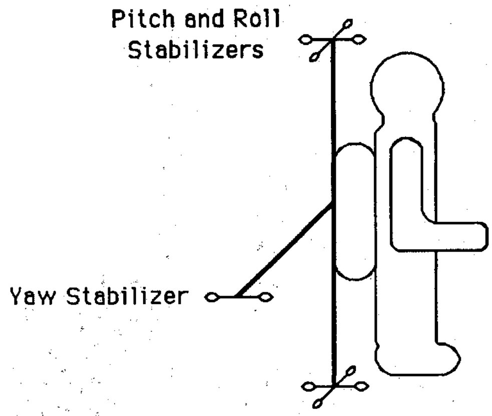


**Fig. 2 Astronaut with pitch and roll axis stabilizer pairs and one of the two yaw axis stabilizer pairs.**

### Rescue Experiment Environment

The thruster simulated here was analogous to the hand-held maneuvering unit (HHMU) used during the Gemini and Skylab programs. This device expelled gas out of one end to produce thrust in the opposite direction. Typical propellants were nitrogen, oxygen, and Freon 14. In VIEW, two gestures were used to command forward and reverse thrusts (i.e., single-fingered point and two-fingered point, respectively). Thrusting was accomplished by aiming the hand in the desired direction and performing one of the gestures. Thrusting continued for the duration of the gesture. Since for this study the velocity increment (delta-V) or fuel consumption was measured as duration of the thruster commands, the actual propellant and thruster geometry was irrelevant. The mass of the fuel can be scaled to account for any combination of thruster geometry and propellant characteristics (e.g., Isp).

Both audio and visual feedback were provided to indicate the action of thrusting. When thrusting, the visual image of the thruster changed from a small, two-dimensional arrow to a larger, three-dimensional arrow that pointed in the direction of the thrust. A low-pitched hiss simultaneously indicated thrusting. Figure 1 shows the thruster arrows in both the inactive and thrusting states.

The simulated astronaut was modeled as wearing an AX-5 space suit with the appropriate mass and moments of inertia. Accurate motions of the visual scene, in response to operator thruster commands, were accomplished through the modeling of the orbital mechanics. VIEW used the Clohessy-Wiltshire solutions to Hill's equations to compute the astronaut's position with the state vector re-initialized at each time step. All thrusts that did not go directly through the center of mass of the astronaut and backpack system caused rotational motion as governed by the equations of simple mechanics. Between thrusts, the simulated astronaut followed an elliptical orbit around the Earth with discrete rotation rates about all three axes.

The attitude hold device was modeled as pairs of thrusters on stalks, two pairs for each axis. (See Fig. 2.) Thrusters appeared in pairs so as to not induce translational motion. Since the astronaut could be tumbling either clockwise or counterclockwise about each axis, two pairs were needed for each axis to stop an arbitrary tumble. Attitude hold was commanded by performing a hand gesture. A pair of thrusters fired (with appropriate audio feedback) to counteract the tumble for each axis. Once the tumble about an axis stopped, the corresponding thruster pair stopped firing. Once tumbling about all axes stopped, attitude hold was automatically turned off. A manual firing of the hand-held thruster also turned off the attitude hold system.

The graphics models of the Earth and space station were kept relatively simple to keep the simulation frame rate high (>11 frames/s). The Earth was modeled as a disk. This pseudo-Earth disk was of a size and distance from the astronaut so that it subtended the same visual angle that the real Earth would. Figure 3 illustrates the relevant geometry.

The radius $r$ of the pseudo-Earth disk is 2,239,738 m, and its distance from the space station, $H + h$, is 841,071 m. These values were found by solving the following equations:

$$\cos(a) = \frac{R}{R + H} = \frac{r}{s}$$

$$\sin(a) = \frac{s}{R + H} = \frac{H + h}{s}$$

where

$$s = \sqrt{(R + H)^2 - R^2}$$

Since it was impractical to keep up with the rapidly changing design of Space Station Freedom, the simulated space station was represented by two intersecting 5-m trusses. The station was modeled as a single keel design with an out-of-plane dimension of 50 m and a height of 100 m. It was located in a 270 n.mi. circular orbit around the Earth. (See Fig. 4.)

These simple graphics objects, coupled with the audio cues, the dynamics, and the interactive capability, were sufficient to create a compelling EVA simulation.

For this study, VIEW created two output files, a summary file, and a detailed data file, for each series of five trials. The summary file contained data on the rescue; thrusting, and attitude-hold durations; number of attitude-hold commands; and the three-axis components of position, orientation, velocity, and spin velocity when rescued. The detailed data file collected data every 10 s or whenever a hand-held thruster or attitude hold thruster changed state (started or stopped firing). Data included time, thruster state, attitude hold state, and components of position, orientation, velocity, and spin velocity.

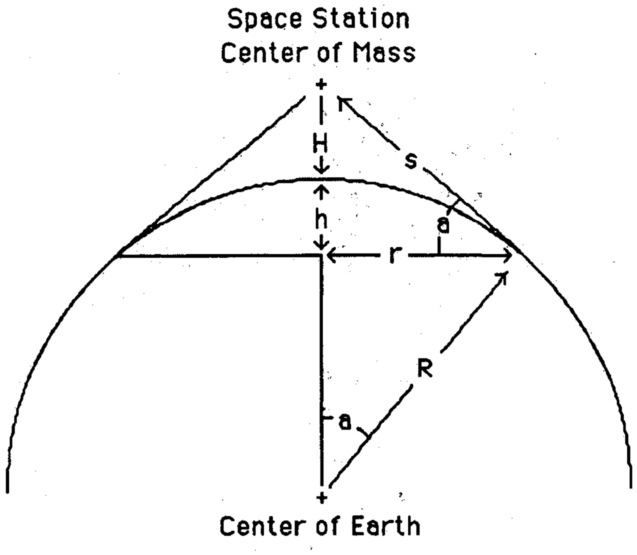


**Fig. 3 Diagram illustrating determination of size of disk to represent the Earth.**

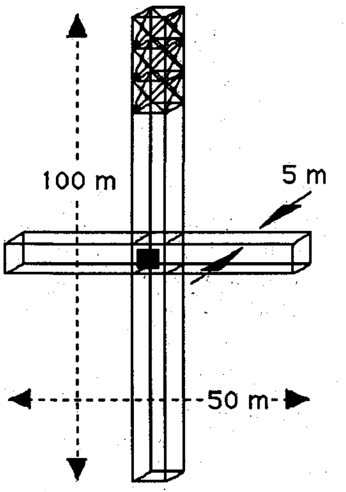


**Fig. 4 Space station model (note: most truss detail omitted for clarity).**

### Hand-Held Maneuvering Unit

Three different models of HHMU were designed for the Gemini program. They all provided throttleable thrust of 0–8.9 N (0–2 lb) and consisted of two tractor nozzles canted away from the astronaut and one pusher nozzle centrally located. Propellants for the HHMUs in Gemini IV, VIII, and X/XI, respectively, were 0.32 kg (0.7 lb) of oxygen, 8.18 kg (18 lb) of Freon 14, and 4.89 kg (10.75 lb) of nitrogen. Total available velocity increment ranged from 1.83 m/s (6 ft/s) in the Gemini IV unit to 25.60 (84 ft/s) in the Gemini X/XI unit.

The Gemini astronauts found the HHMU very useful in flight. Gemini IV's Ed White, after making the first powered EVA, "reported that the gun really worked quite well.... With that gun, I could decide to go to a part of a spacecraft and very confidently go."[24] They also thought that their air-bearing simulations were useful for training. Reports from the Skylab astronauts were mixed. Alan Bean from Skylab 3 noted that "tumble recovery with the HHMU was surprisingly simple" but also claimed that the "HHMU is inadequate and dangerous for EVA."[25]

Several studies were designed to simulate a device similar to the HHMU and determine if it is useful for rescuing oneself from an accidental separation. Of particular concern are fuel (velocity increment) and time requirements since these data are important for fuel tank sizing and mission planning considerations. Obtaining a better understanding of the human factors involved with EVA self-rescue will greatly increase the likelihood of success of such a mission and thereby increase crew safety.[26,27]

## Method

One highly trained subject was used in this study. The subject, situated in the VIEW, experienced sudden separations from the virtual space station to which he was previously tethered. Using hand gestures, which commanded the fore and aft firings of a virtual hand-held thruster, he effected his returns to the station. The subject was trained until he was able to recover consistently from a variety of separation scenarios.

The subject was presented with an assortment of failure scenarios with various initial velocities and rotation rates. The opportunity to use attitude hold was allowed on only half the trials. Since preliminary investigations revealed starting location to have less of an effect on rescue performance than other input parameters, all separations began at the center of mass of the space station. Motion began in the direction of the minus velocity vector.

Three initial (separation) rates (0.5, 1.0, and 1.5 m/s) were used in the study. These values were selected as appropriate based on separation dynamics tests performed on the KC-135 aircraft. In these tests, test subjects were assisted in achieving the maximum separation rates possible; a maximum separation rate of 1.5 m/s (4.5 ft/s) was achieved. The maximum rotation rates were found to be 4.5 rpm (0.47 rad/s) in roll, 10.1 rpm (1.06 rad/s) in pitch, and 5.8 rpm (0.61 rad/s) in yaw.[28] The five rotation rates (−0.3, −0.1, 0, 0.1, and 0.3 rad/s) in this study were crossed with the translation rates to yield a trial set of 15 different trials. Initial rates were the same about all axes. Both negative and positive values were used because preliminary testing suggested a handedness effect might be present.

The capability to use attitude hold was added as another factor raising the number of distinct trials to 30. The subject was presented with two different random orders of these 30 trials in groups of 5. Dependent variables included mission duration, total velocity increment, impact velocity, and maximum range from the station along all three axes.

The subject was allowed one attempt at a rescue. The trial was aborted if he passed the station. These aborted missions were immediately reflown.

The hand-held thruster fired an 8.9 N (2 lb) force along the direction of the hand in either the fore or aft direction. All thrusts that were not directed precisely through the center of mass of the subject, which was located in the center of the subjects back, added rotational motion along one or more axes.

An 8.9 N (2 lb) thruster requires 31 s to accelerate the simulated crew mass of 274 kg to 1 m/s. This thrust must be through the center of mass to avoid adding rotational motion. This is virtually impossible, so achieving a velocity of 1 m/s typically requires more than 31 s.

## Results

Training was performed until the most difficult situations could be resolved consistently. Perceived difficulty increased with separation velocity. However, with practice, it was possible to return oneself to the station reliably from a separation rate as great as 1.5 m/s.

All simulated rescues were achieved in under 6 min. Several successful rescues were accomplished in less than 1 min.

Figure 5 is a plot of a successful trial with an initial velocity of 1 m/s and initial spin rate of −0.1 rad/s. Attitude hold was not available for use. This run exhibited the largest displacement in the $Y$ direction. Final displacements along the coordinate axes in meters were 1, −21.5, and 3.5 for the $X$, $Y$, and $Z$ axes, respectively. Solution time was 99 s, and total velocity increment was 61.2 m/s.

Initial movement along the $Z$ axis was in the up ($-R$-bar) direction. This motion was due to the subject's thrusting since the orbital mechanics effects of a $-V$-bar thrust would be downward. Downward thrusts were ultimately made, which

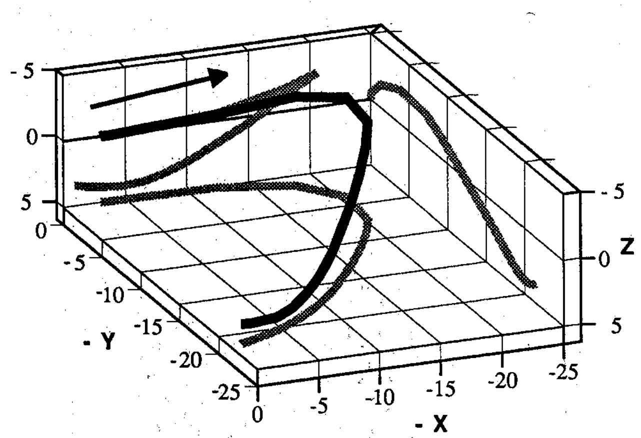


**Fig. 5 Example rescue trajectory (note: the shaded curves on the three orthogonal planes are projections of the trajectory).**

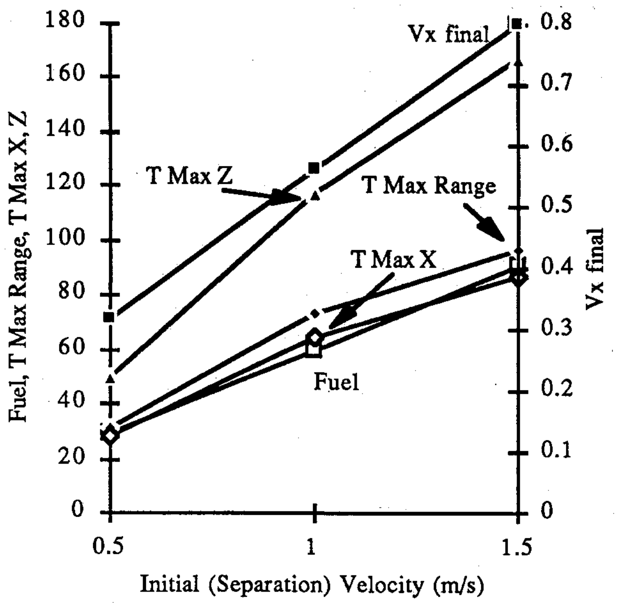


**Fig. 6 Initial (separation) velocity.**

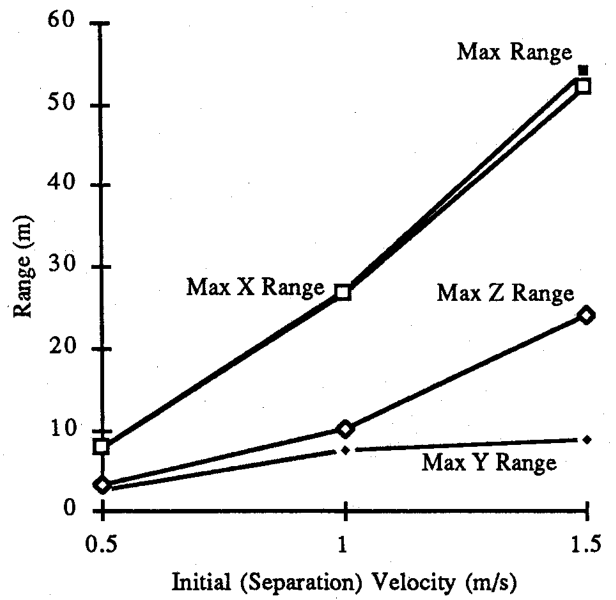


**Fig. 7 Maximum ranges vs initial velocity.**

brought the trajectory to a point below where it had started. This activity, coupled with the out-of-plane motion, produced a projection in the $YZ$ plane that resembles a sinusoid. Displacement in the $X$ and $Y$ directions was roughly equivalent in magnitude. Although the magnitude of the $X$ motion was average, the magnitude of the $Y$ motion was high. Fuel usage also was nominal.

Over all of the trials, separation velocity was found to be an important factor, influencing a large number of dependent variables. Fuel consumption (Fuel), time maximum range (Max Range), time to maximum range (T Max Range), maximum axial range (Max X Range), and axial impact velocity (Vx final) increased with separation rate. Initial spin velocity caused several u-shaped functions, with minimums near 0 rad/s. These effects were seen in fuel consumption, maximum range, time to maximum range, and maximum axial range. A number of other effects were revealed; however, only the most interesting are discussed here. All data presented here were statistically significant at the 5% level.

The following chart illustrates the effect of initial (separation) velocity on fuel consumption (Fuel), time to maximum range ($T$ Max Range), times to maximum $X$ and $Z$ range ($T$ Max $X$, $T$ Max $Z$), and final $X$ velocity (Vx final). The $X$ axis was along the velocity vector, $Y$ was positive out of the orbital plane to the right, and $Z$ was positive toward the Earth.

Fuel consumption (velocity increment) increased linearly with separation velocity. The velocity increment required for rescue was approximately twice the separation velocity. Half of the velocity increment was needed to halt the separation rate; the other half was expended on combating orbital mechanics effects, thrusting errors (and their corrections), and rotation rates. (The fuel consumption axis on the charts has seconds as a unit because that was how fuel consumption was experimentally measured. Thirty-one seconds of thrust directly through the crew's center of mass produced a velocity increment of 1 m/s.) (See Fig. 6.)

The $T$ Max Range also increased with initial velocity. Since the thruster had a fixed magnitude, the subject required proportionately more time to recover from the trials with higher initial velocities. This caused the $T$ Max Range to increase with initial velocity. The plot for time to maximum $X$ range ($T$ Max $X$) was almost identical, but slightly offset from the absolute maximum range plot. The separation was along the $X$ axis; consequently, displacement along the $X$ axis was the largest component of slant range.

Motion in the $Z$ direction was caused by orbital mechanics effects (and thruster inputs). The times for achieving maximum $Z$ displacement were greater than the times for absolute (slant) displacement, indicating that the crewperson continued to drift downward after axial motion away from the station had been halted. These times were also proportional to initial velocity demonstrating the role of velocity in orbital mechanics.

Final $X$ velocity (whose plot uses the right axis in Fig. 6) increased linearly with initial velocity. Essentially, the final velocity increased with the initial velocity despite the fact that they were in opposite directions. There was an overcompensation in the rescue maneuver in that the simulated crewperson returned at a rate proportional to the rate he left. The faster the crewperson left, the higher the rate he had when he returned.

Initial velocity also produced statistically significant effects on maximum slant range and its components. Maximum range and maximum $X$ and $Z$ ranges all increased similarly with initial velocity. (See Fig. 7.) Since recovery times were longer for the higher velocities, maximum ranges were greater. Likewise, the maximum out-of-plane ($Y$) range increased with

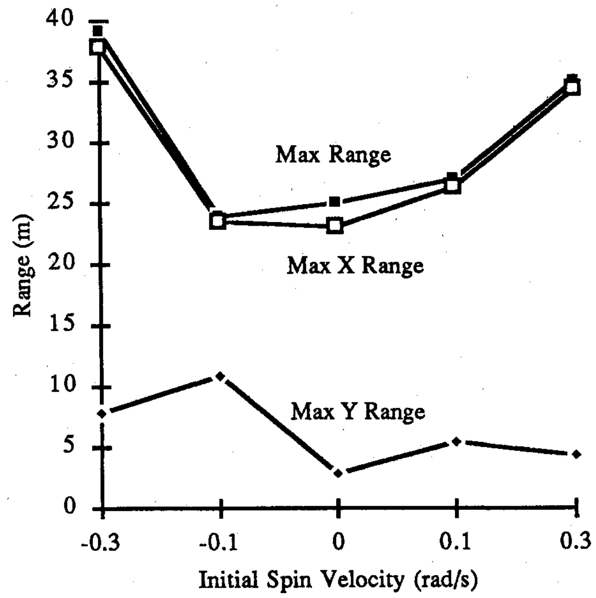


**Fig. 8 Maximum ranges vs initial spin velocity.**

initial velocity. Out-of-plane orbital motion is uncoupled from motion along the other two axes. When objects are released without any initial range or rate in the out-of-plane direction, as the crewperson was here, they will not have any motion along that axis. This increase with velocity is due to the increased duration of thrusting needed to recover from the large separation rate. The greater thrusting time required to recover from the higher separation rates provided more opportunity to become displaced along the out-of-plane axis. This is similar to an effect found in a spacecraft docking study where the likelihood of an out-of-plane incident increased with initial range.[29]

Maximum range in the radial ($Z$) direction (i.e., $R$-bar or perpendicular to the Earth) increased with separation velocity. This is a manifestation of orbital mechanics effects combined with higher velocities providing more time for a radial range to increase. The time at which this maximum range was achieved also increased with velocity as illustrated in Fig. 6.

Figure 8 shows the effect of initial spin velocity on absolute, $X$, and $Y$ maximum ranges. The increase of maximum absolute and $X$ ranges with the absolute value of initial spin rate suggests a correlation between initial spin rate and difficulty. The subject drifted to a greater range when the initial spin velocity was greater. The lack of a u-shape in the maximum $Y$ range plot is currently unexplainable. The fact that the range values for positive initial spin rates are less than those for negative initial spin rates and that the displacements occurred only in the positive $Y$ direction may represent a handedness effect. In any case, the existence of an initial spin velocity caused an increase in displacement along the $Y$ axis.

More fuel was used at higher initial spin rates than at lower rates. This indicates perceived difficulty since spin rate does not inherently affect the amount of fuel needed to return to the station. Stopping the spin rate does not bring the crew closer to the station. (See Fig. 9.)

Although rotation rates about the $Y$ and $Z$ axes were reduced by virtue of thrusting toward the station, the final spin rate about the $X$ axis ($V$spin$Xf$) remained close to the initial spin rate. Thrusts made toward the space station along this axis did not alter the spin rate about this axis. Thrusts were generally made in a forward direction, which would not provide a moment arm to alter the rotation rate about this axis. It is almost as if the axial motion were spin stabilized and opposite components along the other axes canceled each other out.

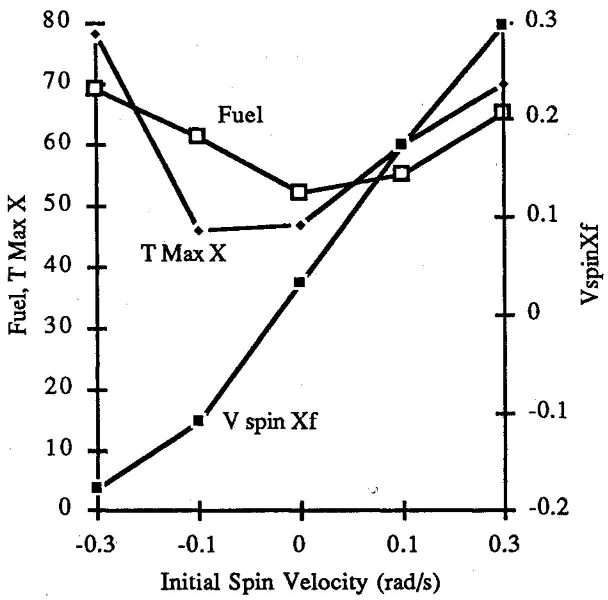


Fig. 9 Initial spin velocity.

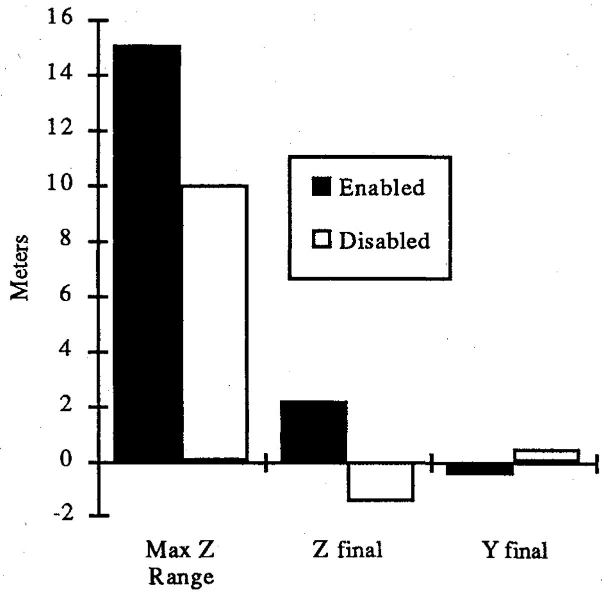


Fig. 10 Effect of attitude hold capability.

The $T$ Max $X$ also increased with initial spin velocity. This is a further indication of an increase in difficulty with an increase in initial velocity. The subject took longer to recover when the initial spin rate was greater.

Attitude hold produced several noteworthy effects. The maximum range in the $Z$ direction (Max $Z$ Range) was greater when the test subject could use the attitude-hold device. Since use of the attitude-hold capability precluded simultaneous translation commands, orbital mechanics continued to move the astronaut toward the Earth (and away from the station) while the tumbling was being damped. (See Fig. 10.) This also caused the final $Z$ displacement ($Z$ final) to be closer to the Earth ($+Z$) when attitude hold was available. The difference in final $Y$ displacement ($Y$ final) caused by attitude hold is probably a handedness effect.

## Discussion

One should not draw strong conclusions from a null effect. However, the fact that no fuel or time advantages were obtained with the attitude hold device suggests that the incorporation of an attitude hold capability in a rescue device may be an unnecessary expense. Several proposed rescue tools have an attitude hold capability, which greatly adds to the systems' complexity, design, manufacturing and life-cycle costs, and weight. Early results indicate that elimination of this capability is possible without a reduction in safety.

The success of the test subject in this preliminary study suggests that a hand-held thruster such as an HHMU has definite possibilities as a self-rescue device. Since it is essentially an off-the-shelf technology, it has a low development and implementation time (and cost). It also would require less power than other rescue possibilities since it does not require sophisticated computational capability. Additional testing is advised to demonstrate its capabilities further.

More work is necessary to quantify the self-rescue problem. Other independent parameters to be varied include initial position, separation direction, thruster magnitude, and other characteristics. Future work will also include studies on some of the other simulators described earlier.

A Space Shuttle flight experiment was performed on STS 49 in May 1992. That study tested the feasibility of the HHMU as a rescue device. Results from this study will be very useful for ongoing simulation and experimentation.

The Astronaut Office and others at the Johnson Space Center have been very interested in the rescue work being performed at NASA Ames Research Center. It is hoped that further work will arise out of this collaboration.

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James A. Martin
*Associate Editor*