Guidance and Control for Cooperative Tether-Mediated Orbital Rendezvous

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The tether-mediated rendezvous procedure involves a free-flying pursuit vehicle that docks with a tether tip vehicle suspended at the end of a tether. The tether tip vehicle is equipped with small thrusters, and its maneuvers, along with the tether length, are controlled in such a way that they assist with the rendezvous. Presented in this paper is an algorithm that optimizes the location of the rendezvous state such that the minimum total maneuvering effort is required of the two vehicles performing the cooperative tether-mediated rendezvous. A variation to this algorithm that permits the maximum proximity time between the two vehicles is also described. The guidance algorithm was tested by simulating perturbations of the pursuit vehicle from its nominal rendezvous trajectory and then by observing the capability of the algorithm to determine corrective maneuvers to allow a successful rendezvous. Results indicate that the algorithm performs well even with large pursuit vehicle perturbations, and the resulting total fuel cost for both vehicles is less than what would be required by having one vehicle alone perform the rendezvous maneuvers.

I. Introduction

SEVERAL missions have been proposed that require a tether-mediated rendezvous.[1] Large amounts of fuel can be saved when compared to the equivalent nontether mission since the pursuit vehicle does not have to expend the fuel to transfer itself into the same orbit as the target vehicle.[2] In addition, collision hazards and exhaust plume impingement on the vehicles can be reduced or practically eliminated, and the entire rendezvous can be performed in a much shorter time than standard rendezvous procedures allow.

In a typical scenario, a tether is suspended downward from a space platform in a circular orbit, and to the lower end of the tether is attached a small maneuverable vehicle—a tether-tip vehicle (TTV)—with three-axis thrust control capability and appropriate docking hardware. For a tether-mediated rendezvous procedure, there exists a coasting trajectory, or orbit, onto which the free-flying pursuit vehicle (PV) can establish itself to match the position and velocity of the TTV at a selected time.

If the rendezvous is observed from an orbiting reference frame, the nature of the approach that the PV makes to the TTV during a tether-mediated rendezvous resembles a "cusp," or an R-bar approach—the PV approaches the TTV from below and behind in the orbit and travels toward the peak of a cusp, which is oriented along the radial direction to the target (see Fig. 1). This differs significantly from the standard V-bar approach techniques in which the PV approaches the target in a direction tangent to the target's velocity vector.[3] R-bar approaches have been proposed and developed by NASA,[4] but no missions involving such an approach have yet been flown.

Many missions based on a tether-mediated rendezvous procedure have been analyzed, but no one has yet proven that this type of rendezvous can successfully be performed. In fact, many studies conclude that the next step must be to develop the guidance for this rendezvous procedure in order to determine whether the proposed missions can be considered feasible.[5,6,7,8]

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This paper presents a viable guidance algorithm for performing such a rendezvous and shows an analysis of its feasibility and practicality by exercising the algorithm under near-realistic operating conditions. Such items as fuel requirements, time spent within proximity of the target, and thruster failure tolerances have been considered.

The approach taken in this study involved analyzing the dynamic behavior of the two vehicles separately—taking advantage of analytical solutions and simplifications where possible. Independent control schemes have been derived for each vehicle, and these controllers determine the fuel-optimal control inputs for maneuvering the respective vehicle from any initial state to a still arbitrary target state. Once the maneuvers from the initial state to a target state are defined, a cost can be associated with any selected target state, and the optimal target, or rendezvous state, can then be determined as the one that minimizes the total costs of the vehicle maneuvers. The rendezvous guidance algorithm, therefore, involves analyzing the maneuvering costs by applying the individual vehicle controllers in order to find the final, optimal rendezvous state (including time). A detailed description of the complete work discussed in this paper is contained in Ref. 9.

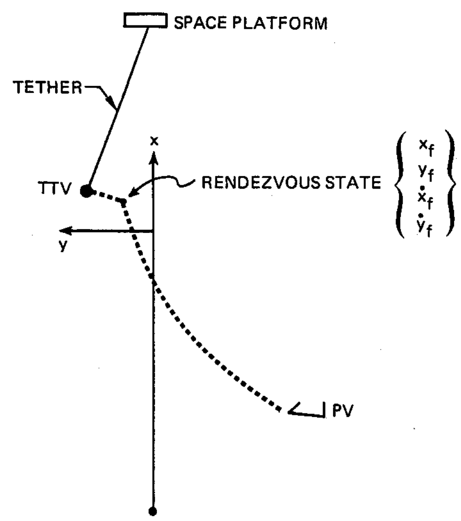

Fig. 1 PV and TTV rendezvous state.

II. Pursuit Vehicle Rendezvous Maneuvers

Pursuit Vehicle Model

The PV is modeled as a point mass with impulsive thrust capability for achieving small changes in velocity. Only the two-dimensional in-plane motion is considered since the uncoupled out-of-plane motion can be independently controlled using traditional guidance and control techniques. The PV can establish itself on, and then follow, a desired orbital path with at least the accuracy achievable by the current shuttle guidance system. (Current capabilities for tracking a desired trajectory are within 1 m/s velocity errors, and within 10 m position errors.[10])

Nominal Rendezvous Trajectory

There exists a nominal rendezvous orbit on which the pursuit vehicle can coast to the rendezvous state without having to perform any further maneuvers, including final braking maneuvers. The parameters for the nominal rendezvous orbit can be determined from the geometry of the tether system. If the center of mass of the platform and tether system is located a distance R from the center of the Earth, the lower end of the tether is nominally at the radius r, and the tether length l is the difference $l = R - r$. The apogee of the nominal rendezvous orbit will simply be at the tether tip, and the perigee, to first order in l/R, is

$$r_p = R\,[1 - 7\lambda_T \nu/(1+\nu)] \tag{1}$$

where $\lambda_T = l/R$ and $\nu = m_2/m_1$, the ratio of the upper tip mass to the lower tip mass. In the case where the upper tip mass is much greater than the lower tip mass, Eq. (1) reduces to $r_p = R - 7l$. Thus, if the platform is in a 500 km altitude orbit, and the tether is 10 km long, the apogee of the nominal rendezvous orbit will be at an altitude of 490 km, and the perigee will be at 430 km.

Two-Impulse Rendezvous Maneuver

Since the target vehicle itself is allowed to maneuver, no conclusions can be made yet about the position or velocity that must be achieved at the final time. For a high-thrust PV in a known Keplerian orbit, a near-optimal means of reaching an arbitrary target state involves performing two impulsive maneuvers—one at the initial state to place the PV on an intercept trajectory with the target and one at the target state to match velocities with the target vehicle.

If a two-impulse maneuver is assumed, the total cost for the maneuver is simply the sum of the delta-V for the impulse at the initial point ΔV_1, and the delta-V for the impulse at the target point ΔV_2, thus

$$J_{PV} = |\Delta V_1| + |\Delta V_2| \tag{2}$$

The delta-V values are found by solving the equations of motion for the velocity as a function of time, given the initial and final conditions.

III. Tether Tip Vehicle Control

Tether Tip Vehicle and Tether System Model

The TTV is modeled as a concentrated tip mass on the tether, with its motion determined by the dynamic behavior of the tether system. Only the two-dimensional dynamics of the tether are considered in this study, thus allowing pitching motions in the orbital plane and reeling motions along the tether length.

The dominant behavior, when tip masses are present, is the rigid-body in-plane libration. The tether is assumed to be massless, and the geometry is set up as shown in Fig. 2.

Controller Implementation

The tether length l varies with time since the reeling acceleration u_l is used as a control input for maneuvering the tether tip. The acceleration from the thrusters, u_α, applied perpendicular to the tether, also serves as an input for control of the TTV position.

To be practical, the reeling acceleration u_l must be smooth and continuous. The acceleration applied to the tether tip, u_α, on the other hand, must match the behavior of the thrusters on the TTV and will therefore be either on or off, with $|u_\alpha| = u_{\alpha\max}$ when on, where $u_{\alpha\max}$ is the nominal acceleration achievable with the TTV thrusters (A value of $u_{\alpha\max} = 0.1$ m/s^2 might be typical.)

Given these system dynamics and constraints on the control inputs, we wish to find a trajectory starting at the initial state that arrives at the desired final state at the specified final time, t_f. To minimize fuel and power consumption, the cost function

$$J_{\text{tether}} = \int_0^{t_f} \left(\beta_\alpha |u_\alpha| + \beta_l u_l^2\right) \mathrm{d}t \tag{3}$$

is used, where β_α and β_l are weighting constants, or gains. This forces the u_α control to either the on or off state, and u_l will be continuous and smooth, as required. This optimal control problem was solved to determine the cost of maneuvering the TTV to an arbitrary final state. Then, based on the form of the optimal trajectory, a simplified, near-optimal control scheme was developed to reduce the computational requirements of finding the maneuvering costs, and this controller was used for development of the rendezvous guidance.

IV. Optimal Rendezvous State Determination

Having developed independent optimal rendezvous strategies for the PV and the TTV, we now wish to apply these strategies to determine the optimal rendezvous state to which both vehicles should simultaneously maneuver. The cost associated with any candidate rendezvous state is found by individually applying the optimal rendezvous strategy for each vehicle and then combining these individual costs in the global cost function. This global cost function is thus

$$J_{\text{total}} = W_{PV} J_{PV} + W_{TTV} J_{TTV} + W_{\text{reel}} J_{\text{reel}} \tag{4}$$

where W represents weighting factors on each control mode and can be varied as desired.

Preliminary Qualitative Results

Initial test runs were performed to study the behavior of various optimization techniques as well as to provide some preliminary information regarding the nature of the optimal rendezvous state. During these and all subsequent runs, the TTV was assumed to have an initial state at rest at the origin of the local vertical, local horizontal (LVLH) frame, and the initial state of the PV was measured in terms of position and velocity perturbations from the nominal rendezvous trajectory at a selected time on that trajectory.

The starting point in the search for the optimal rendezvous state was the origin of the LVLH frame, using the time-to-

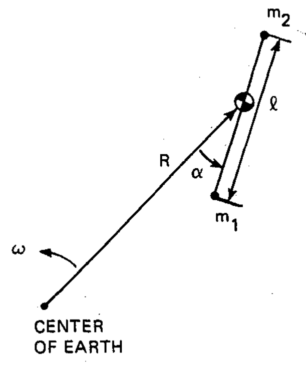

Fig. 2 Dumbbell tether model.

rendezvous on the nominal trajectory as the initial guess for the rendezvous time.

With the cost weighting factors, $W_{PV}=36.0$, $W_{TTV}=1.0$ [as it would be if the PV were a NASA Shuttle and the TTV were a stripped-down orbital maneuvering vehicle (OMV)], and $W_{\rm reel}=10^{-3}$, the optimal rendezvous state that was found was such that it never required the PV to maneuver in order to achieve the rendezvous—the optimal rendezvous state was always found along the coasting trajectory that the PV would follow if it performed no further maneuvers. In addition, for most of the position perturbations ranging from 1 to 100 m, very little thrusting was required of the TTV, and most of the rendezvous maneuvers could be performed with the tether-reeling control. Even when W_{PV} was reduced to 1.0, making it equal to W_{TTV}, the PV was seldom required to maneuver, and the rendezvous was still being performed mostly with the tether-reeling control.

Combined Optimization

The results of the previous section implied that the rendezvous state optimization could initially be reduced to a single-parameter search along the PV coasting trajectory for the rendezvous time that requires the minimal use of the TTV thrusters. Since the optimal rendezvous state may not always occur exactly on the PV coasting trajectory, we need to return to the five-parameter gradient search to determine where the optimal solution actually occurs or to verify that the optimal solution has indeed been found. In both cases, the initial guess for the optimal rendezvous state was the state found by the single-parameter search technique.

The gradient search technique that performed the best, as discussed earlier in this section, involved performing a line search to find the optimal step size for each gradient that was evaluated. When preceded by the single-parameter optimization, this gradient search technique converged very quickly, requiring no more than three gradient evaluations, and often requiring only one. In cases where the gradient was evaluated only once, the algorithm usually terminated without having found any further improvement in the cost, thus confirming that the rendezvous state found by the single-parameter search was indeed optimal under many conditions.

V. Minimum Cost Rendezvous Profiles

Scenario Description

To completely evaluate the rendezvous algorithm developed in Sec. IV, a specific scenario was selected and vehicle capabilities were defined. The following parameters are the conditions under which the rendezvous algorithm was tested:

1) The center of mass of the tether system is in a circular 500-km orbit.

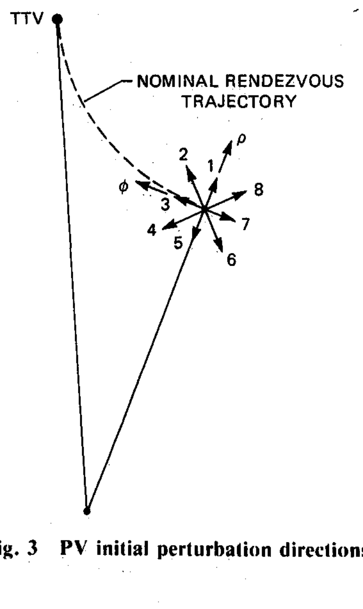

Fig. 3 PV initial perturbation directions.

2) The nominal tether length is 10 km.

3) The TTV has thrusters that can produce a lateral acceleration of 0.1 m/s^2 (based on 100-N bipropellant thrusters and a 1000-kg vehicle mass).

4) The maximum permitted tether reeling rate is 5 m/s.

5) The TTV initially starts from rest at the origin of the LVLH coordinate frame.

6) The initial conditions of the PV are measured in terms of perturbations from a state 100 s prior to rendezvous on the nominal rendezvous trajectory—at a nominal distance of about 180 m [the latest point at which proximity sensors could take over from global positioning system (GPS) navigation].

7) Perfect navigation information is assumed.

Pursuit Vehicle Perturbations Selection

The cases tested were limited to a set of discrete perturbation magnitudes and directions, for both position and velocity perturbations. For each selected magnitude of each of the position and velocity perturbations, eight different directions were investigated. The directions are determined relative to the PV's local (polar) coordinate frame, and are numbered sequentially as shown in Fig. 3.

Interpreting the Trajectory Plots

For each case tested, a plot was generated (see figures in the following sections) on which the axes represent the vertical and horizontal axes of the LVLH coordinate frame, with the origin located at the nominal rendezvous state, indicated by the dotted-line cross hairs. (Unequal X and Y scales are used to best show the data.) Three trajectories are shown on each of the plots, and the symbols on each of the trajectories are spaced at time intervals of 10 s. The dotted line with the open-circle symbols represents the nominal rendezvous trajectory for reference purposes. The point at the lower right end of the nominal trajectory is the state from which the PV initial perturbations are measured. The actual PV trajectory is the solid line with the filled-circle symbols. It begins at its perturbed state and ends at the final rendezvous state.

The TTV trajectory is shown as the dashed line with the filled-box symbols. It always begins at the origin and then proceeds, under the influence of the TTV maneuvers, to the rendezvous state.

Results for the Position Perturbations

Three magnitudes were analyzed for the position perturbations: 1, 10, and 100 m. Sample results from the 10-m perturbation cases are shown in this section.

To demonstrate the cooperative nature of the rendezvous, the cost weighting factors for the PV and the TTV thrusting maneuvers were given the same value. The cost weighting for the TTV reeling maneuvers was given a much smaller value to reflect the inexpensive nature of the electrically powered reeling activity. For the first set of results, therefore, the ratios for the PV thrusting to TTV thrusting to TTV reeling costs were set to $1{:}1{:}10^{-3}$. An example of the resulting rendezvous profiles is shown in the plot in Fig. 4.

Several patterns are immediately apparent in this set of results. Because of the low cost of the tether-reeling activity, this control mode is exploited wherever possible (while still observing the reeling rate limits), and the rendezvous is performed by having the TTV reel out to "catch up" with the PV after the PV has passed through the cusp, or apogee of its orbit. The delta-V requirements for the PV are extremely low—from 0 to 6×10^{-2} m/s depending on the perturbation direction, and the TTV delta-V requirements are not much higher—from about 2×10^{-2} to 6×10^{-2} m/s. This is less than 0.3% of the delta-V, which would be required for a standard rendezvous at the platform altitude. Even for the cases with 100-m perturbations, the delta-V requirements increase only to a few tenths of a m/s. This demonstrates that large position perturbations are not necessarily costly to correct for in this type of rendezvous procedure.

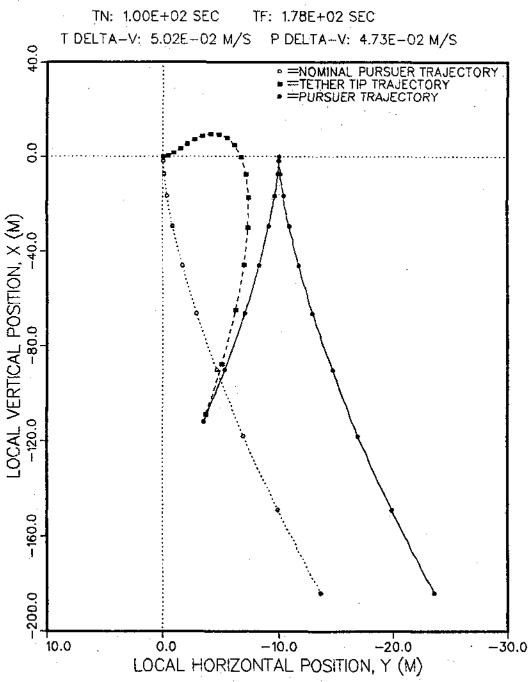

Fig. 4 Direction 7: position perturbation (10 m), cost ratio 1:1:10^{-3}.

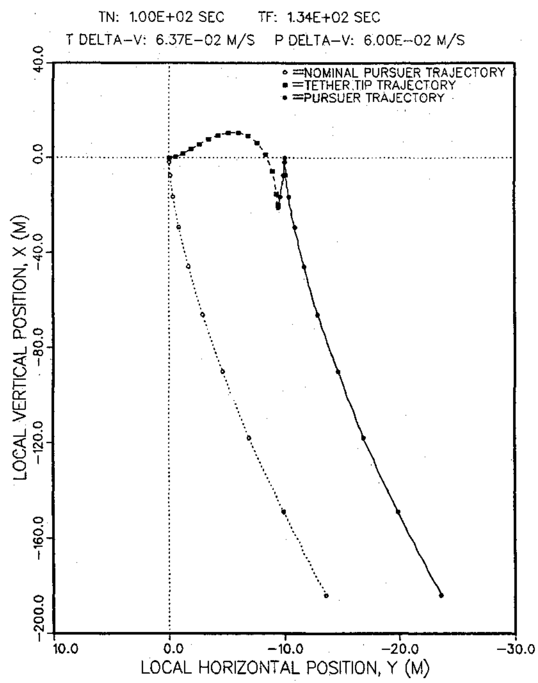

Fig. 5 Direction 7: position perturbation (10 m), cost ratio 1:1:1.

When the results of the 1- and 100-m perturbations are also considered, a pattern emerges in the relative magnitudes of the TTV delta-V and the PV delta-V. Despite the equal cost weighting factors, the results show that it does not become useful to perform corrections to the PV trajectory unless the perturbations are large.

Although a low cost weighting factor for the reeling control may reflect realistic control mode cost ratios, the low cost on the tether reeling activity in many cases leads to an undesirable condition—at the time of rendezvous, the tether is being reeled out at a moderate-to-high rate and that velocity must be nullified after the rendezvous has occurred (now with the PV attached to the tether system). This means more momentum will be lost by the tether system, and greater stress will be placed on the tether and its reeling mechanism. To avoid this, the cost

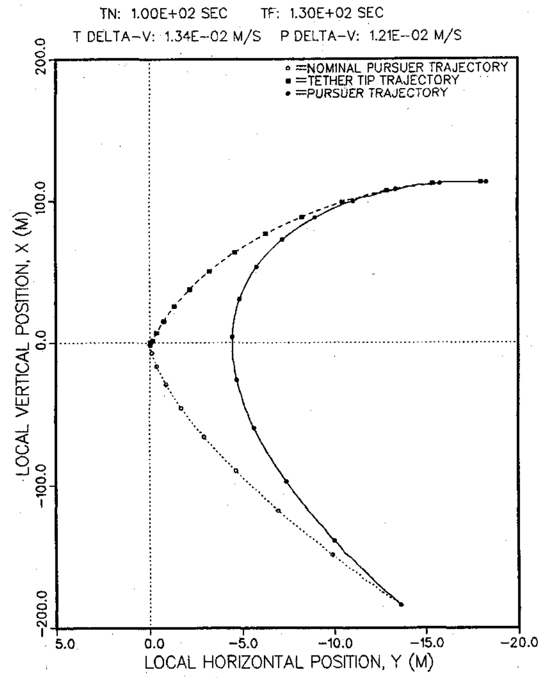

Fig. 6 Direction 1: velocity perturbation (1 m/s), cost ratio 1:1:10^{-3}.

weighting factor for the tether-reeling activity can be increased, and a sample rendezvous profile generated by this 1:1:1 set of cost ratios is shown in Fig. 5.

In these profiles, much less reeling activity is required while only minimally increasing the TTV and PV delta-V. In all cases now, the rendezvous is performed very close to the cusp on the PV trajectory, and the tether-reeling rates at the rendezvous state are lower, averaging around -0.7 m/s rather than the -3 m/s from the cases with the lower reeling cost weighting. These cost weightings can therefore be adjusted as necessary to accommodate practical considerations involved in the rendezvous procedure.

Results for the Velocity Perturbations

Rendezvous profiles were studied for three different velocity perturbation magnitudes: 0.3, 1.0, and 2.0 m/s. As for the position perturbations, the intermediate value represents a realistic upper limit, but a higher value was also tested to examine the behavior of the solution under more extreme conditions. Sample results of the 1.0 m/s case are shown in Figs. 6 and 7.

Whereas the shapes of the resulting PV trajectories are all somewhat different, the rendezvous still occurs close to, or just after, the apogee of the PV's orbit. Compared to the position perturbations, however, the rendezvous states are located further away from the origin—on the average over 100 m horizontal displacement compared to an average of 15 m for the moderate-sized position perturbations. Even at close range to the target, small velocity perturbations can result in large position errors, and therefore the cooperative rendezvous procedure is in general more sensitive to velocity perturbations.

Despite the equal cost weighting factors for the PV and TTV, all but one of the rendezvous profiles in this set required no maneuvering by the PV. This demonstrates the extent to which the tether-reeling capability can be used to reduce the total delta-V required of both vehicles. In most cases, the delta-V required by the TTV is at least 30% less than the total PV perturbation magnitude.

When the cost weighting factor for the tether-reeling activity is increased to the same level as the PV and TTV cost weighting factors (1:1:1), the trajectory requires very little additional maneuvering by the TTV and PV. Those cases that are affected require only a few hundredths m/s additional delta-V for the two vehicles, but the location of the rendezvous state is brought significantly closer to the origin—to roughly two-thirds the original horizontal displacement, as shown in the example in Fig. 8. The cases in which the rendezvous profile is not changed by the increased reeling cost weighting either already require very little reeling activity, or the configuration makes it difficult to reduce the amount of reeling activity without greatly increasing the delta-V that would be required of the TTV or PV.

Control Failures

The three control modes being used in the rendezvous procedure (PV thrusting, TTV thrusting, and tether reeling) are redundant. The rendezvous could still be performed with any two of them, and in some cases just one is required, however, the cooperative capability is then forfeited. To investigate the effect of eliminating one control mode, or to simulate a "failure" of the control mode, the cost weighting factor on that mode was set to a high enough value that the guidance algorithm would avoid selecting it for use in the rendezvous procedure. The results indicate that the rendezvous could still be successfully performed with the remaining control modes. The rendezvous could be completed with the TTV remaining passive since the PV can maneuver to rendezvous with the TTV. If the PV is passive, however, both TTV thrusters and reeling control must be active to complete the rendezvous.

VI. Maximum-Proximity-Time Rendezvous Profiles

In Secs. IV and V, the guidance algorithm and rendezvous state determination were based on a cost function that measured maneuvering costs for the two vehicles. This generated rendezvous profiles that required very little maneuvering by the vehicles but did not consider the amount of time the two vehicles are actually within proximity of each other. In this section, an alternative rendezvous procedure has been developed that maximizes the proximity time for the two vehicles but avoids excessive use of maneuvering fuel.

While proximity time is a very practical concern and perhaps warrants further attention, the algorithm used in this section was designed to find the optimal solution only for the case where the PV remains passive. If the PV were to use its thrusters, in the scenario described in Sec. V, the PV could "hover" under the TTV at the cusp of its trajectory for as long as 608 s, burning 1.19 kg of fuel per second, before it would consume as much fuel as it would have saved by performing the tether-mediated rendezvous. This alternative could be used if absolutely necessary, but the intent of the algorithm described in this section was to study the extent to which the TTV control modes alone could be used to extend the proximity time.

Guidance for Maximum Proximity Time

The guidance algorithm to maximize the proximity time requires that the TTV maneuver to stay with the PV in its orbit. It accomplishes this by matching the position and velocity of the PV at one point, and then releasing tension on the tether by reeling it in or out at the appropriate rate in order to allow the TTV to follow the same orbit as the PV. With both vehicles in freefall, no fuel needs to be expended to keep them within proximity of each other, since they will naturally follow the same orbital trajectory.

It is not practical to allow the tether to go slack, however, and therefore some tension could be maintained by firing low-level thrusters on the TTV along the tether direction. The amount of fuel required to maintain 1 N of tension in the tether is only 1/36 as much as would be required to have the PV stationkeep with the TTV (assuming equal vehicle masses).

The algorithm for maximizing the proximity time involves finding the earliest state along the PV coasting trajectory to which the TTV can maneuver without exceeding its maximum reeling rate constraint. It then performs the rendezvous with the PV and joins it in freefall (or pseudo-freefall if tension is maintained), staying with the PV until the tether-reeling rate limit would again be exceeded. If all goes well, however, the docking would be accomplished within this time.

Interpreting the Trajectory Plots

The trajectories on the plots are the same as those described in Sec. V, with the addition of the chase trajectory, indicated as a dash-dot line with unfilled-square symbols. The TTV and the PV are within proximity of each other on this trajectory segment, which begins at the rendezvous state and terminates

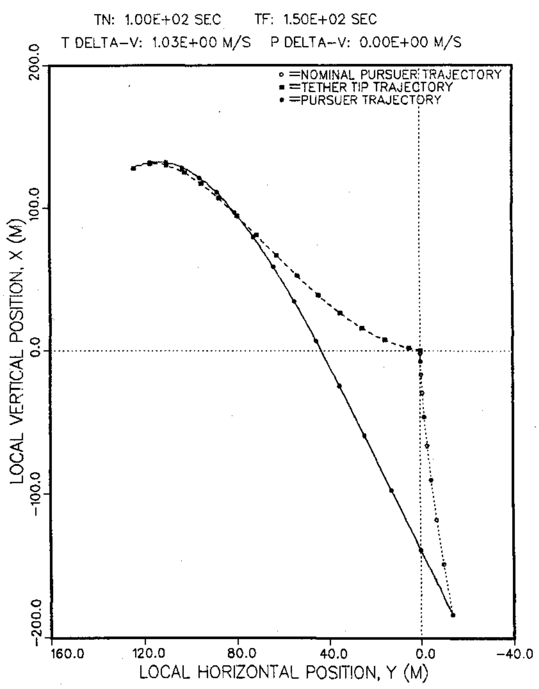

Fig. 7 Direction 2: velocity perturbation (1 m/s), cost ratio $1{:}1{:}10^{-3}$.

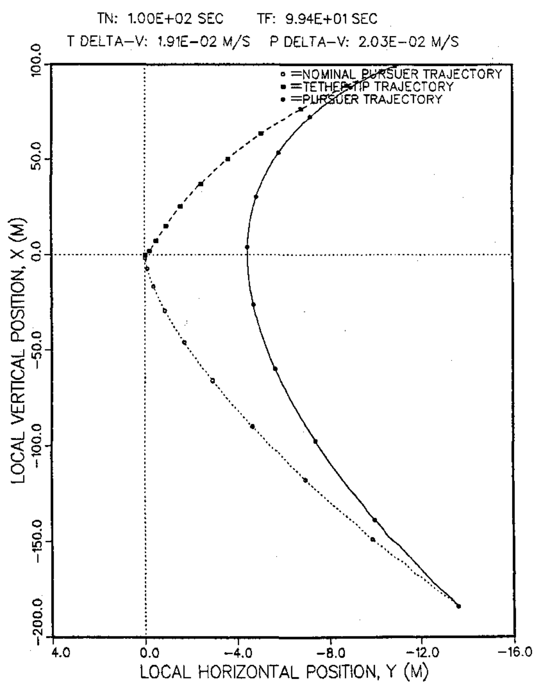

Fig. 8 Direction 1: velocity perturbation (1 m/s), cost ratio 1:1:1.

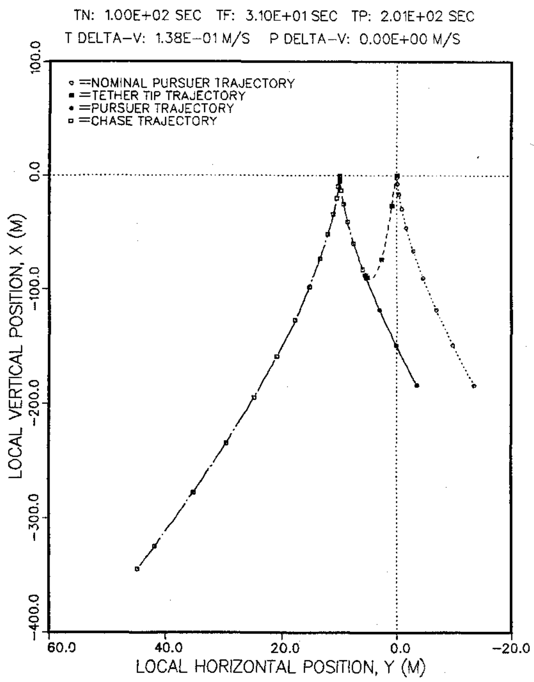

Fig. 9 Direction 3: position perturbation (10 m), maximum proximity time.

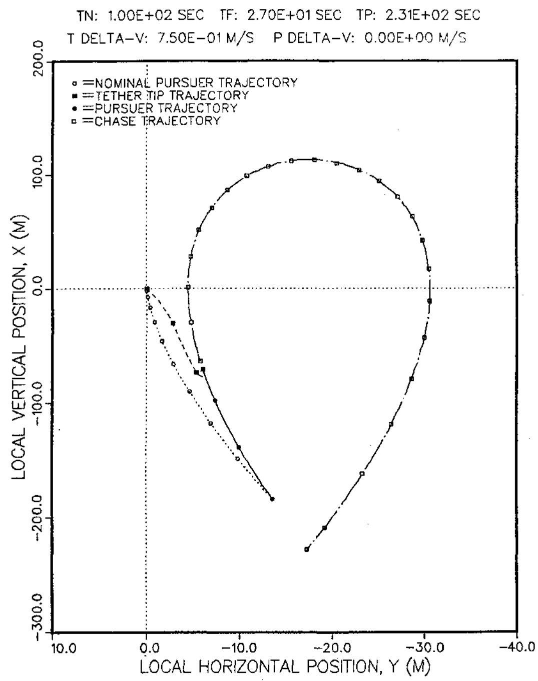

Fig. 10 Direction 1: velocity perturbation (1 m/s), maximum proximity time.

at the point where the TTV must break off. The proximity time is measured from the rendezvous time to the break-off time when the TTV moves to more than 1 m away from the PV.

Results for the Position Perturbations

The set of PV perturbations selected to study the maximum-proximity-time rendezvous algorithm are the same as those described in Sec. V. A sample of the resulting rendezvous profiles for position perturbations of 10 m is shown in Fig. 9.

In the rendezvous profiles in this set, the tether begins reeling out immediately, and the TTV is able to rendezvous with the PV in about 30 s—after a quick turnaround of the tether-reeling rate is performed in order to have the TTV match the PV velocity. (Maximum acceleration levels of around 0.7 m/s^2 are encountered during this turnaround maneuver, but these could be decreased by initiating the rendezvous maneuvers earlier than 100 s before nominal rendezvous.) The TTV is then allowed to go into pseudo-freefall, maintaining some tension on the tether, and a total proximity time of around 200 s is achieved. The cost for this procedure is slightly higher than for the minimum-cost procedure, as expected, but is still well within acceptable limits, with no more than about 1.8 m/s delta-V required by the TTV for the least favorable perturbation direction (direction 8).

Results for the Velocity Perturbations

In this set of rendezvous profiles, the rendezvous time again occurs at around 30 s, but the total proximity time varies more than for the position perturbations, ranging from 131 to 231 s, depending on the perturbation direction, with most of the directions resulting in a proximity time of less than 200 s. An example rendezvous profile resulting from a velocity perturbation of 1 m/s is shown in Fig. 10. If the PV were exactly on its nominal rendezvous trajectory, the maximum possible proximity time would be 201 s. The proximity times resulting from the 2.0 m/s perturbations ranged from 66 to 261 s, with the average less than 140 s.

Additional Options for Extending the Proximity Time

These results shown in the previous sections hold for the case in which the procedure is initialized 100 s prior to rendezvous on the nominal rendezvous trajectory. If started earlier, the TTV could start its maneuvers sooner, and thus the rendezvous state itself could be located earlier on the PV coasting trajectory, thereby allowing a longer proximity time. The limit will be reached when the relative velocity on the PV coasting trajectory exceeds the maximum tether-reeling rate. For the 10-km tether length, this maximum nominal value (without perturbations) would be close to 270 s prior to rendezvous, and therefore the achievable proximity time would be 540 s.

If the rendezvous is not performed successfully within this time, the PV could perform an orbit transfer in order to reestablish itself on the nominal trajectory and repeat the attempt. The orbit transfer would require two impulsive maneuvers and would still be less costly than using the PV thrusters to continuously stationkeep with the TTV. Multiple attempts could thus be performed at low cost.

VII. Discussion

Minimum-Cost Algorithm

As a result of repeated testing of the minimum-cost guidance algorithm under a variety of conditions, the following statements can be made:

1) The combination of the single-parameter search along the PV coasting trajectory with the gradient search for the minimum-cost rendezvous state generates the optimal solution quickly and with relatively few iterations.

2) Physical system constraints, such as maximum tether-reeling rates or maximum tether-angular excursions, can be easily incorporated into the algorithm.

3) The algorithm can find its own initial feasible solution and need not be given any prior knowledge of its location.

4) The algorithm is tolerant of control mode failures and can still find a solution in the absence of any single control mode or for the case of one vehicle remaining entirely passive.

Maximum-Proximity-Time Algorithm

The maximum-proximity-time algorithm is much simpler than the minimum-cost algorithm because enough restrictions have been placed on it, in order to avoid excessive fuel use, that only a single-parameter search is required to find the opti-

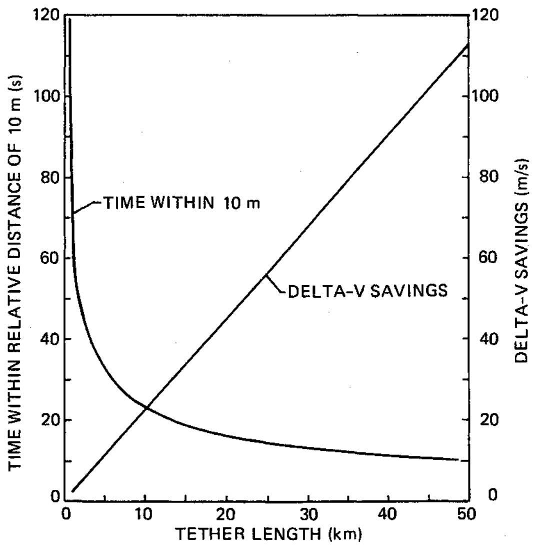

Fig. 11 Tether length influence on fuel savings and proximity time.

mal solution. The following general statements can be made about the behavior of the algorithm:

1) The algorithm requires very little iteration, and no gradient calculations, in the process of finding the solution.

2) The TTV maneuvering constraints are easily incorporated, and additional constraints, such as maximum tether-reeling acceleration limits, could easily be added.

3) The algorithm finds its own initial feasible solution and requires only the PV perturbations and the TTV current state as input.

Minimum-Cost Rendezvous Profiles

The rendezvous profiles presented in Sec. V demonstrate the capabilities of the minimum-cost guidance algorithm and display the nature of the resulting rendezvous profiles. A number of statements can be made about these results:

1) Relatively large PV position errors can be tolerated (errors far larger than those likely to occur with modern onboard guidance systems) provided they are not also coupled with large velocity errors.

2) Moderate-sized PV velocity errors can be tolerated (also larger than those likely to occur with modern guidance systems), but it is best to correct large velocity errors (larger than 2 m/s) before implementing the rendezvous guidance.

3) The most fuel-efficient solutions involve using the tether-reeling capability as much as possible, and even for large perturbations, very little PV or TTV thruster use is required.

4) When the PV is the same mass as the TTV, it is optimal to require the PV to maneuver only when the perturbations are very large. Otherwise, for small perturbations or a high PV mass, the PV should remain passive and allow the rendezvous to be performed by the TTV.

Maximum-Proximity-Time Rendezvous Profiles

Even without using the PV thrusters, the TTV alone can do a great deal to increase the proximity time between the two vehicles. It can increase the proximity time to roughly 200 s by performing the rendezvous with the PV as early as possible and then matching orbits with the PV while artificially maintaining tether tension with small thrusters. The rendezvous profiles shown in Sec. VI lead to the following conclusions:

1) The TTV alone can easily be used to inexpensively extend the proximity time for the two vehicles to a fixed maximum value (which depends only on the tether length and reeling rate limit and the orbital altitude).

2) Most perturbations to the PV nominal rendezvous trajectory tend to reduce the maximum possible proximity time.

The maximum proximity time that can be achieved with the TTV maneuvers alone is dependent on the tether length (assuming a constant 500-km orbital altitude for the tether system c.g.), with longer tethers yielding a lower maximum proximity time than short tethers. The rate at which the PV will consume fuel is also directly proportional to the tether length, and the amount of fuel saved by performing the tether-mediated rendezvous will determine for how long it makes sense to use the PV thrusters to help extend the proximity time. Figure 11 shows the effect of tether length on two of these factors. The delta-V saved by performing the tether-mediated rendezvous compared to a traditional rendezvous is a linear function of the tether length, whereas the time that the PV spends (on its nominal rendezvous trajectory) within 10 m of the LVLH frame origin starts off at infinity for a zero length tether and drops steeply until around 10 km, where it then starts to level out.

If proximity time is the primary concern, the tether length can be chosen such that it permits whatever amount of proximity time is necessary to insure that the rendezvous can successfully be performed.

VIII. Conclusions

Two in-plane guidance algorithms have been developed that demonstrate the feasibility of tether-mediated rendezvous. The first minimizes the total fuel cost for the maneuvers of the PV and the TTV and demonstrates the extent to which the tether-reeling capability can further reduce fuel requirements. The second algorithm maximizes the proximity time for the two vehicles and shows that a reasonable amount of time can easily be made available for performing the docking maneuvers while still requiring very little fuel. Both algorithms are tolerant of large position and velocity perturbations of the PV from its nominal rendezvous trajectory, and both require far less fuel than a standard, nontether rendezvous would require.

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