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SELF-RESCUE STRATEGIES FOR EVA CREWMEMBERS EQUIPPED WITH THE SAFER BACKPACK

Trevor Williams[1] and David Baughman[2]

An extravehicular astronaut who becomes separated from a space station has three basic options available: grappling the station immediately by means of a "shepherd's crook" device; rescue by either a second crewmember flying an MMU or a robotic-controlled MMU; or self-rescue by means of a propulsive system. The first option requires very fast response by a tumbling astronaut; the second requires constant availability of an MMU, as well as a rendezvous procedure thousands of feet from the station. This paper will consider the third option, propulsive self-rescue.

In particular, the capabilities of the new Simplified Aid for EVA Rescue (SAFER) propulsive backpack, which is to be tested on STS-64 in September 1994, will be studied. This system possesses an attitude hold function, so can automatically detumble an astronaut after separation. On-orbit tests of candidate self-rescue systems have demonstrated the need for such a feature. SAFER has a total Δv capability of about 10 fps, to cover both rotations and translations, compared with a possible separation rate of 2.5 fps. But the Δv required for self-rescue is critically dependent on the delay before return can be initiated, as a consequence of orbital effects. A very important practical question is then whether the total Δv of SAFER is adequate to perform self-rescue for worst case values of separation speed, time to detumble and time for the astronaut to visually acquire the station.

This paper shows that SAFER does indeed have sufficient propellant to carry out self-rescue in all realistic separation cases, as well as in cases which are considerably more severe than anything likely to be encountered in practice. The return trajectories and total Δvs discussed are obtained by means of an "inertial line-of-sight targeting" scheme, derived in the paper, which allows orbital effects to be corrected for with only the visual information available to the pilot, namely the line-of-sight direction to the station relative to the stars.

INTRODUCTION

A space station which is in orbit for an extended period of time will require a great deal of Extra-Vehicular Activity (EVA) by astronauts for service and repair work. There is therefore a significant possibility that an EVA crewmember will at some point become separated from the station. Such a separation could occur, for instance, if a safety tether

1 Associate Professor, Department of Aerospace Engineering, University of Cincinnati, Cincinnati, Ohio 45221. Phone: (513) 556-3221; e-mail: twilliam@uceng.uc.edu. Senior Member, AIAA and AAS.

2 Acoustics and Vibration Associate Engineer, General Dynamics Electric Boat Division, 75 Eastern Point Road, Groton, Connecticut. Phone: (203) 433-1696. Member, AIAA.

broke or were not fastened correctly. Examination of data from the Weightless Environment Training Facility (WETF) at NASA Johnson Space Center suggests[1] that this may be expected to occur about once every 1,000 EVA hours. Unfortunately, unlike the Space Shuttle Orbiter, a station is not a maneuverable spacecraft. It therefore cannot chase and recover a drifting astronaut. Also, even if an Orbiter or Soyuz spacecraft were docked to the station when a separation occurred, the long lead time required for undocking and backing away from the station would make these vehicles unsuitable for EVA rescue. Some other rescue technique is therefore required.

The various types of system studied to date for EVA rescue can be summarized as follows. The first possibility is to have the separated crewmember rescued by another astronaut flying the Manned Maneuvering Unit (MMU)[2]. However, this requires constant availability of both the MMU and the second crewmember, as the reaction time of such a system is critical. Even allowing only 10 minutes for the second astronaut to reach, ingress, checkout and launch the MMU, rendezvous with the drifting crewmember occurs[3] thousands of feet from the station. At these distances, orbital effects play an important role, making it necessary to use a closed-loop rendezvous targeting scheme[4] if rescue is to be achieved without exhausting MMU propellant. This would likely require the addition of hardware, for instance ranging equipment or a Global Positioning System (GPS) receiver, to the MMU. The EVA Retriever[5], a proposed robotic-controlled MMU, would allow the initial reaction time to be reduced; however, this vehicle would be expensive to develop, and so is not likely to be available for near-term space station applications.

The other available alternatives all involve some form of *self-rescue* of the drifting astronaut. The simplest type of approach makes use of a "shepherd's crook" to allow the crewmember to grapple the station. Four examples of this type of system were flown, but not actually tested, on the STS-49 mission in 1992[6,7]. These devices, which are typically 12 - 20 feet long when fully deployed, would be useful in cases where the initial separation velocity and tumble rates are comparatively low. However, there are many credible separation scenarios where this will not be the case[8]. For these cases, it is necessary to consider propulsive self-rescue systems. The simplest such system is a Hand-Held Maneuvering Unit (HHMU), or "gas gun", of the type flown on Gemini[9], Skylab[2,10], and on STS-49 as the Crew Propulsive Device (CPD)[7]. These work adequately for short translations. However, a major difficulty for the self-rescue application is that they require the crewmember to visually determine his tumble rates about all three axes, and then position the HHMU in such a way as to null these rates. This would be likely to prove very challenging in practice, given the limited visual cues available to a crewmember tumbling away from the station, possibly at night. For this reason, one of the recommendations that followed from the CPD on-orbit test was[7] that any self-rescue device provide an automatic detumble function.

The Simplified Aid for EVA Rescue (SAFER) backpack[11-13], to be flown on STS-64 in September 1994, is planned to satisfy this requirement. This system, essentially a minimized derivative of the MMU, provides full six degree-of-freedom control by means of a set of 24 cold-gas thrusters. It also possesses an automatic attitude hold function, so allowing detumbling to be achieved automatically, and provides a total Δv of 10 - 12 fps. Self-rescue strategies based on the capabilities of this system are the subject of this paper. These make use of an "inertial line-of-sight targeting" scheme which does not require that either range or range rate data be accessible to the pilot. Instead, only the visual cues that are readily available to the astronaut, namely the motion of the line-of-sight to the target relative to the stars, are required. Both realistic separation cases, which may actually occur in practice, and more extreme cases will be examined. The extreme cases, with either quite high initial Δvs or long delay times until return can be initiated, serve to clarify the boundaries of the performance envelope of SAFER-equipped self-rescue. This study will show that all credible separation cases, and many extreme ones, are easily within the capabilities of SAFER.

EVA SELF-RESCUE DETAILS

Analysis carried out early in the Space Station Freedom program suggested that it would be possible for an EVA crewmember to separate from the station at rates of up to 3.5 fps. However, considerable uncertainty existed in this value; furthermore, estimates of the associated tumble rates were difficult to derive analytically. For these reasons, a series of tests were carried out on the Precision Air-Bearing Floor (PABF) at NASA Johnson, as well as in the KC-135 aircraft while flying zero-gravity parabolas[8]. Various types of possible separation scenarios were tested with four test subjects of differing sizes. Based on input from a test subject astronaut with EVA experience, the following two of these scenarios were deemed to be the most representative of possible actual on-orbit separations:

> *one-arm moderate push-off*, simulating a translational maneuver carried out untethered;
>
> *breakaway*, simulating the failure of a tether, or an article to which the astronaut is tethered, while under tension.

The separation speeds and tumble rates obtained in these tests varied considerably from individual to individual, and indeed from run to run for each individual. Taking all results together, the following values appear to be reasonable upper limits for use in practice:

Separation speed:	2.5 fps;
Pitch rate:	55 deg/s;
Roll and yaw rates:	20 deg/s.

It should be noted that these limits are somewhat conservative, in that a separation that yields a high linear velocity may well only produce low angular rates, and *vice versa.* The test case currently being used in Space Station self-rescue studies at NASA Johnson, namely a speed of 2.0 fps and angular rates of 30 deg/s about all three axes, is in line with this observation.

For comparatively benign separations (velocity less than 1.0 fps; total tumble rate less than 10 deg/s), some form of "shepherd's crook" may suffice to perform a self-rescue by grappling the station. Four versions of this basic type of system were flown on STS-49 in May 1992 as part of the Crew Self-Rescue (CSR) flight experiment[7]: these were the Inflatable Pole (IP), the Bi-Stem Pole (BP), the Telescopic Pole (TP), and the Astrorope (AR). The ranges of these devices were between 12 and 20 feet. The first three involved poles which were extended by nitrogen pressure (IP), an EVA power tool (BP) and manually (TP); all three could be fitted with an end effector designed to grapple a handrail or strut. The AR consisted of two cleat-like end effectors at the end of a Kevlar cord; this was intended to be thrown bola-fashion. Unfortunately, none of these devices were able to be tested on STS-49: the Intelsat capture and repair took three EVAs rather than the planned one, leaving less time than planned for CSR tests. However, it is clear from ground studies and tests that none of these devices is an adequate solution for crew self-rescue in all credible separation cases: they are too bulky when stowed, would be difficult for a tumbling astronaut to aim, and are not guaranteed to successfully grapple the station in the brief time available. Consequently, some form of propulsive system seems necessary to completely satisfy the requirement for self-rescue.

One such system was flown, and actually tested, on STS-49 as part of the CSR experiment. This is the Crew Propulsive Device, a redesign of the Gemini Hand-Held Maneuvering Unit. The HHMU is a pistol-like device which can provide positive or negative thrust directed along a single line. In principle, the crewmember can produce pure translational commands by holding the HHMU so that it thrusts through his center of mass. Attitude control is obtained by offsetting the thrust axis so as to produce the desired torque; unfortunately, translational inputs also inevitably result from the non-zero applied force. An HHMU was tested[9] during the first U.S. EVA, on the Gemini 4 mission, and a more capable unit flown on Gemini 10. This was found[2] to be adequate for short, straight-ahead translations where precise control was not required. However, it demanded a high level of crewmember concentration, as well as physical exertion due to the resistance of the pressure suit arm to bending. Similar conclusions were drawn as a result of the HHMU tests carried out inside the large Skylab workshop as a part of the M509 experiment[10], as well as after the tests of the CPD[7,14].

One of the main conclusions reached after the CSR tests[7] was that any self-rescue system should provide an automatic detumbling facility. The crewmember who tested the CPD felt that it was quite challenging to correctly identify multi-axis tumbles purely by eye. In fact, he estimated that he was only correct about half the time, despite being in the Orbiter payload bay with its rich visual cues. This identification problem would be considerably worse for a drifting astronaut, especially at night. An HHMU-based system with automatic detumbling was described and studied in[16]: this had an HHMU for translation, and a system of dedicated attitude jets and rate gyros for detumble built into the upper backpack of the proposed advanced Space Station suit. However, this is quite a complicated hybrid system, and still suffers from the extensive cross-coupling problems and high pilot workload of any HHMU. A much better approach appears to be to use a propulsive backpack such as SAFER. The background to this new system is the subject of the next section.

SAFER BACKGROUND AND DESCRIPTION

A propulsive backpack makes use of a set of fixed thrusters to provide the EVA astronaut with independent attitude and translational control, typically about all six axes simultaneously. Pilot workload is consequently greatly reduced; it is reduced even further if an attitude hold feature is provided. The Gemini Astronaut Maneuvering Unit (AMU) was the first example of a space-qualified backpack: this was carried on Gemini 9, but problems encountered when the pilot attempted to don the AMU prevented it from being tested[9]. The first on-orbit tests of an AMU vehicle were then carried out during Skylab, as part of the M509 experiment[10]. As was the case for the HHMU, these tests were conducted inside the Skylab workshop. The Skylab AMU proved to be very successful, and led directly to the development of the Space Shuttle MMU[15]. It was this vehicle that performed the first ever self-propelled untethered EVA, as a part of the STS-41B mission in early 1984. On two subsequent shuttle flights that same year, the MMU was used to participate in the Solar Maximum Mission spacecraft repair and to capture the Palapa B-2 and Westar-VI communications satellites for their return to Earth.

Although the MMU is an extremely versatile spacecraft, it is too bulky and expensive to be carried on all shuttle flights. There is therefore a need for a propulsive system which is small enough to be flown on every mission, and which is adequate for performing inspection or repair EVAs to otherwise inaccessible external surfaces of the Orbiter. Ideally, it would provide an attitude hold capability, in order to facilitate work in areas without handholds. This system would also be extremely desirable for the space station self-rescue requirement.

SAFER[11], shown shaded in Figure 1, is designed to satisfy both shuttle and station EVA requirements. It is a small, lightweight system which attaches to the underside of the standard Primary Life Support Subsystem (PLSS) backpack. It provides full six-axis control, as well as attitude hold, by means of a set of 0.8 lbf cold-gas nitrogen thrusters. Total Δv is at least 12 fps after the initial ground charge of the tanks, and at least 10 fps after subsequent on-orbit recharges. SAFER can be stored in the Orbiter middeck or airlock on a routine basis, then donned if needed for a contingency EVA. This type of operation is scheduled to be first tested on the STS-64 mission in September of this year. It is also envisioned that SAFER will be worn by all crewmembers on station EVAs.

Note that SAFER uses, for compactness, a single modified Apollo translational hand controller, together with a translation/rotation mode switch, to command all six degrees-of-freedom. On the station production version, this hand controller will be stowed in the side of the main SAFER compartment during normal EVA operations. In the event of separation from the station, automatic attitude hold is immediately engaged once the crewmember unstows the hand controller. Thus, the only delay before detumble of the astronaut is begun is the time that is required for him to free his hand of any equipment he may be carrying and reach the hand controller. This has the very desirable consequence of reducing the self-rescue reaction time as much as possible.

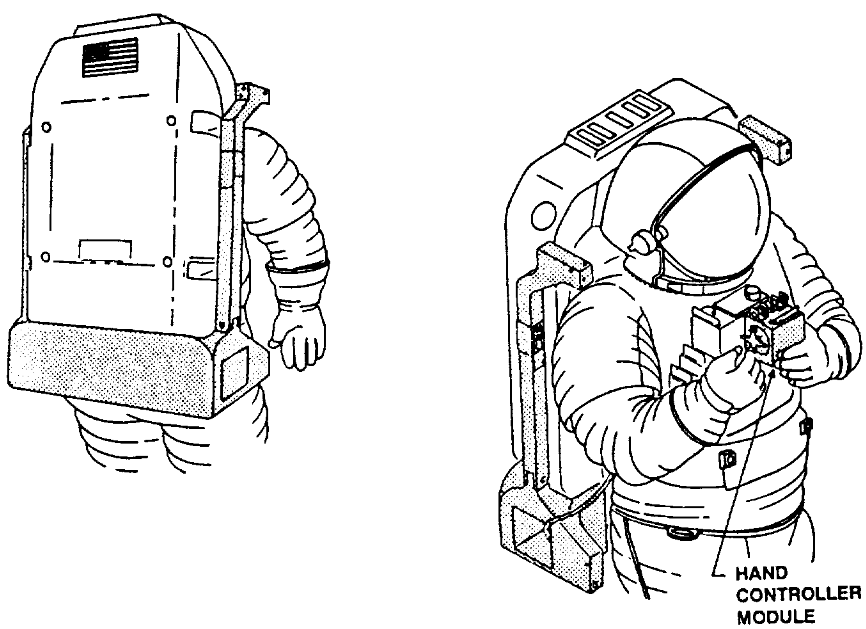

Figure 1 SAFER General View

ORBITAL DYNAMICS OF SELF-RESCUE

The motion of an object relative to another in a nearby circular reference orbit of angular rate ω is described by Hill's equations[17]. In the Local Vertical/Local Horizontal (LVLH) coordinate system that is normally used to describe on-orbit proximity operations, these become

$$
\begin{aligned}
\ddot{x} &= 2\omega\dot{z}, \\
\ddot{y} &= -\omega^2 y, \\
\ddot{z} &= 3\omega^2 z - 2\omega\dot{x},
\end{aligned}
\tag{1}
$$

where the x-axis is directed along the velocity vector (or VBAR) of the reference body, the z-axis along the negative local vertical (or RBAR), and the y-axis along the orbit normal. Note that the equation in y is decoupled from those in x and z; it represents simple harmonic motion out of the orbital plane. These equations have closed-form solutions, known as the Clohessy-Wiltshire (CW) equations[18], which can be used to determine in a straightforward way the motion that results from an initial known velocity. These expressions are

$$
\begin{aligned}
x(t) &= \{-2\dot{z}_0 \cos\omega t + (4\dot{x}_0 - 6\omega z_0)\sin\omega t - (3\dot{x}_0 - 6\omega z_0)\omega t + (2\dot{z}_0 + \omega x_0)\} / \omega, \\
y(t) &= \{\omega y_0 \cos\omega t + \dot{y}_0 \sin\omega t\} / \omega, \\
z(t) &= \{(2\dot{x}_0 - 3\omega z_0)\cos\omega t + \dot{z}_0 \sin\omega t - (2\dot{x}_0 - 4\omega z_0)\} / \omega,
\end{aligned}
\tag{2}
$$

where $\{x_0, y_0, z_0\}$ and $\{\dot{x}_0, \dot{y}_0, \dot{z}_0\}$ are the initial relative position and velocity of the body, respectively. Eq. (2) can of course be differentiated to give equally simple closed-form velocity expressions. The CW equations also lead to closed-form expressions for the magnitude and direction of the initial velocity required to transfer from a given position to a desired one in a specified time. This property makes them extremely useful in the terminal approach phase of the rendezvous problem. (See, for instance, [4] for details.)

The CW equations form the basis for a preliminary study of the self-rescue problem. First, Eq. (2) can be used to compute the position of an astronaut, who separated from the station with known initial velocity, after some drift time t_d. The net velocity required to return after some additional return time t_r can then also be found. Hence, as the velocity at the end of drift period is known from differentiating Eq. (2), the magnitude and direction of the burn required to initiate return can be found by subtracting these two velocities. While such a scheme is not usable in practice, as the EVA crewmember knows neither his velocity nor his position with great precision, it will serve to illustrate some important trends in the self-rescue problem. These will now be described, with special emphasis given to the in-plane motion. Out-of-plane behavior, being decoupled and sinusoidal, is quite simple to analyze separately and adds nothing of substance to what follows.

The first point to be made is the critical importance of initiating return as soon as possible. Consider the case of an astronaut who separates from the station (taken to be at an altitude of 185 n.mi.) at a rate of 3.0 fps in some arbitrary direction in the orbital plane, drifts while getting ready to maneuver back, and then applies an impulse derived from CW targeting. Figure 2 shows the dependence of the total Δv on both the drift and return times for the worst-case departure direction. It can be seen that total Δv increases extremely rapidly with increasing drift time. By contrast, increasing the return time reduces Δv slowly; note the different scales on the two axes. Thus, it is very important to keep the drift time as short as possible; return time can be extended somewhat if Δv must be reduced modestly. (Note that, in this example, the total Δv included both the burn to initiate return and a final braking burn to null approach rates. In practice, the braking burn could be deleted if necessary.)

The second point that follows from a CW analysis of self-rescue is that, if drift and return times are long enough, a simple burn directly back towards the station no longer gives a successful return trajectory. This can be seen from Figures 3 and 4 for a separation rate of 3.0 fps, a drift time of 5 min and a return time of 10 min. The solid curve in Figure 3 shows the offset between the line-of-sight (LOS) to the station and the direction along which the Δv should be applied as a function of departure angle (measured counter-clockwise from VBAR); the dashed curve gives the magnitude of the burn. The trajectories in Figure 4 then are as follows: outbound (solid); return after correct CW burn (dashed); return after a burn of the correct CW magnitude, but directed along the LOS (dash-dot). It can be seen that a pointing error in the return burn of only about 6 deg leads, in this case, to miss distances of about 200 ft.

It should be noted that the initial velocity, drift time and return time are all somewhat unrealistically high in this example, so as to more clearly illustrate the effects of orbital mechanics. However, it does serve to highlight a practical difficulty. On the one hand, a separated astronaut cannot implement a CW rendezvous scheme, as he has neither precise position and velocity information nor the computing capability required. On the other hand, if he fires directly along the LOS, he may miss the station altogether. Fortunately though, looking at the trajectories of Figure 4 in a "pseudo-inertial" coordinate system, i.e. one that has its origin fixed on the station but does not rotate to follow the LVLH frame, suggests quite a straightforward solution. In these coordinates (Figure 5), the outbound and desirable CW return trajectories can be seen to follow approximately straight paths. Therefore, a maneuver technique which produces nearly straight trajectories in these non-rotating coordinates and makes use only of the limited visual cues available to the astronaut, namely the LOS direction to the station, should lead to a good practical solution to the self-rescue problem.

The following "inertial LOS targeting" scheme satisfies these requirements. Beginning at the end of the drift phase, it proceeds as follows:

(1) Apply a Δv perpendicular to the LOS to (approximately) null any rotation of this line in inertial coordinates, i.e. relative to the stars.

(2) Apply a Δv along the LOS sufficient to set up a closing rate which will give recontact after roughly the desired return time.

(3) At periodic intervals (taken here as every 30 sec), the pilot checks the position of the station relative to the stars. If the inertial LOS direction has shifted by more than some deadband (taken here as 0.5 deg, the diameter of the Moon), a small Δv is applied perpendicular to the LOS and in the same direction as the shift. The magnitude of these corrective burns is taken here as 0.1 fps, which corresponds[11] to 0.5 sec of SAFER thrusting.

(4) (Optional) Apply a final braking burn along the LOS to reduce the final contact speed.

This scheme sacrifices some efficiency for the sake of feasibility. For instance, combining the two burns in steps *(1)* and *(2)* into a single one would lead to a reduced total

Δv. However, it would also make it harder for the astronaut to determine the correct direction along which to fire. Simulation studies to date suggest that inertial LOS targeting typically requires about 10 - 20% more propellant than would CW targeting. This modest increase seems well worthwhile, given the greatly improved robustness properties of the new scheme that result from its man-in-the-loop feedback. (A similar point was made in [19] concerning the sensitivity of Lambert rendezvous targeting.) As a final comment on efficiency, it should be noted that the parameters of the LOS scheme, i.e. interval length, deadband and transverse Δv magnitude, were all selected, after extensive simulation studies, so as to reduce the total Δv as much as possible while still ensuring recontact with the station.

SELF-RESCUE USING SAFER

The example in the previous section used a relatively large separation rate and drift and return times, in order to better illustrate orbital effects. More realistic values for these quantities will now be used, so as to demonstrate the most challenging return cases that may reasonably be expected to occur in practice.

The sequence of events involved in using SAFER for self-rescue is as follows:

(a) Astronaut frees right hand (if initially carrying equipment or tools) and unstows the hand controller. This automatically initiates SAFER automatic attitude hold (AAH), so beginning the detumbling phase.

(b) Once detumbling is complete, astronaut performs a visual search for the station.

(c) Astronaut carries out the inertial LOS targeting scheme described above.

The worst-case delays and Δv requirements for each of these stages can be found from the characteristics of SAFER and those of the self-rescue problem. On the basis of discussions with EVA personnel, a delay of 30 sec appears to be the longest that may be expected for step *(a)*; this phase of course requires no Δv. For single-axis rotations, SAFER has angular acceleration magnitudes[20] of approximately 4.25 deg/s^2 in pitch, 4.5 deg/s^2 in roll and 9.8 deg/s^2 in yaw; each second of such thrusting consumes propellant equivalent to a linear Δv of 0.1 fps. Consequently, nulling the worst expected tumbling rates (55 deg/s in pitch; 20 deg/s in each of roll and yaw) should take no more than about 19 sec and equate to a Δv of 1.9 fps.

A visual search pattern for step *(b)* that appears reasonable, again after discussions with EVA personnel, is to first perform a yaw scan at 20 deg/s. In the worst case, the station may be either directly above or directly below the crewmember, so this scan will not bring it into view. In that case, the yaw scan is halted after covering 360 deg and a pitch scan, again at 20 deg/s, is initiated instead. The field-of-view of the EVA helmet is large enough that these two scans should guarantee that the station will be visually acquired. In the worst case, this acquisition will occur near the end of the pitch scan.

Taking these considerations into account, the worst-case delay time to be expected in practice is as given below. Also listed is the propellant consumption required for the various "non-translational" maneuvers involved.

	Time (s)	Δv (fps)
Initial delay before activating AAH:	30	0.0
Stabilizing attitude using AAH:	20	1.9
Search pattern to find station:	50	1.2
Attitude control during return:	--	0.5
Sub-total:	100	3.6

Thus, a total delay time of 2 min appears to be a conservative worst-case value. (Of the numbers tabulated above, the only one for which significant uncertainty exists is the allocation of 0.5 fps for attitude control during the return cruise. This appears to be a reasonable value, but is subject to further analysis.)

Figure 6 shows the trajectories that result, in rotating LVLH coordinates, for an initial separation rate of 2.5 fps, a delay time of 2 min and a time for the return leg of 5 min. The solid curves are the outbound trajectories, and the dash-dot ones the returns obtained using the inertial LOS targeting scheme described previously. For completeness, departure angles ranging from 0 to 315 deg, in steps of 45 deg, are shown. Figure 7 gives the same trajectories in non-rotating coordinates, showing how close to straight both outbound and return trajectories are. The minimum Δv required for return (with no final braking burn) for the various departure angles is 4.08 fps and the maximum 4.16 fps, giving a grand total self-rescue Δv of about 7.7 - 7.8 fps. This is clearly easily within the capability (at least 10 fps) of SAFER. It is interesting to note that using a classical CW scheme would require a return Δv ranging between 3.44 and 3.63 fps for this example. Thus, the greatly enhanced feasibility of the new inertial LOS scheme was achieved with a performance penalty of only 15 - 19 %. Also, increasing the return time up to about 8 min or so modestly reduces the inertial LOS return Δv. Going beyond this time causes the Δv to increase again, as a result of the more numerous trajectory corrections required. This contrasts somewhat with the CW case, where increasing return time continues to reduce Δv (see Figure 2).

Two rather more extreme cases will now be considered. Although these should never actually be encountered in practice, they serve to quantify the performance reserves that SAFER possesses for self-rescue. In the first of these, the same 2.5 fps separation as above is assumed, but the delay is increased from 2 to 5 min and the return leg from 5 to 7 min. The resulting trajectories, in LVLH rotating coordinates, are given as Figure 8. Note that the inertial LOS targeting scheme achieves a successful return here despite the increased orbital effects introduced by the greater delay (compare the return trajectories in Figure 8 with those in Figure 4). The return Δv required in this case ranges between 4.98 and 5.49 fps, giving a grand total range of about 8.6 - 9.1 fps. This is still within the minimum specified capability of SAFER. (The performance penalty range of the inertial LOS scheme relative to CW targeting widened somewhat to 12 - 24 % in this example.)

Finally, Figure 9 shows the trajectories obtained for a drift time of 2 min, a return leg of 5 min, and a very high initial separation rate of 5 fps. Inertial LOS targeting again achieves successful returns in this case, with return leg Δvs now of between 6.38 and 6.16 fps; these are 7 to 16 % higher than the corresponding CW values. Once again, SAFER can be seen to be able to deal successfully with a rather extreme separation scenario.

CONCLUSIONS

This paper has studied the problem of self-rescue for an EVA crewmember who becomes separated from a non-maneuverable spacecraft such as a space station. As a first step, a discussion of plausible separation cases was given, yielding upper limits on expected separation speeds and tumble rates. The performance of the SAFER propulsive backpack was then described; of particular importance for self-rescue applications are its automatic detumble feature and its full six degree-of-freedom control. It was then noted that return to a space station after separation is complicated by the effects of orbital mechanics, as well as by the comparatively low Δv capability of SAFER. However, an "inertial line-of-sight targeting" scheme to accomplish this return was then described which requires only the visual cues that are readily available to the pilot, namely the motion of the line-of-sight to the station relative to the stars. This simple scheme was shown to allow successful return to the station with the Δv available using SAFER for all credible, and indeed some quite extreme, EVA separation cases.

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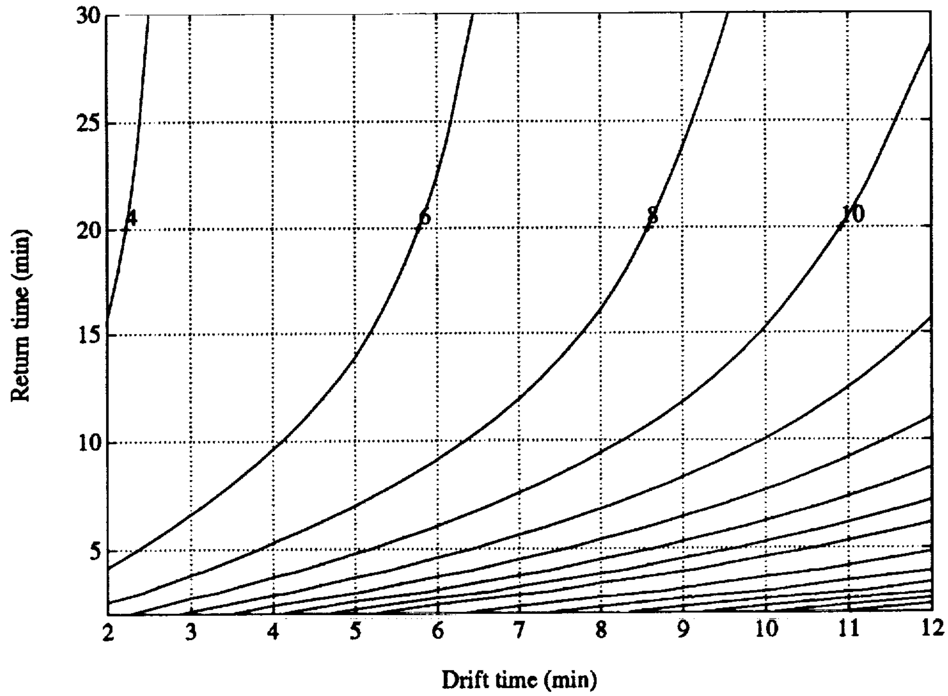

Figure 2 Worst Case Δv (fps) for Return Plus Braking

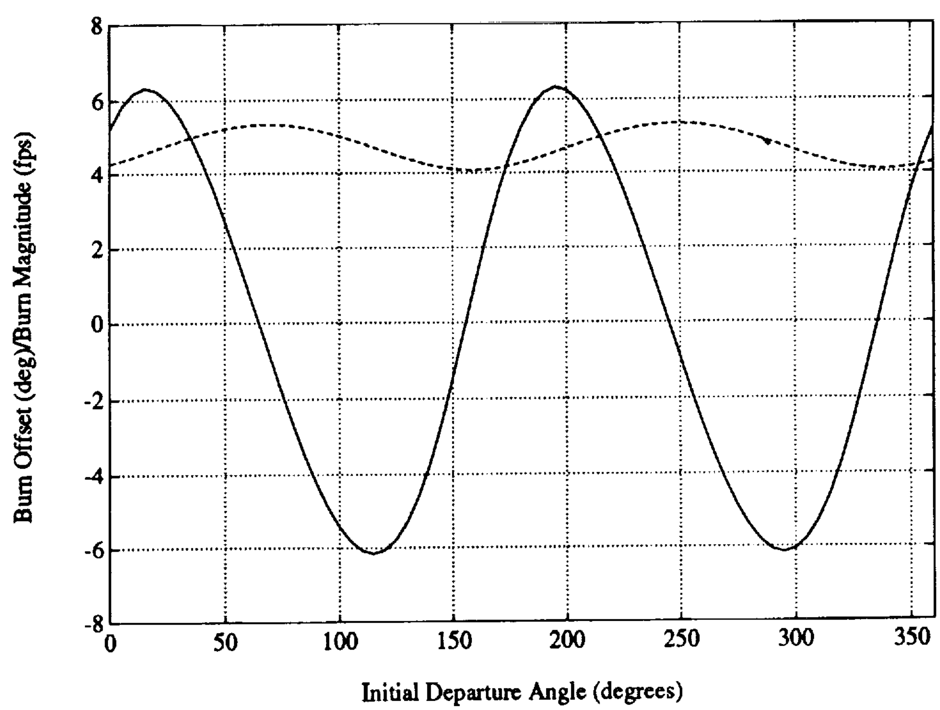

Figure 3 Direction and Magnitude of Return Δv

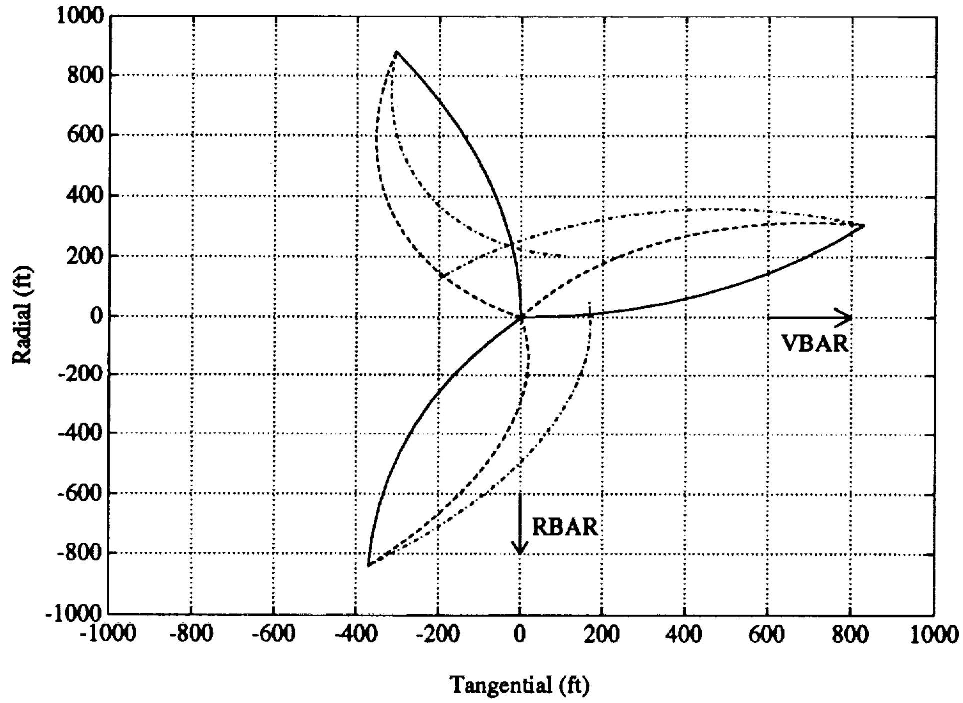

Figure 4 LVLH Outbound and Return Trajectories

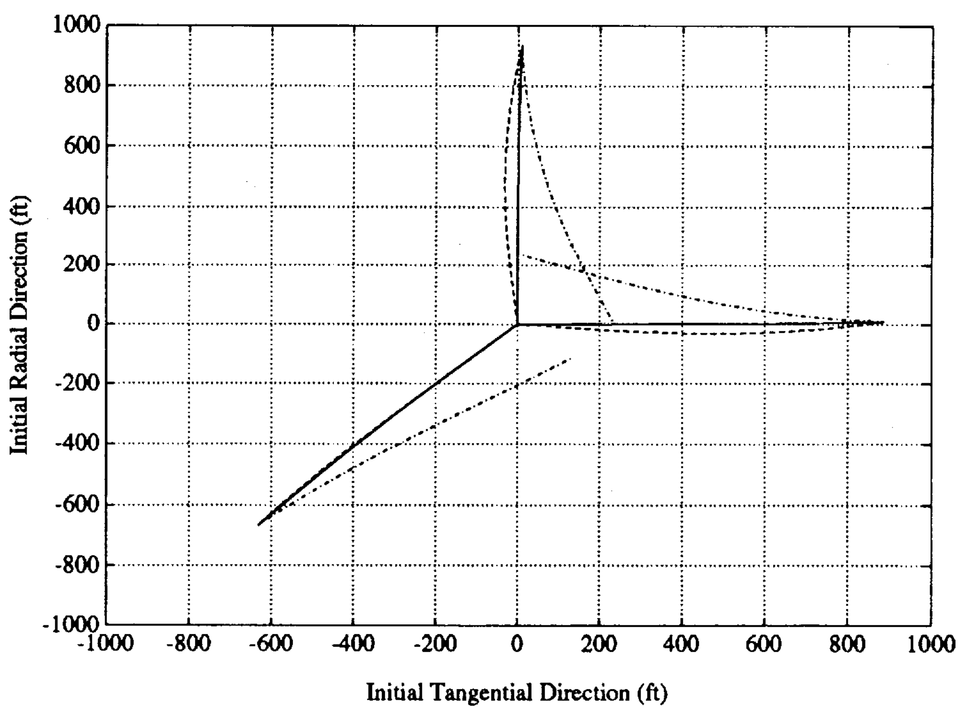

Figure 5 Trajectories in Non-Rotating Coordinates

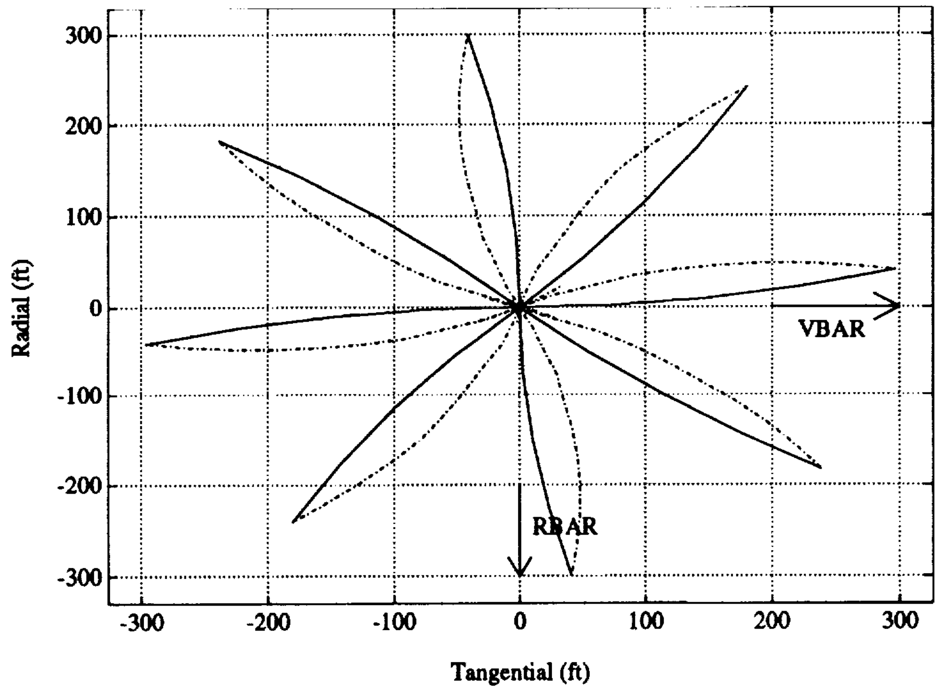

Figure 6 LVLH Trajectories, Worst Practical Case

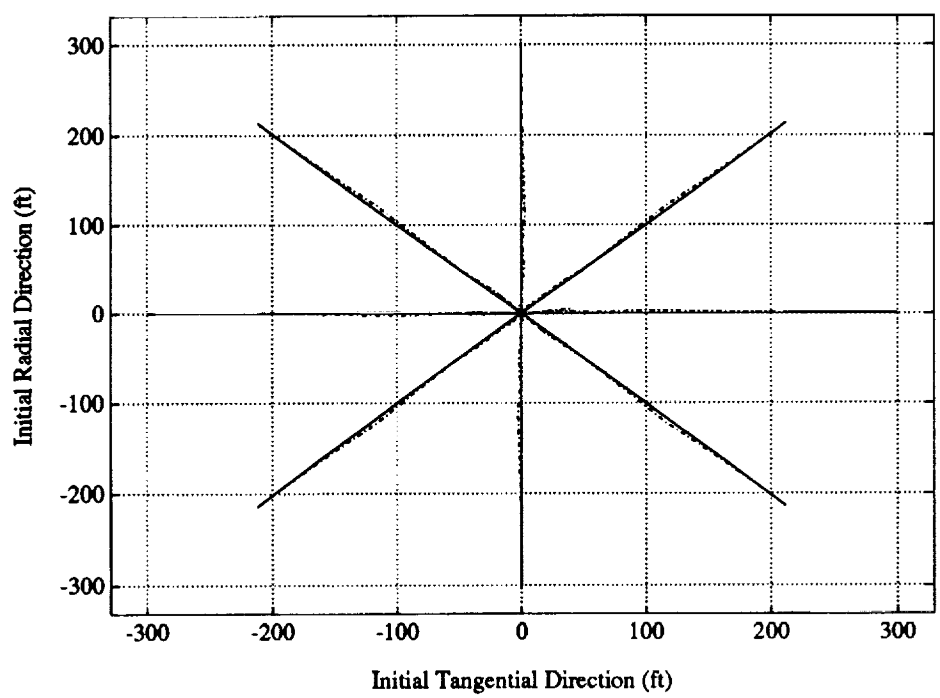

Figure 7 Trajectories in Non-Rotating Coordinates

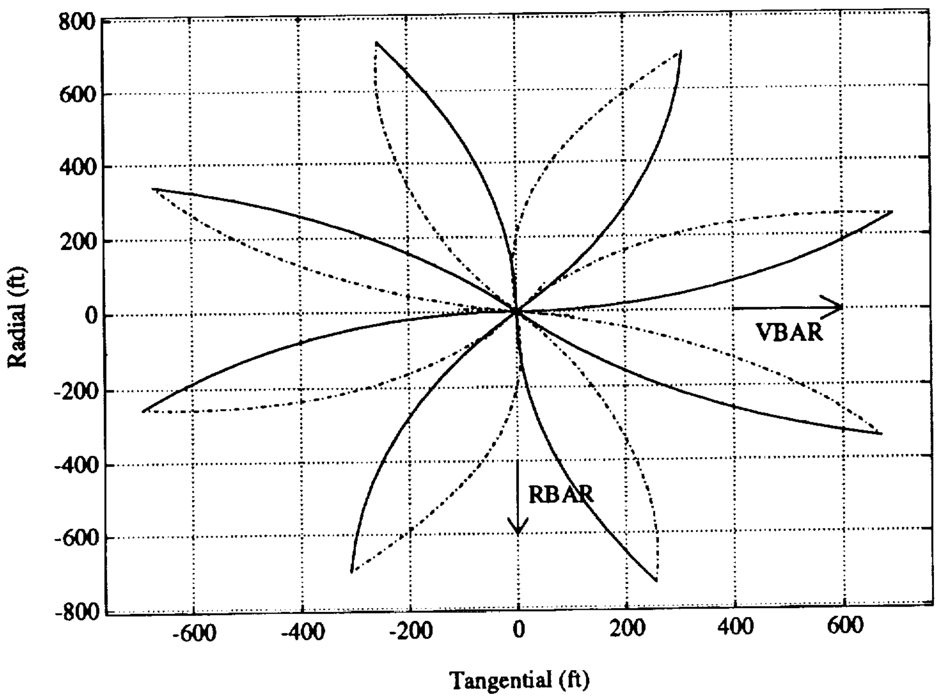

Figure 8 LVLH Trajectories, Long Delay Case

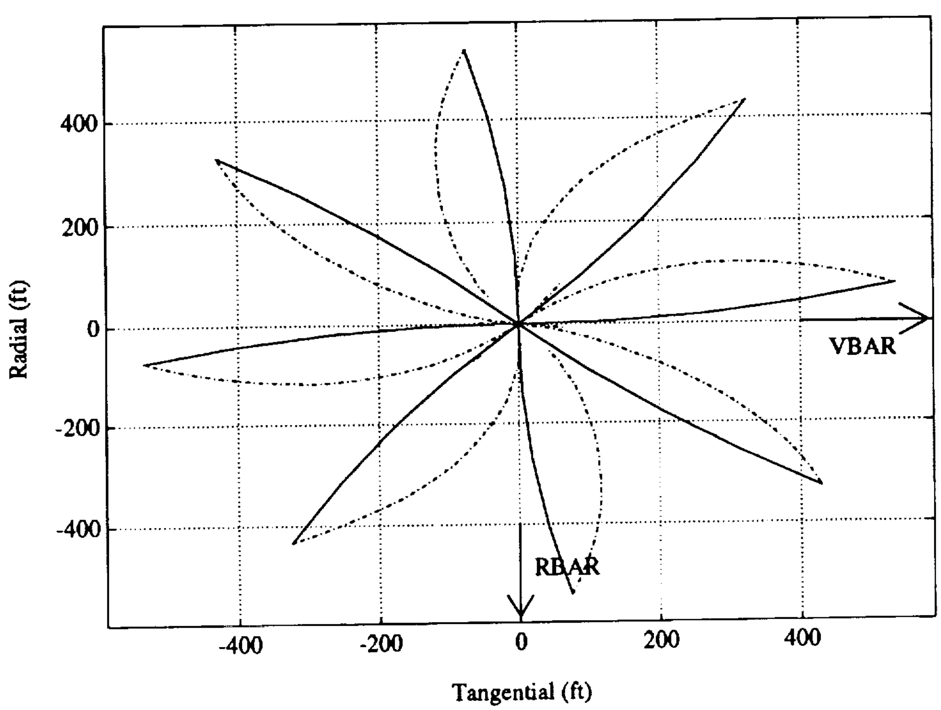

Figure 9 LVLH Trajectories, High Separation Rate Case