# Design of an Interim Space Rescue Ferry Vehicle

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**This paper proposes a stop-gap nonoptimum vehicle for transferring astronauts from a tumbling stranded spacecraft to a nearby rescue spacecraft. The design is limited to the use of available or "soon-to-be" available flight-qualified hardware and consists of three major components: the manned maneuvering unit, the personnel rescue enclosure, and the apogee kick motor capture device. The apogee kick motor capture device is modified to serve as the connection between the manned maneuvering unit and the personnel rescue enclosure. The performance of this interim rescue vehicle is analyzed with NASA flight simulation software to test the feasibility of the design. Results show that the control system of the manned maneuvering unit adequately limits uncommanded rotations during all simulated maneuvers in the primary control mode but not during transverse translations in the backup control mode. Impingement of thruster plumes on the personnel rescue enclosure is shown to be of some importance in certain maneuvers. The satellite stabilization mode of the control system is found to have significant rotational-to-translational coupling that has associated adverse affects on flying qualities, making the mode undesirable for the rescue mission.**

## Introduction

CURRENTLY, U.S. astronauts conduct routine space operations without the safety net of a ready and tested space rescue plan for the emergency situation in which a Space Shuttle Orbiter becomes stranded in orbit. Previous U.S. manned space programs were conducted with the same deficiency. During the early 1960's NASA conducted analyses to determine rescue requirements and capabilities for the Mercury, Gemini, and Apollo programs. Development was not pursued, however, because planners realized that successful space rescue would require an ambulance spacecraft to be available for immediate launching, and maintaining such a capability was deemed impractical at that time.[1] In the future, however, the lack of a rescue vehicle may be resolved by an increasing Space Shuttle flight rate, which might allow each Shuttle mission to serve as the standby rescue vehicle for the flight immediately preceding it.

However, space rescue in the Shuttle era is complicated by the lack of two capabilities: 1) current Shuttle Orbiters cannot dock with other spacecraft. Therefore, stranded personnel must conduct extravehicular activity (EVA) to transfer to the rescue vehicle;[2] and 2) even though Shuttle crews usually number from five to eight astronauts, mass and volume constraints allow only two space suits to be carried on all Shuttle missions.[3] Consequently, some mechanism is necessary for transferring unprotected astronauts across the open void between the two spacecraft.

The personnel rescue enclosure (PRE) was developed by NASA in 1975 to meet this requirement. Illustrated in Fig. 1, the PRE is an inflatable life-support sphere that provides a thermally protected, puncture resistant, pressurized environment within which a nonspace-suited astronaut can survive for about 1 h, long enough to be transported to the rescue Orbiter. The PRE is 34 in. in diameter and is equipped with a penetration plate and connectors for attaching air umbilical and communication lines. A small viewing window is provided and a relief valve limits internal pressure to 5.25 psia. Two external carrying loops positioned 180 deg apart on the sphere facilitate handling and a waist restraint belt restricts relative movement of the PRE and occupant. Entry is through a zipper, once disconnected from the air umbilical, a 1 h supply of breathing air is furnished by a portable oxygen system currently under development.[4] Two prototype models of the PRE were built and tested in 1976, but were not man-rated. Currently, an updated PRE is under construction by the Crew and Thermal Systems Division at the Johnson Space Center to be man-rated for use on future Space Shuttle flights.

Development of the PRE led to a proposal of three transfer techniques by Brown[2] in 1977. The first two require no relative motion between the rescue Orbiter and the stranded Orbiter and close formation between the two vehicles. The first of these requires the remote manipulator arm to pluck PRE spheres from the airlock of the stranded vehicle. A space-suited rescue crewman, attached to the manipulator arm by foot restraints, rides on the arm and grasps the PRE by one of its handles. The arm operator then repositions the arm to allow the PRE to be inserted into the airlock of the rescue Orbiter. In the second technique, the remote manipulator arm is moved to a stationary position near the side hatch or airlock door of the stranded vehicle. The arm then serves as the supporting structure for a continuous wire loop trolley on which the PRE's are attached and transported to the rescue vehicle. Two space-suited rescue crewmen operate the trolley. The third technique provides additional capability, in that rescue from an Orbiter tumbling out of control is possible. Here, a ferry vehicle is employed to rendezvous and dock with the stranded vehicle. A PRE is then attached to the ferry vehicle and transported to the rescue vehicle. The procedure is repeated until all victims requiring a PRE are transferred.

The concept of using a ferry vehicle to transfer PRE's from

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a tumbling stranded Orbiter to a rescue Orbiter has been developed further by specifically proposing the manned maneuvering unit (MMU) for the transfer. Rogers[5] reports that preliminary simulations indicate that an MMU/PRE combined vehicle retains adequate performance and stability for use in a space rescue scenario. Consequently, the pursuit of an optimum method of attaching the PRE to the MMU seems to have merit for developing rescue capability in the long term. For the near term, however, that rescue capability may be made available if a suboptimal device can be fabricated to connect the PRE to the MMU forming an interim space rescue ferry vehicle with adequate performance and stability.

This paper proposes an interim suboptimal design of a space rescue ferry vehicle composed of a PRE connected to an MMU with the apogee kick motor capture device (ACD) modified to accommodate the PRE. The ACD was originally built for use with the MMU to capture two spin-stabilized satellites, but can be easily modified to mate with the PRE. In the development to follow, the requirements that led to the proposed design will be discussed. The necessary modification to the ACD will be described. Then, the analysis to validate the design will be presented along with representative results to show how the combined vehicle should perform when various modes of the MMU control system are employed to execute typical maneuvers in a rescue sequence.

## Design Requirements

Since the MMU is already flight-qualified and the PRE is on its own development schedule, an immediately available device for connecting the MMU and PRE would ensure the availability of an interim rescue vehicle (IRV) simultaneously with the availability of the PRE. Consequently, the first requirement for the connecting device is that it be constructed from currently available or soon-to-be-available hardware. Beyond this primary requirement, the others are related to either operations or performance.

For operational considerations, six factors affect the design of the MMU/PRE connecting device.

1) The IRV pilot must have adequate visibility with the PRE connected to the MMU to allow safe flight maneuvers.

2) The connecting device should be easy to use by the IRV pilot—all controls should be within the IRV pilot's reach.

3) The connecting device should be capable of being stowed in the Orbiter's payload bay using currently available payload mounting hardware.

4) Critical fits should be avoided—the operation of a mechanism should not depend on precise dimensions of another part or mechanism.

5) The proposed IRV must be ready for flight within several hours of notification of an impending rescue mission—all hardware modifications must be permissible in advance or achievable in minimum time.

6) Redundant systems should backup critical components so that foreseeable possible failures do not prevent completion of the rescue mission or cause injury to crew members.

Since the IRV is to be flown using the existing control modes of the MMU, performance considerations suggest that the connecting device should produce an IRV that is very nearly a rigid body with mass properties not greatly changed from those of the MMU. Also, the connecting device should avoid or minimize the adverse effects of thruster plume impingement on itself and the PRE. Impingements reduce thruster effectiveness and, where not symmetric, cause undesired rotational motion that must be countered by the control system.

## Modified Apogee Kick Motor Capture Device

Tests conducted at the Johnson Space Center in June and July 1985 revealed that the apogee kick motor capture device (ACD), an existing piece of flight-qualified hardware, could be modified to meet most of the above criteria adequately and serve as the MMU/PRE connection device. Fig. 2 shows the ACD mounted on the MMU and the combined system being flown toward a spin-stabilized satellite to effect a recovery. Fig. 3 shows the ACD in more detail. ACD operation is not important to what follows and is not described here. Of significance, however, is that in modifying the ACD, the method of connection to the MMU has not been changed.

The MMU/PRE connection device is formed from the ACD quite simply by removing four parts or subassemblies from the ACD. Referring to Fig. 3, the circular guide ring visible in the rear view is removed from the ACD structure subassembly identified in the top view. The toggle finger subassembly and control box subassembly are also removed. The entire grapple fixture assembly is removed. The resulting structure is shown in Fig. 4 and, when mounted on the MMU, forms a basket in which the PRE neatly fits, as shown in Fig. 5. The modified

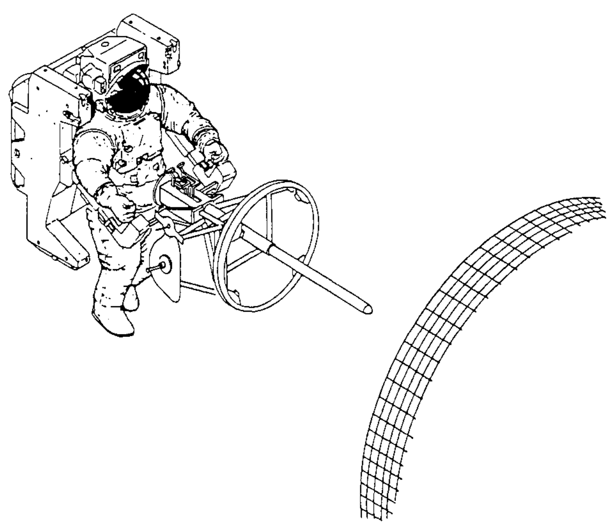

Fig. 2 Manned maneuvering unit/apogee kick motor capture device.

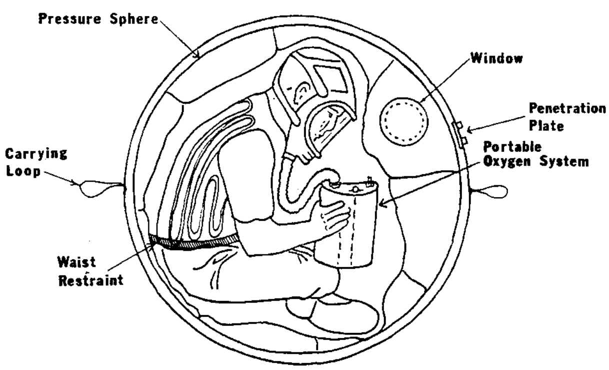


Fig. 1 Personnel rescue enclosure.

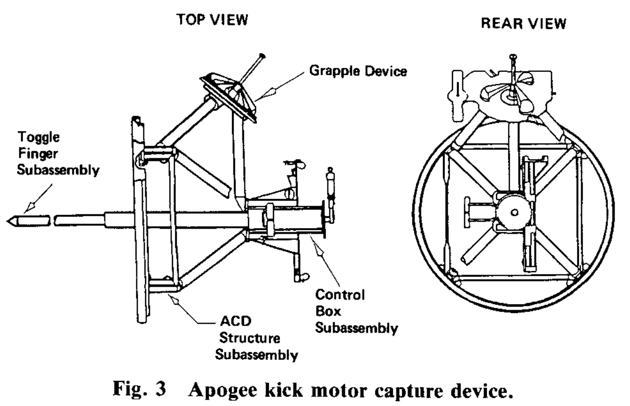


Fig. 3 Apogee kick motor capture device.

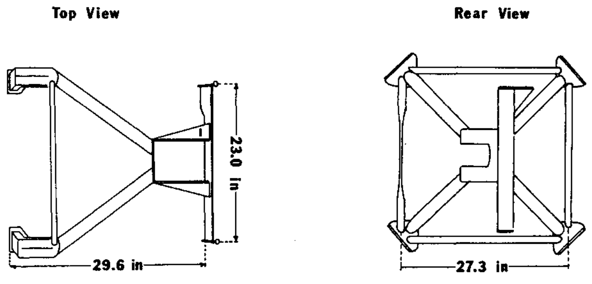


Fig. 4 Modified apogee kick motor capture device.

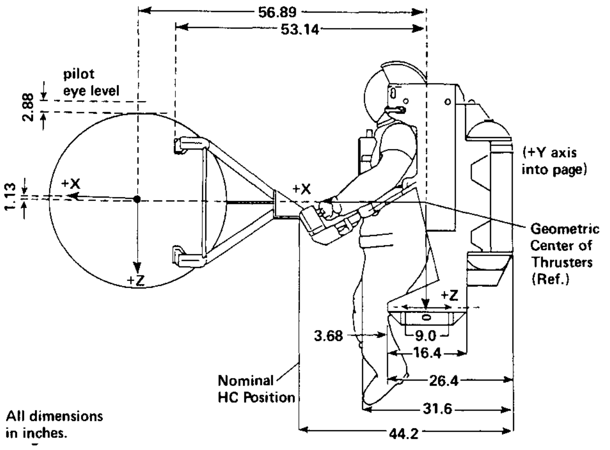


Fig. 5 Interim rescue vehicle.

ACD contacts the PRE at eight points. Four contact points lie midway along the four cross support struts, which form the outer square in the rear view of Fig. 4. The other four contact points are the four foot pads located at the vertices of the same square. These eight points of contact distribute the contact force on the PRE and prevent puncture of the Kevlar shell.

The PRE is held firmly against the modified ACD by two tethers connected to one of the PRE carrying straps. The primary tether consists of a standard adjustable wrist tether with its other end hooked to one of two waist attachment rings located on the front torso of the pilot's space suit. The secondary tether is the 4-ft adjustable self-reeling tether that is an integral part of the mini-workstation carried on the pilot's chest. All of this equipment used to secure the PRE is standard flight-tested EVA equipment.

The ACD and all of the equipment used to secure the PRE to the modified ACD are on-the-shelf. Consequently, the proposed connecting device satisfies the overall design requirement and is immediately available. In the following sections, the proposed design will be compared to the operational and performance requirements and the results of a computer simulation of the performance of the proposed IRV will be presented to show that the proposed design appears to be a viable candidate for serving as an interim space rescue ferry vehicle.

## Operational Analysis

The first operational requirement is adequate visibility for the IRV pilot. The average IRV pilot's horizontal line of sight lies 2⅞ in. above the top of the PRE in the proposed IRV design. This corresponds to a look-down angle of 3.34 deg. An experiment conducted by Halsell[6] and an astronaut interview, also conducted by Halsell,[6] indicate that this provides adequate visibility for the most delicate task of docking the IRV with the Orbiter airlock hatch.

The second operational requirement (ease of use) is not satisfied by the basic design, but can be satisfied by two simple modifications. The shortcoming in the proposed design is that the carrying handle of the PRE falls 8 in. short of the IRV pilot's reach when the PRE is positioned in the modified ACD. Consequently, the IRV pilot cannot connect the two tethers to the PRE handle. This problem is solved by first lengthening the PRE carrying handles from their current 6 in. to 20 in. This is quickly done by attaching 14-in. extender loops to the present straps. Next, the IRV pilot must be equipped with a hook tool to ensure that he can reach the extender loops and pull them to within his grasp to connect the tethers. The hook tool is easily fabricated by adding a hook to a standard EVA probe tool; see Fig. 6. With these two modifications, all IRV pilot-operated items are current or slightly modified EVA support equipment pieces.

The proposed MMU/PRE connecting device is fully capable of being stowed in the Orbiter payload bay. The modified ACD can still be carried on the same bracket used for an unmodified ACD. The carrying bracket can then be mounted on the get-away special beam, a standard flight hardware item, by drilling several holes in the carrying bracket to match the existing holes in the beam. The get-away special beam itself can be mounted in 30 different locations in the Orbiter payload bay.[3]

Critical fits are avoided in the design and operation of the proposed connecting device. The modified ACD retains its flight-tested connection to the MMU and forms a natural basket for the PRE. The extender loops for the PRE carrying straps and the modified EVA probe tool provide sufficient tolerance to ensure that the extender loops can be reached by the IRV pilot and attached to the tethers.

The proposed MMU/PRE connecting device is also capable of quick response. The ACD can be modified in 2 man-hours; it is estimated that modifications to the 2 EVA probe tools, to the 12 carrying straps of 6 PRE's, and ACD carrying bracket will total an additional 36–48 man-hours if the required materials are on hand. A crisis action team can probably complete this work in half a day.

The design and operation of the proposed connecting device seem to provide sufficient safety to support its use. Either PRE carrying strap with an extender loop can be used to secure the PRE with the two tethers. The two tethers provide redundancy, but the carrying strap and extender loop are each single failure points. The loads on these devices, however, are intended to be only a small fraction of maximum rated strength to achieve a virtually rigid connection of the PRE to the MMU. These single-failure points can be backed up by using cord to lash the PRE to the modified ACD by the other carrying strap; however, this would have to be done by a space-suited astronaut in the stranded vehicle.

In summary, the major operational requirements of an MMU/PRE connecting device seem to be satisfied adequately by a modified ACD with only minor modifications to the PRE and two other pieces of flight-qualified hardware. Preliminary operational procedures for using the PRE, MMU, and modified ACD are discussed further by Halsell[6] for rescue of a crew of eight from a stranded tumbling Orbiter. In the next section, the performance analysis of the proposed IRV will be discussed to show the extent to which MMU control system performance is degraded.

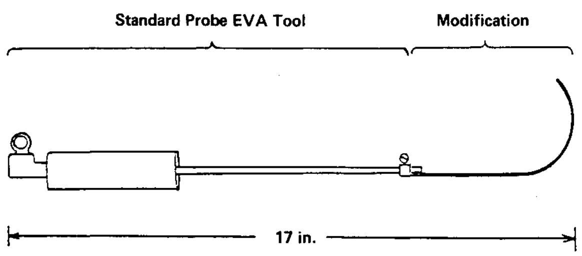


Fig. 6 Modified probe tool.

## Performance Analysis

Since the IRV is essentially an MMU with an attached structure, MMU performance and operation will be reviewed briefly to establish the baseline from which to judge IRV performance. This will be followed by a description of the software used to simulate MMU and IRV flight. The methods for determining the mass properties of the IRV and the control system adjustments for plume impingements on the PRE will then be discussed. Finally, MMU and IRV performance will be compared by using maneuvers that are typical of those required in a rescue operation. This comparison will be made assuming the PRE and occupant are rigid and motionless relative to the MMU. Occupant motion is highly restricted, and maneuvers are not expected to excite significant relative motion. Any such motion would, of course, affect IRV handling qualities.

The MMU is a one-man propulsive backpack attached to the standard NASA space suit. Equipped with completely redundant propulsion, electrical, and control subsystems, the MMU is permitted to fly untethered from the mother ship. The propulsion subsystem is fueled by two bottles of gaseous nitrogen. Each bottle supplies a separate set of 12 cold jet nozzles that produce translational forces and rotational moments. Propellant cross feed is possible to make all propellant available to either set of 12 thrusters. Two batteries are the heart of the electrical subsystem. Dual hand controllers and dual control electronics assemblies (CEA) are the basis of the control subsystem. The CEA's contain gyros, control logic, and amplifiers that interpret hand controller inputs and deliver commands to the thrusters. Full six-degree-of-freedom maneuvering is possible.[7]

MMU performance can be quantified in terms of total velocity change capability, and translational and rotational acceleration capabilities. Each thruster produces 1.7 lb of force and the 24 thrusters are employed by the control system to give a translational acceleration capability of approximately 0.28 ft/s/s and a total velocity change capability of approximately 67 ft/s from 0.72 slugs of usable gaseous nitrogen. Angular accelerations about the three MMU axes of Fig. 5 can be produced[8] in the range of about 8.7 to 9.2 degrees/s/s. These quantities provide a check of the simulation software to be described later.

The MMU control system has three modes of operation, and an automatic attitude hold submode (AAH) is available in each mode. Thruster select logic tables for each mode provide the inputs required by the CEA's to convert hand controller commands to thruster firing commands. Thrusters are either on or off as required. The primary control mode makes use of the full capability of both halves of the propulsion subsystem. If one half should become unavailable because of some failure, operation reverts to a backup mode. The third mode is pilot selectable and is called the satellite stabilization mode. This mode was designed to stop the rotation of a spinning satellite connected to the MMU with the ACD and is not optimized for translational motion. Instead, thruster plume impingement on the satellite is minimized by avoiding where possible the use of forward-firing jets; control moments are increased by firing more thrusters or by firing thrusters with longer moment arms. This third mode is also of interest because it provides an alternative to the primary mode when considering IRV control.

The AAH submode is pilot selectable and is used to stop all MMU rotation and hold the vehicle in the resulting attitude. Subsequent single-axis rotational commands disable the AAH only about that axis until the pilot re-engages the AAH. During translational maneuvers, AAH maintains the MMU in the nominal attitude. About each axis of the MMU shown in Fig. 5, AAH functions to reduce the angular rate to $\pm 0.20$ deg/s by commanding appropriate thrusters full on. Then AAH holds the angular displacement to within $\pm 1.25$ deg of the angular position that exists at the instant the angular rate goes within the rate limits. Once within the rate limits and except during translational maneuvers, the thrusters fire only as a result of angular displacement errors. When the error is between 1.25 and 6.0 deg, the appropriate thrusters pulse to produce an angular rate greater than 0.01, but less than 0.20, deg/s in the opposite direction. If the error should become greater than 6.0 deg, the appropriate thrusters are commanded full on to produce the required angular rate in the opposite direction. During translational maneuvers, AAH will also use full-on thrusters to counteract induced rotational rates in excess of $\pm 0.20$ deg/s even if the displacement deadband is not exceeded. Any temporary excursions of the 1.25 deg deadband, including those caused by pilot limb motion, are filtered by a time delay to conserve propellant.[7]

MMU and IRV flight using the MMU control system can be simulated and analyzed using a flight simulation program called MILMU (man-in-the-loop-maneuvering-unit) implemented on a Hewlett-Packard 9825T minicomputer. MILMU is an adaption of NASA's desk top flight simulator, which models the flying qualities and performance of the MMU. The system model uses rigid body dynamics, but does not account for the time delay filter in the AAH submode. MILMU allows the user to specify the mass properties and the initial translation and rotational state vectors of both the MMU and a nearby free-flying satellite. Thruster effectiveness can also be modified to account for plume impingement. Translational and rotational commands are generated either by the user or by MILMU's duplication of the AAH submode of the MMU. In response to maneuver commands, MILMU updates the state vectors of the two bodies by integrating the equations of motion with a point-slope method.

While the MILMU is capable of producing various outputs, including graphic displays of the two bodies, only those directly related to MMU performance and stability are used here. Initial and final state vectors, maneuver time, and fuel used provide information on average acceleration and velocity change capabilities and average specific fuel comsumption. Phase plane plots of angular rotations and angular rates about each body axis illustrate the stability properties of the nominal attitude during commanded maneuvers. IRV performance is analyzed from similar output produced by changing the MMU mass properties and by modifying the thruster effectiveness data to account for plume impingement. All phase plane plots produced by MILMU with AAH engaged show angular excursions slightly smaller than actual because the effects of the time delay in the AAH submode are not present. Motion of the free-flying satellite modeled by MILMU is of no interest in this study.

Besides an initial MMU state vector, MILMU also requires the MMU mass properties. In this study, two configurations are important. The first is the MMU with a pilot, which yields one set of mass properties. The second is the MMU/pilot plus a modified ACD, a PRE, a PRE occupant, and an oxygen bottle, which yields another set of mass properties. In each case, the composite system mass center must be referenced to the MMU coordinate system fixed at the geometric center of the MMU thrusters as shown in Fig. 5. Furthermore, in each case the inertia matrix of the system must be expressed in an axis system at the mass center with its axes parallel to the axes fixed in the MMU in Fig. 5.

**Table 1 MMU/pilot mass properties**

| Mass, slugs | Mass center, in. | Inertia matrix about mass center, slug·ft$^2$ |
|---|---|---|
| 24.67 | $x = 0.55$ | $I_{xx} = 37.21$ |
| | $y = -0.05$ | $I_{yy} = 40.08$ |
| | $z = -2.54$ | $I_{zz} = 26.12$ |
| | | $I_{xy} = 0.06$ |
| | | $I_{xz} = 2.59$ |
| | | $I_{yz} = 0.01$ |

The mass properties of the MMU with a pilot as a single component have been calculated and validated by flight experience. The combined system mass properties are given in Table 1 for an MMU with full propellant tanks, an average male astronaut, hand controller arms at the "E" (average) length, a helmet television camera, helmet lights, and a mini-workstation.

The mass properties of the IRV are formed from the mass properties of Table 1 and the mass properties of the other four components identified above. The mass properties of the modified ACD are listed in Ref. 9. The mass properties of an inflated PRE are not yet documented, so the mass of the PRE was measured and its inertia properties were calculated by assuming that it was a 34 in. diam, homogenous, spherical shell. The mass properties of the PRE occupant, however, had to be obtained by considering the folded shape of the occupant, his orientation inside the PRE, and the orientation of the PRE relative to the modified ACD.

The folded shape of the PRE occupant was modeled with the assistance of the Air Force Aerospace Medical Research Laboratory's articulated total body model software. In this software, the body of the average male Air Force pilot is divided into 15 segments. The software operates to allow the user to articulate the body into any feasible shape and then to calculate the mass properties of each segment with respect to a user-defined coordinate system. The body model articulated nicely to fit inside the PRE as shown in Fig. 7. The resulting mass properties were then calculated and documented by Halsell.[6]

The orientation of the occupant inside the PRE is determined by the restraining strap, but the PRE can be secured to the modified ACD by either carrying strap and in any orientation angle about the $x$ axis of the PRE as shown in Fig. 5. In this analysis, the PRE was secured to the modified ACD to achieve the mass properties most favorable to IRV performance. This is done by using the carrying loop closest to the PRE occupant's back in Fig. 1 to secure the PRE to the modified ACD and by orienting the PRE so that the head of the PRE occupant, on the $+z$ axis of the PRE, is down as shown in Fig. 5.

With the PRE occupant's orientation relative to the MMU determined, the oxygen bottle was then modeled as a homogenous 0.78 slug cylindrical shell 18 in. long and 6 in. in diameter with flat circular end disks. The bottle was positioned between the occupant's legs at the location and orientation selected by Halsell.[6]

Further details on the mass properties of the modified ACD, the PRE, the PRE occupant, and the oxygen bottle are available in the work of Halsell.[6] This work is summarized in Table 2 where the composite mass properties of the IRV system are given. Tables 1 and 2 can be compared directly to see the effect of adding the four components to the MMU/pilot to form the IRV. Note that from a mass properties consideration the modified ACD is not the optimal connecting device between the MMU and PRE. Halsell[6] points out that the mass of the modified ACD is 1.13 slugs, while a similar device could be designed from scratch with a mass of only about 0.4 slugs. This represents a mass savings of only about 1%, but the favorable effects on the inertia matrix could be more significant. The two tethers used to secure the PRE and the extender loops on the PRE carrying handles were considered to have negligible effect on the mass properties.

Turning now to plume impingement effects, the proposed IRV design suggests that only those thruster plumes directed in the $+x$ direction in Fig. 5 would impinge significantly on the modified ACD and PRE. There are four thrusters on the MMU so oriented. The forces and moments exerted by these and all other MMU thrusters on the IRV are provided to MILMU in a look-up table. Consequently, the table entries for the four affected thrusters must be modified to assess IRV performance. A plume impingement model[10] was used to modify the look-up table entries for these four thrusters. In doing so, the modified ACD was ignored and the impingement effects were assumed to be dominated by the spherical shape of the PRE. The plume impingement model integrated the local dynamic pressure of each plume over the surface of the PRE to compute four impingement force vectors and their points of action on the PRE. From these data, the force and moment components of each of the four thrusters were adjusted in the look-up table in MILMU. All such data are presented in detail by Halsell.[6]

To study the performance of the IRV relative to that of the MMU, MILMU was used to generate response data of each piloted vehicle to translational commands along all three axes and to rotational commands about all three axes. This was done in the primary control mode for the MMU to establish a baseline and confirm the software. For the IRV, this was done in the primary control mode and in one of two similar backup modes. IRV response data in the satellite stabilization mode was produced only for rotational maneuvers, however, because they were required only to verify the analysis by Halsell,[6] which concluded that use of this control mode was undesirable. This analysis will be described later. In all of these simulations, the AAH submode was engaged.

Translation maneuvers were performed in the $\pm x$, $+y$, and $+z$ directions. Thruster periods of 5 s were used for each maneuver. Then, each simulation was continued until AAH reduced the induced rotation rates below 0.1 deg/s with an algebraic sign opposite to the attitude error. Average translational accelerations were computed by dividing the velocity change achieved in 5 s by that same time. Specific propellant consumption was determined by dividing the mass of propellant consumed in 5 s by the velocity change achieved in that time. Phase plane plots showed histories of the attitude excursions from nominal during the simulations.

Positive rotational maneuvers of 1 or 2 s were ordered about the $x$ axis, and 5 s positive rotational maneuvers about the $y$ and $z$ axes. Again, these simulations were continued to null undesired rotations in the same manner as in translational simulations. Average rotational accelerations and specific propellant consumptions were computed as above, using angular velocities and appropriate time intervals. Phase plane plots also showed attitude excursions as above.

From the simulations of the two piloted vehicles in the primary control mode, acceleration capabilities and specific fuel consumptions were calculated and are compared in Table 3.

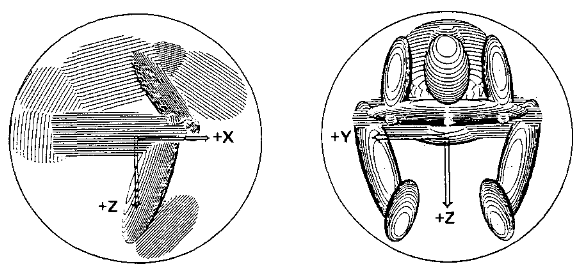


**Fig. 7 Computer simulated passenger in PRE.**

**Table 2 IRV mass properties**

| Mass, slugs | Mass center, in. | Inertia Matrix about mass center slug·ft$^2$ |
|---|---|---|
| 32.33 | $x$ = 12.71 | $I_{xx}$ = 42.62 |
| | $y$ = −0.03 | $I_{yy}$ = 154.50 |
| | $z$ = −1.58 | $I_{zz}$ = 139.61 |
| | | $I_{xy}$ = 0.18 |
| | | $I_{xz}$ = 11.54 |
| | | $I_{yz}$ = 0.00 |

The values in Table 3 for the MMU generally agree with the published MMU performance data discussed earlier. IRV translational accelerations along all three axes were degraded due to the increase in mass. The effect of plume impingement is seen by comparing $+x$ data to $-x$ data. The larger performance degradations in $+y$ and $+z$ maneuvers are explained by referring to the mass properties data in Tables 1 and 2. Note the 12 in. shift of the mass center in the $x$ direction between the two tables. This forces the AAH submode to modulate thruster on times to cancel induced rotational moments. Acceleration capability is reduced accordingly and corresponding increases in specific propellant consumption result. IRV rotational accelerations were degraded by the increases in moments of inertia and specific propellant consumption increased accordingly except in roll maneuvers. Here, specific propellant consumption is further increased, possibly due to plume impingement effects on AAH submode efficiency. Further studies are necessary to verify this.

The phase plane plots of these simulations are all documented by Halsell[6] and are too numerous to include here except for a representative example. For this purpose, the two plots for the $+y$ translational maneuvers are shown in Figs. 8 and 9. Figure 9 for the IRV shows larger excursions of angular error than does Fig. 8 for the MMU, but Fig. 9 also indicates that the AAH submode is capable of adequately limiting these excursions. This is indeed the case in all IRV maneuvers using the primary control mode with the AAH submode engaged.

IRV performance was also studied in one of two backup modes. The results, however, are also generally applicable to both modes. In a backup mode, two thrusters are used to produce a moment about an axis just as in the primary mode. Consequently, in this mode IRV rotational performance is basically the same as in the primary mode. On the other hand, translational forces are produced by only two thrusters in a backup mode, while four are used in the primary mode. Here, IRV acceleration capability is reduced an additional 49% in each of the $x$ directions, 11% in the $+y$ direction, and 25% in the $+z$ direction. Specific propellant consumption was approximately the same as in the primary mode except in a roll maneuver about the $x$ axis where an unexpected 50% propellant savings occurred. Analysis of the phase plane plots suggested this to be caused by more effective control of coupled yaw, but further simulation is required to bear this out.

Also in the studied backup mode the AAH submode was found to be incapable of limiting angular errors about the $z$ axis (yaw) during $+y$ axis translation commands. This is shown clearly in Fig. 10. Upon termination of the translation command, however, AAH reduced the yaw rate and reestablished the yaw attitude stability of the IRV. This implies that an IRV pilot forced to operate in a backup mode should limit $y$ axis translations to short duration followed by a quiet period to allow AAH to correct the resulting yaw error. Alternatively, an adjustment to the control law might eliminate the instability.

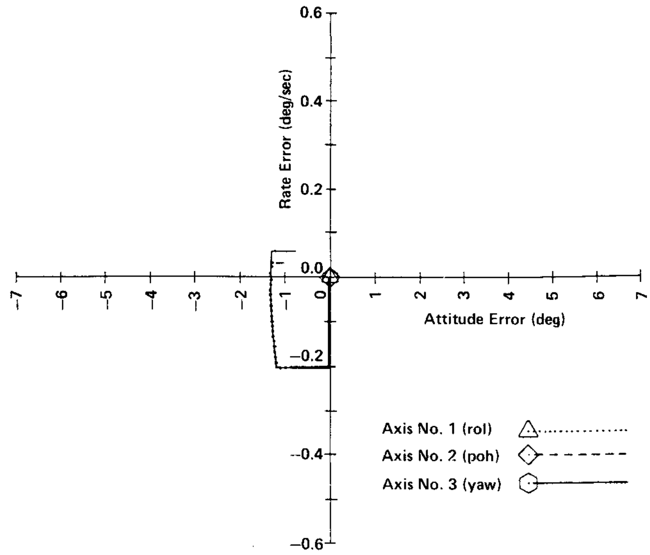


**Fig. 8 $+y$ translation of MMU in primary mode.**

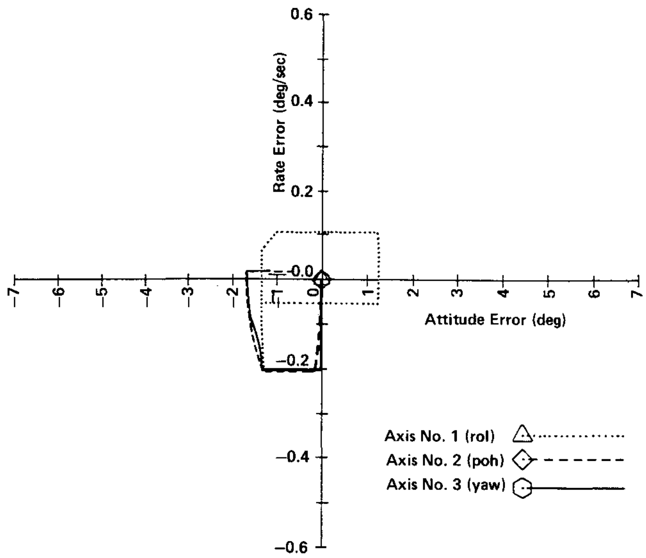


**Fig. 9 $+y$ translation of IRV in primary mode.**

**Table 3 MMU/IRV performance in primary mode**

| | Translational acceleration, ft/s/s | | | Specific propellant consumption, lb/ft/s[a] | | |
|---|---|---|---|---|---|---|
| Direction | MMU | IRV | % Change | MMU | IRV | % Change |
| $+x$ | 0.246 | 0.198 | −20 | 0.390 | 0.390 | −31 |
| $-x$ | 0.246 | 0.176 | −28 | 0.390 | 0.568 | +46 |
| $+y$ | 0.240 | 0.114 | −53 | 0.400 | 0.937 | +134 |
| $+z$ | 0.270 | 0.136 | −50 | 0.397 | 0.807 | +103 |

| | Rotational acceleration, deg/s/s | | | Specific propellant consumption, lb/deg/s | | |
|---|---|---|---|---|---|---|
| Direction | MMU | IRV | % Change | MMU | IRV | % Change |
| $+x$ (roll) | 9.08 | 7.80 | −14 | 0.009 | 0.057 | +533 |
| $+y$ (pitch) | 8.51 | 2.02 | −76 | 0.007 | 0.030 | +329 |
| $+z$ (yaw) | 8.27 | 0.41 | −83 | 0.010 | 0.049 | +390 |

[a]lbs = slugs × 32.2

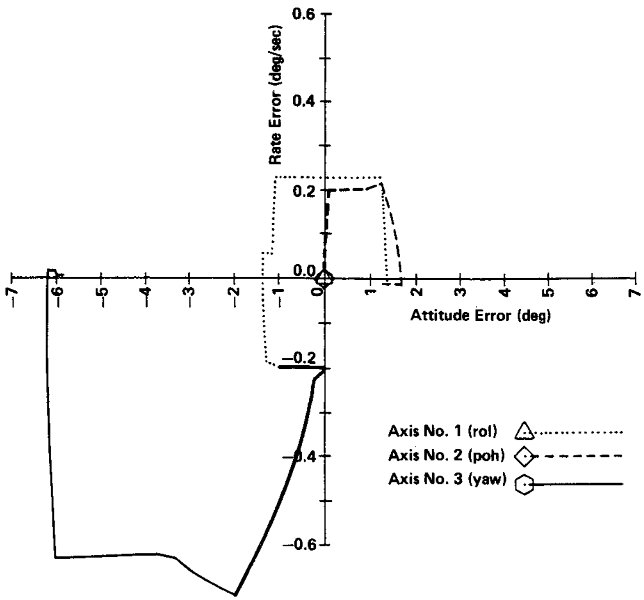


**Fig. 10** **+*y* translation of IRV in backup mode.**

IRV performance using the satellite stabilization mode was initially analyzed by studying the method by which thrusters are employed to perform different maneuvers and calculating IRV response to the thruster forces and torques. This mode operates to produce rotations without using forward-firing thrusters, so that maximum torques are applied while avoiding plume impingement. Specifically, yaw and pitch are produced from rotations coupled with translations. This appears to be of no benefit to the IRV, however, because it is much less massive than the system composed of the MMU, ACD, and a satellite. Consequently, the IRV can experience translational accelerations on the order of 0.100 ft/s/s during rotational maneuvers in this mode. This does not appear desirable for the delicate maneuvering required to rendezvous in the rescue scenario. To verify this analysis, rotational maneuvers were simulated using the satellite stabilization mode, and the expected coupling between translation and rotation during pitch and yaw was indeed seen.

## Conclusions

A specific design for an interim space rescue ferry vehicle (IRV) has been presented. The design was based on the manned maneuvering unit (MMU) augmented with a modified apogee kick motor capture device (ACD) to form a vehicle capable of transporting a stranded astronaut in a personnel rescue enclosure (PRE) from a disabled Space Shuttle Orbiter to a rescue Orbiter. An analysis of IRV performance using NASA simulation software tends to verify a previous preliminary analysis that suggests that the MMU might be used as a space rescue ferry vehicle. The design presented here is not optimal, however. The modified ACD is more massive than necessary and does not optimally position itself and the PRE relative to the MMU. Furthermore, in a backup control mode to the primary mode, an instability was found that may be unacceptable and require a control law adjustment. On the other hand, the MMU and the ACD are immediately available flight-qualified hardware. When the PRE becomes man-rated, this rescue vehicle might provide an immediate means by which a rescue mission could be executed.

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