An Unaided EVA Rendezvous Procedure

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A backup EVA procedure for astronaut use in rendezvous with the shuttle is described. Crude range and range-rate data are needed, but no computations by the astronaut are required. Planar rendezvous information is presented to the astronaut in chart form. A preset average closure rate is employed to render the rendezvous trajectory unique. From any nearby in-plane initial position, the chart-directed rendezvous procedure results in a path that approximates the two-impulse rendezvous trajectory having the same average closure rate. Trajectories produced by the chart-directed rendezvous procedure are compared with the corresponding two-impulse trajectories and with a set of near-rectilinear trajectories produced using a procedure suggested by D.D. Mueller.

Introduction

ONCE the space shuttle becomes operational, astronauts will perform numerous EVA tasks using maneuvering units that are not attached in any way to the shuttle. Situations can be visualized in which it would be desirable for the astronaut to be able to return to the shuttle independent of externally provided guidance. (This procedure will be called unaided rendezvous.) In any case, the astronaut should be able to return to the shuttle along a fuel-conserving path in a reasonably short period of time. Also, the velocity of the astronaut relative to the shuttle upon arrival at the shuttle should be low to avoid high fuel comsumption during braking and/or possible hard impact upon arrival.

It is desirable that the maneuvering unit (MMU) be directed along paths that conserve fuel. Mueller[1,2] has shown that an EVA astronaut almost always would be better off without a tether line. The present study assumes that the astronaut is in the vicinity of the shuttle (close enough to discern its orientation) and has no tether attaching him to the shuttle. It also is assumed that there is no computation capability aboard the MMU. (This may change as the MMU develops.) There is no radio contact assumed between the shuttle (communications may have failed) and the astronaut, and the shuttle crew is aware of this fact.

The only actions assumed taken by the shuttle crew in this situation are as follows. First, the shuttle is reoriented so as to give the EVA astronaut the visual clues he needs concerning orbit plane, altitude, and direction of flight. It is assumed in this study that the shuttle is aligned with wings level, longitudinal axis in the orbit plane, and nose along the velocity vector (i.e., a "straight and level flight" orientation), although any predetermined attitude could be used. A prime constraint on shuttle attitude should be to keep the EVA astronaut in view at all times. When the astronaut views the shuttle in any known orientation, he can discern whether he is 1) above or below the shuttle (reference is the plane of the wings in the assumed orientation), 2) to the left or right of the orbit plane (reference is the shuttle plane of symmetry), and 3) ahead or behind the shuttle. In daylight, there are other visual clues that also would be available to the EVA astronaut, such as apparent ground track. Next, the shuttle crew uses its on-orbit maneuvering system to null any relative velocity between the shuttle and astronaut (visually or using radar) and then signals the astronaut via visual signal to initiate his rendezvous maneuver (flashing lights, etc.)

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Mathematical Model

A simple two-body model in which both the EVA astronaut and the shuttle are treated as particles orbiting a spherical Earth is employed in the equations of motion, since transfer times and separation distances are small. Any perturbing accelerations act equally on astronaut and shuttle because of the small separation distance. The shuttle orbit is presented here as circular to keep the demonstration of the procedure simple, although elliptic orbits have been modeled, and no major complications arise.

The shuttle-centered coordinate system used is the shuttle manufacturing coordinate system, shown in Fig. 1. The x axis points out the tail of the shuttle along the vehicle centerline, the y axis is upward normal to the plane of the wings, and the z axis points along the orbit angular momentum vector (out the left wing). Note that the velocity vector is in the $(-x)$ direction. This coordinate system is not a standard aircraft system but is that used by Dunning.[3]

In the shuttle-centered coordinates, the position of the astronaut is given by $\bar{r}_{A/S}$, whereas the positions of the shuttle and astronaut relative to the center of the Earth are given by $\bar{r}_S$ and $\bar{r}_A$, respectively. The velocity of the shuttle relative to the Earth is designated $\bar{v}_S$, and the angular rate of the shuttle around the Earth is $\dot{\nu}$ (constant for the circular orbit case).

The unaided EVA rendezvous procedure developed involves a set of linearized equations developed by Dunning.[3] These equations model the motion of the astronaut relative to the shuttle and are given by

$$\ddot{x} = 2\dot{y}\dot{\nu} + x\dot{\nu}^2 - \frac{\mu x}{[x^2 + (y+r_s)^2 + z^2]^{3/2}} \tag{1a}$$

$$\ddot{y} = -2\dot{x}\dot{\nu} + (y+r_s)\dot{\nu}^2 - \frac{\mu(y+r_s)}{[x^2 + (y+r_s)^2 + z^2]^{3/2}} \tag{1b}$$

$$\ddot{z} = \frac{-\mu z}{[x^2 + (y+r_s)^2 + z^2]^{3/2}} \tag{1c}$$

where μ is the gravitational parameter of the Earth, and r_s is the magnitude of the $\bar{r}_s$.

A comment concerning the fuel capacity of the MMU is in order at this point. Current MMU planning indicates that a nominal total $|\Delta\bar{v}|$ (velocity change capacity) of more than 20 m/sec will be available for any given EVA. In the simulation, no limit on available $|\Delta\bar{v}|$ is set. However, the $|\Delta\bar{v}|$ expended is monitored and checked against that projected as being available. Note that all of the $|\Delta\bar{v}|$ available at the start of the EVA will not be available to return to the shuttle. In the

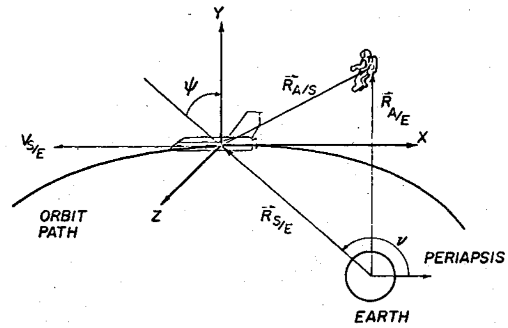

Fig. 1 Shuttle-centered coordinates.

present study, less than one-half of the available pre-EVA $|\Delta \bar{v}|$ is assumed available for return to the shuttle.

Rendezvous Procedure

The rendezvous problem under study can be stated simply. Given an initial position (x_0, y_0, z_0) and a zero initial relative velocity for a particle (astronaut plus MMU) at time t_0, find a velocity impulse $\Delta \bar{v}$ such that at some later time t_I the particle will pass through the origin of the coordinate system (the shuttle). When the particle arrives at the origin, a second $\Delta \bar{v}$ impulse can be used to null its velocity relative to the origin of the coordinates. The particle moves in accordance with Eq. (1) and orbital effects are quite apparent for all trajectories except those that involve extremely short transfer time $(t_I - t_0)$. Since short transfer times involve high relative velocities and $\Delta \bar{v}$'s, orbital effects will be apparent on all MMU rendezvous paths.

The freedom to choose transfer times results in an infinite number of possible rendezvous trajectories from any given initial state. Once a transfer time is chosen, then the two-impulse rendezvous trajectory becomes unique. For the present problem, the transfer time must be chosen in such a way that the total $|\Delta \bar{v}|$ requirement is small and the transfer time is reasonably short (Long transfer times are not desirable because of life support system limitations.) The two requirements on transfer times conflict because low $|\Delta \bar{v}|$ implies long transfer times.

Fortunately, compromises are possible which allow reasonable closure rates with low $|\Delta \bar{v}|$ requirements. For the present study, transfer times were chosen so that average closure rates of 0.5, 1.0, and 2.0 m/sec were obtained. For example, with the 1.0-m/sec closure rate, an astronaut 1625 m (about 1 statute mile) from the shuttle at t_0 would ideally reach the shuttle 1625 sec (about 27 min) later.

The in-plane (xy plane) rendezvous procedure will be discussed first, and then the modifications necessary to handle the out-of-plane case will be represented. The out-of-plane (z) motion is almost decoupled from the in-plane motion [see Eq. (1)] and is handled separately.

Once a unique transfer time has been defined for each point in the xy plane near the shuttle, the required relative velocity components become functions of position only. These can be presented graphically by plotting required relative velocity magnitude contours and superimposing short arrows at grid points to indicate the directions of the required relative velocities at the grid points. Figure 2 shows a plot of this type in which range circles have been added to the contours and arrows. In this plot, the range units are meters (500, 1000, 1500), and the required $|\Delta \bar{v}|$ units associated with the contours are meters per second (1, 1.5,...,5). The plot shown provides in-plane rendezvous information for the region $-2000 \text{ m} \leq x \leq 2000 \text{ m}$, $-2000 \text{ m} \leq y \leq 2000 \text{ m}$. Figure 3 shows a similar plot for a 1000-m region around the shuttle.

Note that, in the central region of Fig. 2 (parallel to the x axis, all $|\Delta \bar{v}|$'s are between 1.0 and 1.5 m/sec, whereas in the central region of Fig. 3, all $|\Delta \bar{v}|$'s are between 1.0 and 1.25

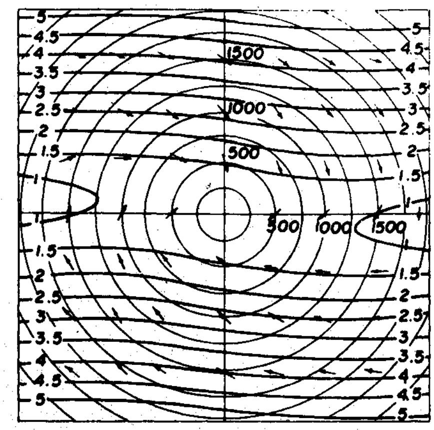

Fig. 2 EVA rendezvous information chart (average closure rate = 1.0 m/sec).

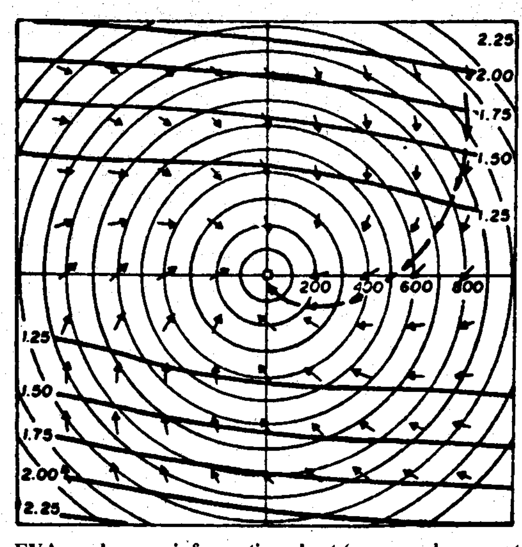

Fig. 3 EVA rendezvous information chart (average closure rate = 1.0 m/sec).

m/sec. Ideally, rendezvous from points inside the central region then should require less than 1.5 m/sec to effect intercept and then less than 1.5 m/sec again to null the relative motion at the shuttle. This is very important, since, if the astronaut goes out to service a satellite, etc., the most efficient stationkeeping positions for the shuttle are directly ahead and directly astern of the satellite. Thus, it could be expected that the astronaut might rendezvous most often starting from inside the central region.

To use the rendezvous charts, the astronaut first determines his range and range rate using a hand-held radar (current plans for the MMU include such a unit) or some other ranging device. He then estimates his position in the xy plane (or the projection of his position onto the x-y plane if he has a nonzero z coordinate). A vector component chart such as that used in determining aircraft landing crosswind components might be of use to him in this respect (see Fig. 4). He then examines the appropriate EVA rendezvous information chart (Fig. 2 or 3) and determines the direction and magnitude of the velocity impulse required for rendezvous. He then has two choices. He can either orient himself to thrust along the required direction (as best as he can estimate the required direction and point himself) and apply the required $|\Delta \bar{v}|$ (as best as he can estimate it), or he can use the vector component chart (Fig. 4) to get the x and y components of the required velocity impulse and then apply these separately while holding himself in a fixed attitude with thrusters aligned along coordinate axes (as best as he can). Which of these procedures would be best will depend on hardware capabilities and can be determined only in a high-fidelity simulation or in space because of the interrelated problems of angle estimation, $|\Delta \bar{v}|$ estimation (through timing of thruster firings or by using range-rate feedback from radar), and pointing accuracy.

After the $\Delta \bar{v}$ has been applied, the astronaut drifts along a path, which, if he has been accurate in carrying out the rendezvous procedure, will result in shuttle intercept at a low relative velocity. The astronaut can visualize what his path should look like by interpolating and following the relative velocity direction arrows from his initial point to the shuttle on the EVA rendezvous information chart (see Fig. 3).

If at any point the astronaut feels that he is deviating from the rendezvous path as he has visualized it, he can make a velocity correction. He will be able to determine range rate (using radar or a range finder and timer) and can estimate speed perpendicular to the line of sight by using estimated angular rate and range. Estimation of angular rate is a difficult problem, and procedures and/or equipment likely will have to be developed to aid the astronaut in carrying out the task. An operational procedure for making such corrections might call for the astronaut to 1) determine range and range rate, 2) refer to the charts and determine the desired relative velocity components at the current position, 3) estimate the current relative velocity components from range rate and line-of-sight rate, and 4) apply some fraction (75%-90%) of the estimated correction needed. In this way, overcorrection could be minimized.

It would be possible, of course, for the shuttle to cooperate in the rendezvous by observing the astronaut's initial $\Delta \bar{v}$ and then computing and applying a shuttle $\Delta \bar{v}$ that would compensate for any inaccuracies in the initial astronaut $\Delta \bar{v}$ application. If this type of shuttle cooperative rendezvous is used, the compensation should be made as soon as possible after the initiation of the rendezvous by the EVA astronaut to minimize shuttle fuel expenditure. In the present study, no such compensation is considered, since the objective is to test the unaided rendezvous procedure.

A final point should be made prior to discussion of simulation results. Although the shuttle has been modeled as a point mass, its finite size is accounted for in the simulation by setting the goal of the rendezvous procedure as arrival within 10 m of the shuttle center of mass, with a relative velocity of less than 0.1 m/sec. Even this is probably an overly strict requirement, since motion within a sphere of radius of 50-100 m about the shuttle can be considered to be rectilinear for MMU rendezvous purposes.

Simulation Results

The effectiveness of the chart-directed procedure was tested for in-plane rendezvous by starting the astronaut out at many points in the xy plane near the shuttle. The extremes of these points are represented by eight equally spaced points on a circle of radius 2000 m in the xy plane centered on the shuttle. The points were numbered sequentially (1 through 8) around the circle, with point 1 being directly behind the shuttle (on the position x axis), point 3 being directly above the shuttle (on the positive y axis), etc. The shuttle orbit was assumed circular at an altitude of 250 n. mi., and EVA rendezvous charts were produced for this orbit.

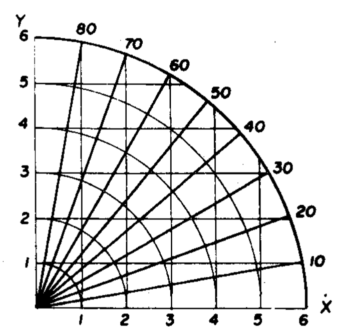

Fig. 4 Velocity component chart.

This distance of 2000 m was chosen for the initial conditions because it was felt that this distance would be an extreme for the chart procedure, even for rendezvous from dead ahead and dead astern of the shuttle. It is questionable as to how well the astronaut could discern shuttle orientation beyond this distance without a telescope of some sort.

In the simulation, three trajectories are compared from each initial point chosen. The reference solution is a two-impulse transfer (called the ideal two-impulse trajectory) having the same average closure rate as the chart-directed procedure. A second trajectory from each point is generated, based on a brute force rendezvous procedure suggested by Mueller[1] [called the linear (Mueller-type) trajectory], in which an attempt is made to fly at a constant relative velocity equal to the chosen average closure rate along a straight line from the initial point to the shuttle.

The chart-directed procedure was simulated interactively on a CDC 6600. This display consisted of a crude graphical representation of the position in three dimensions, plus numerical display of range, range rate, and relative velocity components. The range, range rate, and relative velocity had only two significant figures displayed to account for the fact that, in space, these quantities would have to be estimated. Of course, if radar were used to determine range and range rate, these quantities would be known more accurately, but this fact was ignored in the simulations.

Figures 5-7 show Mueller-type, chart-directed, and ideal two-impulse trajectories starting from points, 4, 6, and 7 on

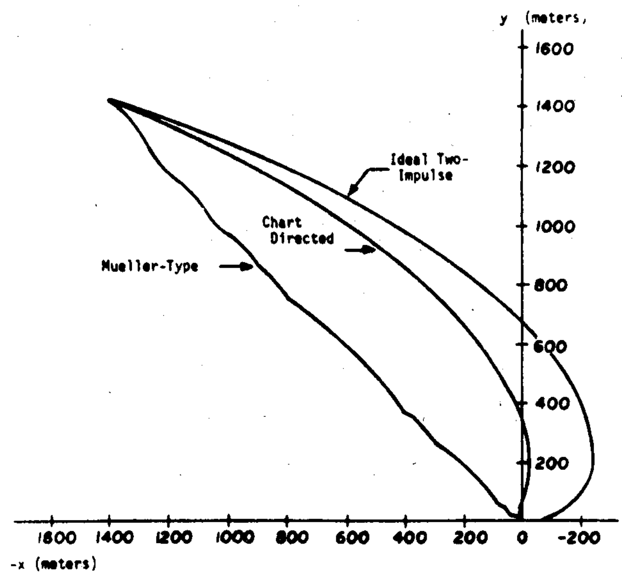

Fig. 5 Trajectories from starting position 4.

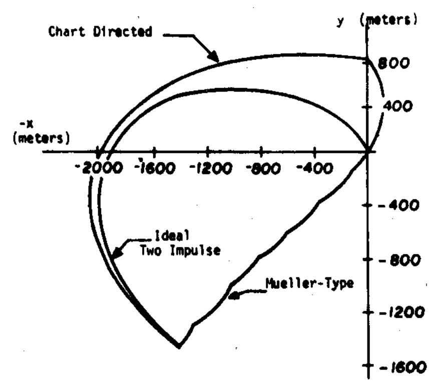

Fig. 6 Trajectories from starting position 6.

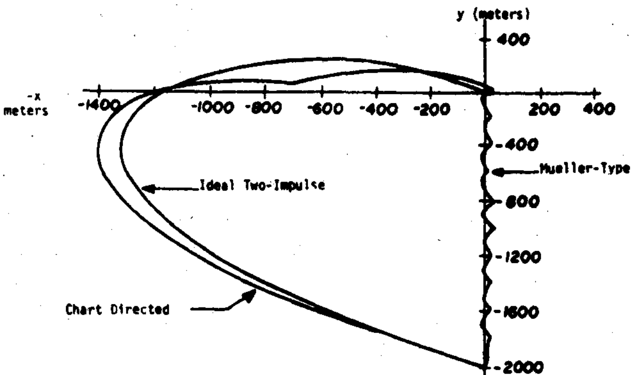

Fig. 7 Trajectories from starting position 7.

the 2000-m in-plane circle. These trajectories are typical of in-plane trajectories starting at many points near the shuttle. Note that the ideal two-impulse trajectory in each case contains only two $\Delta \bar{v}$'s (one at the initial point and one at the shuttle), whereas the Mueller-type and chart-directed trajectories contain additional Δv's when corrections are made. Table 1 lists the $|\Delta \bar{v}|$'s required for all three rendezvous trajectories from each of the eights points on the 2000-m circle.

From Table 1, it can be seen that the chart-directed procedure results in a $|\Delta \bar{v}|$ expenditure of a little less than twice that required by the ideal two-impulse rendezvous but that, in all cases, the $|\Delta \bar{v}|$ required for the chart-directed procedures was within the limits set in the assumptions. In all cases except the rendezvous from position 4, the time required to rendezvous is within 18% of the nominal 2000 sec set by the chosen average 1.0 m/sec range rate.

Note that the linear (Mueller-type) trajectory requires about twice as much $|\Delta \bar{v}|$ expenditure in all cases as does the chart-directed procedure. In addition, the Mueller procedure requires very frequent corrections and would be prone to overcorrection. As implemented in the comparison, corrections were applied automatically. First, a velocity toward the shuttle was established, and then at 100-sec intervals a $\Delta \bar{v}$ correction was made to keep the astronaut moving toward the shuttle at the selected rate. In order to keep the astronaut moving toward the shuttle and to minimize deviations from the straight line, all computed velocity deviations larger than 0.05 m/sec were corrected, whereas smaller deviations were neglected. Obviously, the astronaut could not detect velocity deviations this small, compute the corrections in his head, and implement such small corrections manually, but, in order to show the Mueller procedure in its best light, such corrections were assumed possible and were used in the simulations.

Note the transfer time in Table 1 for chart-directed rendezvous from position 4. This shows that it is possible, at least from some positions, to reduce transfer time markedly with little total $\Delta \bar{v}$ penalty and that errors in $\Delta \bar{v}$ application also might increase the $\Delta \bar{v}$ required significantly. In using the chart-directed procedure at position 4, small inaccuracies in the initial impulse (mainly a small error is estimating velocity components) resulted in a trajectory that had a higher average closure rate than planned. The difference between the actual trajectory and the planned trajectory was too small to be detected at first. Then, since the actual trajectory was accomplishing the rendezvous quite well, it was allowed to continue, and a single correction resulted in a successful rendezvous. This indicates that at some points the trajectory specified by one average closure rate differs from another only in the direction of the velocity at that point and not in its magnitude. This, in turn, suggests that it might be possible to produce EVA rendezvous charts similar to the one in Figs. 2 and 3 with the directions indicated by the arrows optimized in terms of transfer time for the velocity magnitude specified at that point. (This remains to be investigated.)

It is especially important to note rendezvous from points 1 and 5 in Table 1. These are the dead-astern and dead-ahead cases, which are likely in many situations. Note that both the two-impulse procedure and the chart-directed procedure had minima in $|\Delta \bar{v}|$ for these cases, and the linear procedure had minima for points 1 and 4, with the point 5 value close to that of point 4. (The linear procedure minima are much larger than the minima for the other procedures.) Also note that the $|\Delta \bar{v}|$ required for the chart-directed procedure in these cases is quite reasonable (less than 4 m/sec). Thus, the chart-directed procedure seems to perform best under the most likely set of rendezvous conditions and exhibits acceptable performance in all cases studied.

The ideal two-impulse procedure always exhibits the lowest $|\Delta \bar{v}|$ expenditure, as expected. However, implementation of this procedure would require the MMU to have a preprogrammed onboard computing capability, plus a highly accurate way of controlling thrust magnitude and direction. Such equipment is not planned currently for the MMU.

Out-of-Plane Rendezvous

The modification to the chart-directed procedure necessary to effect rendezvous from points not in the orbit plane of the shuttle is minor. Mueller[1] showed that the out-of-plane motion is nearly independent of in-plane motion for an out-of-plane coordinate of up to several kilometers. This means

Table 1 Simulation results

	Chart-Directed		Linear (Mueller-Type)		Ideal Two-Impulse	
Starting Position	Elapsed Time	Total ΔV	Elapsed Time	Total ΔV	Elapsed Time	Total ΔV
1 (0°)	2034 sec	2.67 m/sec	2010 sec	6.46 m/sec	1999 sec	1.95 m/sec
2 (45°)	2100 sec	9.28 m/sec	2025 sec	17.4 m/sec	2000 sec	4.81 m/sec
3 (90°)	2159 sec	9.43 m/sec	1963 sec	17.11m/sec	2000 sec	5.51 m/sec
4 (135°)	1296 sec	4.23 m/sec	1999 sec	9.00 m/sec	2000 sec	3.29 m/sec
5 (180°)	2150 sec	3.31 m/sec	2030 sec	9.10 m/sec	2001 sec	1.95 m/sec
6 (225°)	2287 sec	7.89 m/sec	2054 sec	17.66 m/sec	2000 sec	4.81 m/sec
7 (270°)	2351 sec	7.71 m/sec	1965 sec	16.75 m/sec	2000 sec	5.51 m/sec
8 (315°)	1844 sec	4.66 m/sec	1971 sec	9.80 m/sec	2000 sec	3.39 m/sec

that the x and y components of the rendezvous can be carried out as before, with the z displacement being corrected separately.

In considering corrections of a z-coordinate displacement, several items should be noted. First, the z-coordinate displacement will be periodic, with period equal to the orbit period. Thus, if the astronaut can wait long enough (always less than one-half the shuttle orbital period), he will drift back into the xy plane. If the z component of his velocity is back toward the xy plane, he must wait less than one-fourth of an orbit to drift back into the xy plane. For a 250-n.mi. circular orbit, one-fourth of the period is around 1400 sec, and, so, if the initial z velocity component is toward the xy plane and the rendezvous transfer time is to be more than 1400 sec, then the astronaut should do nothing about his z-coordinate error until he passes through the orbit plane, at which time he nulls the z velocity component and continues the rendezvous in the xy plane.

If the z component of relative velocity is away from the xy plane and it is desired that the rendezvous take place in less than one-fourth of the orbital period, the astronaut must use his thrusters to null the z velocity component and establish a z component of velocity back toward the xy plane. In all simulated cases, the correction of z-coordinate errors is simple and presented no problems.

Co-Elliptic Orbits

Charts for unaided rendezvous for co-elliptic orbits have been produced, and simulations similar to those just described have been run successfully using them. However, for highly elliptic orbits, the details of the rendezvous chart for a particular orbit also become functions of true anomaly, and the procedure becomes more complex. To effect rendezvous in such a situation, the astronaut would need a series of charts, plus a knowledge of the period, time of perigee passage, and the current time. With this information, he would be able to select the charts corresponding to his current approximate true anomaly and carry out the rendezvous. In the elliptic rendezvous case, the predetermined attitude to which the shuttle crew orients the shuttle still would be related to the velocity vector and the orbital angular momentum vector.

The equations of motion, corresponding to Eq. (1), for the elliptic orbit case are

$$\ddot{x} = 2\dot{y}(\dot{\nu}-\dot{\psi}) + y(\ddot{\nu}-\ddot{\psi}) + x(\dot{\nu}-\dot{\psi})^2 + (2\dot{r}_s\dot{\nu}+r_s\ddot{\nu})\cos\psi$$

$$+ (r_s - r_s\dot{\nu}^2)\sin\psi - \frac{\mu(x-r_s\sin\psi)}{[(x-r_s\sin\psi)^2+(y+r_s\cos\psi)^2+z^2]^{3/2}}$$

$$\ddot{y} = -2\dot{x}(\dot{\nu}-\dot{\psi}) - x(\ddot{\nu}-\ddot{\psi}) + y(\dot{\nu}-\dot{\psi})^2 + (2\dot{r}_s\dot{\nu}+r_s\ddot{\nu})\sin\psi$$

$$-(\ddot{r}_s - r_s\dot{\nu})^2\cos\psi \frac{\mu(y+r_s\cos\psi)}{[(x-r_s\sin\psi)^2+(y+r_s\cos\psi)^2+z^2]^{3/2}}$$

$$\ddot{z} = \frac{-\mu z}{[(x-r_s\sin\psi)^2+(y+r_x\cos\psi)^2+z^2]^{3/2}}$$

The quantity ν is now true anomaly, and ψ is the angle between the positive y axis and the local vertical. All other symbols are as previously defined.

Conclusion

A chart-directed procedure for unaided EVA rendezvous has been presented. Comparisons between trajectories produced by the chart-directed procedure, a two-impulse procedure, and a procedure that results in almost rectilinear trajectories have been made. The chart-directed procedure appears to be a good candidate for a backup rendezvous procedure because of its simplicity and the low cost and weight of the equipment required. The charts on mylar cards would be of negligible weight, and the radar unit is likely to be part of the standard MMU equipment. (A mylar card range finder[4] could be used with a timer in the absence of the radar to determine range and range rate.)

The use of the chart-directed rendezvous procedure does not require the astronaut to be proficient in orbital mechanics but rather only to be able to estimate angles and angular rates reasonably well. Finally, and most importantly, the chart-directed procedure provides a way for the astronaut to return to the shuttle along a fuel-conserving path in a reasonable time without shuttle aid or a computer.

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