Path-Constrained Maneuvering Near Large Space Structures

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Spacecraft and personnel maneuvering in the vicinity of large space structures must take path constraints imposed by the structure itself into account. In this paper, the restricted path-constrained transfer problem is introduced and discussed. Further, the results are presented of numerical simulations in which the merits of a variety of techniques are developed and evaluated for the circumnavigation of large orbital structures of varying size and geometry. Also discussed are several aspects of the Generalized path-constrained transfer problem in which large space structures of unspecified shape and rotational characteristic are permitted; this area of research pertains to operations near asteroidal, as well as man-made, objects.

Nomenclature

A	= minimum altitude above the forbidden zone from which both transfer end points can be simultaneously observed
CW	= Clohessy-Wiltshire
d	= distance
GEO	= geosynchronous Earth orbit
H	= cylindrical LSS half-height
ISS	= initial standoff separation
ITP	= intermediate target point
k	= ITP scaling factor
LEO	= low earth orbit
LSS	= large space structure
R	= LSS radius
t	= time
TS	= transfer strategy
v	= velocity
$\hat{x}$	= CW coordinate vector antiparallel the orbital velocity vector
$\hat{y}$	= CW coordinate vector parallel the orbital radius vector
$\hat{z}$	= CW coordinate vector parallel the orbital angular momentum vector
x'	= LSS-target point vector $\hat{x}$ coordinate
y'	= LSS-target point vector $\hat{y}$ coordinate
z'	= LSS-target point vector $\hat{z}$ coordinate
τ	= transfer time, s
ω	= orbital angular rate

I. Introduction

IT is now apparent that the United States Space Transportation System (STS), i.e., Shuttle, is a dramatic technical success. The advent of routine, manned surface to-orbit transportation has greatly spurred both the nature and number of space projects under way. Among these projects, one observes a trend toward increasing spacecraft size; this is currently most evident in the evolution of communications platforms operating at goesynchronous (GEO) orbit. Soon, permanently manned stations, factories, and (eventually) large power production facilities will reside on-orbit; large man-tended telescopes, military systems, and tether-lattice networks may also be constructed. Recent estimates place the characteristic physical dimensions of such structures on the order of 0.1-10 km on a side.

Because gravity is an inverse square central force field, maneuvering between points in orbit about Earth is a nonrectilinear exercise. In this paper, we show that many orbital structures will be large enough to require proximity rendezvous guidance targeting in order to negotiate transfers in the vicinity of their exterior surfaces. We then discuss the difficulties inherent in conducting such rendezvous transfers due to the physical constraint surfaces imposed by the structure itself. The remainder of this paper is largely devoted to developing and evaluating a number of operationally feasible transfer techniques that circumvent the path constraints inherent to maneuvering about large space structures (LSS), under the assumption of certain restrictions. Finally, we discuss several isolated aspects of the generalized analytical solution to path-constrained rendezvous about large space structures and the important eventual application to such techniques to asteroidal exploration and exploitation.

II. Analysis

It is a well-known consequence of orbital mechanics that maneuvering between distant points in Earth orbit requires the implementation of nonrectilinear guidance. In order to quantify the boundaries over which nonrectilinear guidance must be employed, Stern[1] conducted an analytical study in which he derived an altitude-dependent transfer *time* limit on any rectilinear transfer with specified end-point accuracy. Because rectilinear motion implicitly couples the combination of transfer path length D and velocity V to transfer time τ, it is possible to transform Stern's time limit into a *distance* limit by specifying V. We take advantage of such a transformation here.

Figure 1 presents a graph of the maximum path length that may be traversed (in the orbital plane) as a function of altitude, under the constraint that the end-point transfer error cannot exceed 30% of the transfer path length. From this graph we see that characteristic transfer velocities of 1 m/s give a 40 m transfer length limit in low Earth orbit (LEO); this limit grow to about 300 m at altitudes near 16,000 km. In general, this transfer path length constraint is directly proportional to the given end-point accuracy constraint. We conclude from this brief analysis that operations in low Earth orbits requiring transfer path lengths exceeding a few tens of meters will require transfer guidance more accurate than rectilinear (i.e., aim-and-shoot) schemes can provide. Because many of the large space structures envisioned for the 1980s and 1990s

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exhibit characteristic dimensions equal to or exceeding such limits, construction and maintenance operations in their vicinities will require point-to-point transfer guidance strategies that are more accurate than the rectilinear technique.

Perhaps the most widely familiar proximity guidance equations in use today are the Clohessy-Wiltshire (CW) equations of relative motion, which were developed over 20 years ago in support of the first orbital rendezvous flight demonstration programs[2,3] These equations, whose solutions are presented below, were originally developed by Hill in 1878 (for an entirely different purpose). Without development, we give here the CW equations of relative motion,

$$x(t) = 2\left(2\frac{\dot{x}_0}{\omega} - 3y_0\right)\sin(\omega\tau) = 2\frac{\dot{y}_0}{\omega}\cos(\omega t) + \left(6y_0 - 3\frac{\dot{x}_0}{\omega}\right)\omega t + 2\frac{\dot{y}_0}{\omega} + x_0 \tag{1a}$$

$$y(t) = \left(2\frac{\dot{x}_0}{\omega} - 3y_0\right)\cos(\omega t) = \frac{\dot{y}_0}{\omega}\sin(\omega t) - 2\frac{\dot{x}_0}{\omega} + 4y_0 \tag{1b}$$

$$z(t) = z_0\cos(\omega t) + \frac{\dot{z}_0}{\omega}\sin(\omega t) \tag{1c}$$

where ω is the orbital angular rate, t is the elapsed time, and the coordinate system employed is as depicted in Fig. 2. These equations, which were derived by linearizing the differential equations of relative motion for a massless point in circular orbit about the center of mass a massive spherical body, have been discussed in detail many times in the literature.[4] Of particular importance is their accuracy,[4,5] which is generally restricted to transfers requiring less than one-quarter of the orbital period. For LEO, this implies a transfer path length constraint of about 1850 m (again assuming a 1 m/s characteristic transfer velocity); similarly, the CW equations are restricted to transfer path length constraints of 26 km at GEO. Therefore, we conclude that the CW equations retain the requisite accuracy necessary to conduct proximity operations requiring transfers between extremal points on any foreseeable large space structure. We note, however, that the CW equations do not contain steering algorithms in the avoidance of path constraints along the transfer trajectory.

It is useful to digress (momentarily) and describe how a transfer from any point to any other point in the CW coordinate frame can be operationally mechanized. Equation (1) can be used to target a rendezvous intercept by locating the coordinate origin at the desired end point of the transfer and then solving these equations for the necessary relative velocity at $t=0$ by forcing the x, y, and z separations to zero (i.e. rendezvous) at some time τ, which we will henceforth refer to as the transfer time. Equations (2), which give the axis-wise transfer initiation relative velocity requirements, are the result of such manipulations,

$$\dot{x}_0(\tau) = \frac{x_0\omega\sin(\omega\tau) + y_0\omega\{6\omega\tau\sin(\omega\tau) - 14[1-\cos(\omega\tau)]\}}{3\omega\tau\sin(\omega\tau) - 8[1-\cos(\omega\tau)]} \tag{2a}$$

$$\dot{y}_0(\tau) = \frac{2\omega x_0[1-\cos(\omega\tau)] + y_0\omega[4\sin(\omega\tau) - 3\omega\tau\cos(\omega\tau)]\}}{3\omega\tau\sin(\omega\tau) - 8[1-\cos(\omega\tau)]} \tag{2b}$$

$$\dot{z}_0(\tau) = \frac{-\omega z_0}{\tan(\omega t)} \tag{2c}$$

By implementing the initial velocities specified by Eqs. (2), one guarantees arrival at the desired target after τ seconds, so long as τ does not exceed the CW accuracy time constraint discussed above. In order to complete an *operational* transfer, one must null all velocities at target intercept; the directions and magnitudes of such a maneuver can be computed by evaluating the values of the time derivatives of Eqs. (1) at $t=\tau$. The cost of a given CW directed transfer can therefore be computed by taking the rms sum of the transfer initiation and transfer completion maneuvers. It is important to note that, from an operational standpoint, CW-directed rendezvous requires accurate range, range rate, and attitude information, as well as the computational capabilities requisite to numerically solve the above equations; Lutze[6] discusses the effect of maneuver misapplication errors.

Returning to the problem of operating in the vicinity of large space structures, we note that the CW equations impose only pointwise boundary conditions on the rendezvous; they do *not* allow explicit control over the path between the transfer end points, save a range constraint that is an implicit consequence of the finite energy input of the transfer initiation maneuver. In any case, large space structures impose a real and a significant path constraint: their physical surfaces. Therefore, in order to conduct successful transfers either in their vicinity, or from one point on their surfaces to another, it will be neccessary to devise targeting schemes that circumnavigate the LSS-imposed path constraint.

In the most general sense, one could imagine a large space structure of highly complex surface geometry that is not symmetrical with respect to the topology of the CW equations and

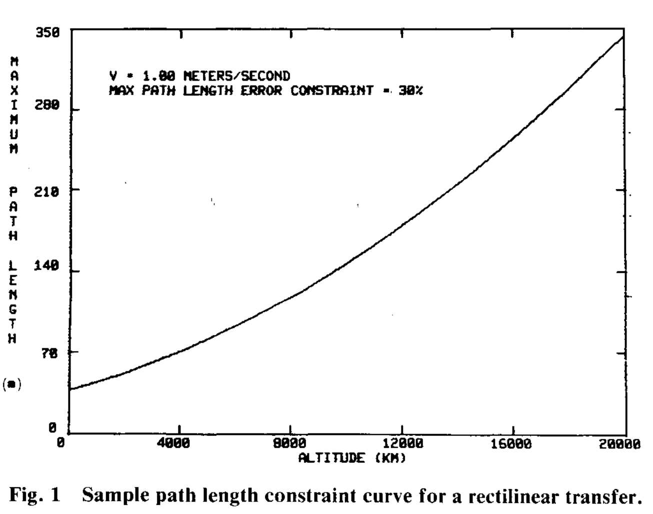

Fig. 1 Sample path length constraint curve for a rectilinear transfer.

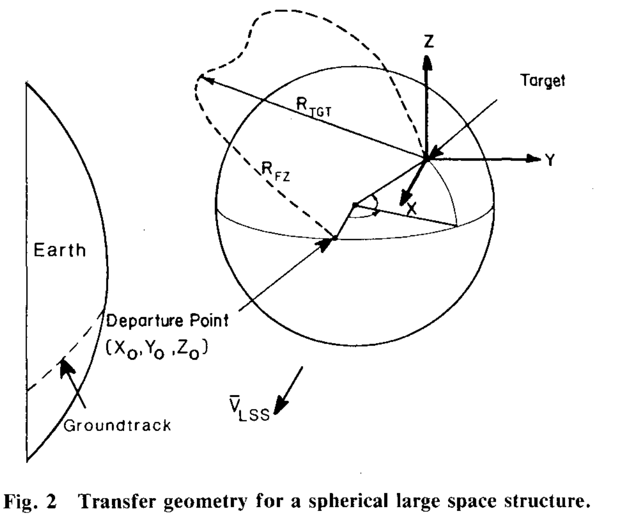

Fig. 2 Transfer geometry for a spherical large space structure.

that is rotating about some arbitrarily varying axis at some arbitrarily varying rate. We will discuss the difficulties of the solution to this complex, generalized problem at the end of this paper. It is more useful, however, to restrict this generalized path-constrained transfer problem to the most likely operational problem that one expects to encounter in the near-term era of space exploration. These circumstances include relatively simple surface gometries rotating at orbital rates (omega) about an axis of symmetry coaligned with a CW coordinate axis. We shall refer to this more relevant case as the restricted path-constrained transfer problem.

III. Guidance Strategies for the Restricted Path-Constrained Transfer Problem

Our approach to the restricted path-constrained transfer problem[7] has been to represent the LSS by an encapsulating mathematical surface that serves as a modeling representation of the volume of space through which motion is forbidden. We then numerically simulate CW transfers from one point on that surface to another; from the information provided by Eqs. (1), it is then possible to determine whether a given transfer trajectory penetrates the mathematical constraint surface, which we henceforth call the forbidden zone. This transfer success criteria may be generally defined by

$$R(t)>0 \quad \text{for} \quad t(0,\tau) \tag{3}$$

where $R(t)$ is the distance metric to the nearest point on the constraint surface. It is important to note that such volumes need not represent only physically impassable regions (i.e., walls), but also any other region in which motion is prohibited, such as hazardous antenna or thermal radiation volumes.

In order to make the restricted path-constrained transfer problem even more tractable, we have reduced the number of forbidden zone (FZ) geometries examined in this introductory study to: sphere and straw (a cylinder with height much greater than its radius). Although the number of conceivable FZ geometries is virtually unlimited, we have found that many complex LSS designs can be closely represented combinations of the sphere and/or straw prototypes. Both the sphere and the straw possess inherent symmetries that conform well to the CW topology (particularly since the CW equations can be transformed into both spherical and cylindrical coordinate systems). We note that the cylinder with radius much greater than its height (the plate) is also a convienient forbidden zone representation for certain structures. Figures 3 and 4 depict geometry of the restricted path-constrained transfer problem for the sphere and the straw, respectively; one can easily imagine complicated LSS geometries such as the proposed U.S. space station being represented by an assemblage of these two "primary FZs."

We now explicitly give the transfer success criteria for these two primary forbidden zones. For the sphere, we require

$$[x(t)-x')^2+[y(t)-y']^2+[z(t)-z']^2-R^2>0 \quad \text{for} \quad t(0,\tau) \tag{4}$$

and for the straw, we require

$$[x(t)-x']^2+[y(t)-y']^2+R^2>0 \quad \text{for} \quad t(0,\tau) \tag{5}$$

whenever the criteria $[z(+)-z']<H$ obtains. In Eqs. (4) and (5), $x(t)$, $y(t)$, $z(t)$ are given by Eqs. (1), R is the spherical (or cylindrical) radius, H the cylinder half-height, and x', y', z' the time-invarient components of the transfer target point to FZ-center vector.

Table 1 summarizes the seven techniques, or transfer strategies (TS), employed in our numerical simulations. Each TS represents a different operational approach to LSS circumnavigation. TS-I is defined as the baseline strategy in which

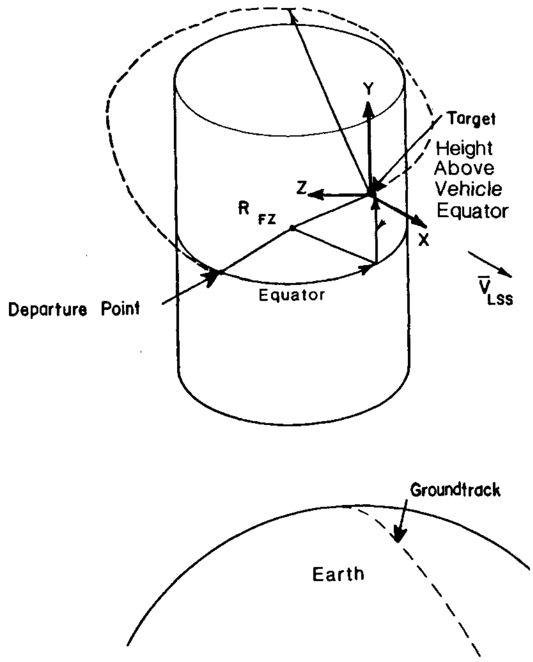

Fig. 3 Transfer geometry for a cylindrical gravity gradient stabilized large space structure.

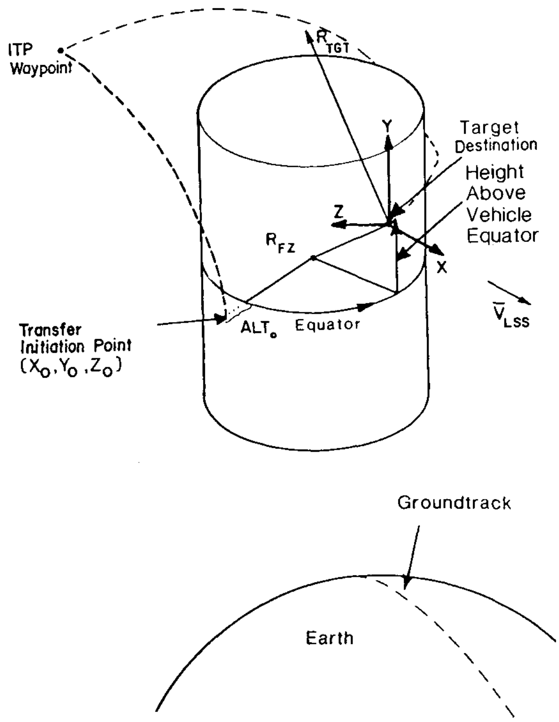

Fig. 4 Transfer geometry with pretransfer displacement (ALT_0) and intermediate target point for a cylindrical LSS.

Table 1 Details of the seven transfer strategies

Strategy	Initial separation, m	ITP k value
TS-I	0	0.00
TS-II	25	0.00
TS-III	0	1.00
TS-IV	0	1.33
TS-V	0	2.00
TS-VI	25	1.00
TS-VII	25	2.00

direct CW rendezvous with no FZ avoidance effort is employed. Transfer strategies II-VII, as described in Table 1, employ either initial standoff separations (ISS) from the FZ surface at the transfer initiation point or intermediate target points (ITP) or combinations of both. The ISS technique was derived on the basis of the experience gained in evaluating the baseline (TS-I) strategy over many, many test cases. From this exercise, it was found that most FZ penetrations were caused by initial motion toward the target through the forbidden zone. Similarly, the ITP technique (Fig. 4) developed as it became clear that for many transfers, the CW-directed trajectories tended to drive in a curvilinear but nearly direct path toward the target, which in general lies across some chord of the forbidden zone. The intermediate target point formulation employed by our simulation arbitrarily placed the ITP at a point half-way between the Transfer Initiation and Transfer Target points, and at an "altitude" above the forbidden zone surface equal to kA, where A is the minimum altitude from which an observer over the half-way point could have an unobstructed view of both the transfer initiation and transfer target points, and k is a scaling factor of order unity. We found in our simulations that surface-to-surface transfers are generally the most difficult to accomplish successfully; that is, as one removes either the transfer initiation or transfer target point from the vicinity of the FZ surface, the path constraint imposed by the FZ becomes less important; one can visualize this intuitively by considering the limiting case in which both the initiation and target points are far removed from the FZ.

IV. Analysis of Simulation Results

We constructed a Fortran simulation program to evaluate the merits of the baseline and ISS/ITP transfer strategies described above. The only criterion used for evaluation was the successful (i.e., nonpenetrating) accomplishment of transfers from one point on a FZ surface to another.

Our simulations involved a great variety of test cases. Both the sphere and the straw were tested in each of two size classes, as well as two orbits: LEO and GEO; in all, this provided for eight FZ/orbit combinations. For both LEO and GEO, 20 standardized transfers were conducted for the sphere in each of its two size classes; for the cylindrical configuration, 24 standardized transfers were tested for each size class. Pure inplane (the orbital), out-of-plane, and combined transfers were simulated. The test case described above spanned the range from short (chord-spanning) to long (diameter-spanning) transfer arcs across the FZ. In all, 352 unique FZ/orbit/endpoint combinations were run. Each of the seven transfer strategies described in Sec. III were run against each of the 352 runs. A statistical summary of the results of these 2464 test cases are presented in Tables 2 and 3.

Table 2 depicts the results for the LEO orbit. The transfer success likelihood values given in this table are the ratio of transfers that could be successfully accomplished by the given transfer strategy (for the given LSS geometry/size combination) to the total number of standardized transfers run for that LSS. One should note that a success was logged only if one or more of 10 τ-search modulated trajectories resulted in a nonpenetrating transfer. No extra points were given to strategies that produced successful transfers for more than one value of τ. In essence, this scoring tecnique is an unbiased evaluation of transfer strategy feasibility (as opposed to flexibility). The success ratio data presented here contain no information about the relative costs of the competing transfer strategies nor their operational suitability.

Several conclusions are evident in the LEO data set. First, we note that for all transfer strategies there is a trend toward greater success likelihood for the small-size class structures. Generally speaking, 10:1 LSS size differentials translate into an approximately 3 (or 4):1 loss in success likelihood. These data also indicate that there is no great differential in success likelihood for a given transfer strategy as a function of the (spherical or straw-like) LSS geometry. This result has obvious importance to potential LSS designers.

Perhaps the most important conclusions derivable from Table 2 concern the relative merits of the seven transfer strategies themselves; these data indicate that:

1) Transfer success is *highly* unlikely under the baseline CW transfer strategy with no avoidance targeting (TS-1), thus indicating that path-constrained transfers require the use of constraint avoidance techniques.

2) The pure ISS (initial standoff separation) technique (TS-II) provides for only marginal increases in transfer success likelihood.

3) The ITP (intermediate target point) techniques (TS-III-V) represent a highly promising method of enhancing transfer success likelihood; a nearly 1:1 gain in success likelihood is obtained for each increase in the ITP altitude scaling factor k.

4) The *combination* of ISS and ITP transfer strategies (TS-VI and VII) appear to represent the most successful and generally applicable FZ avoidance strategy. As a corollary to this result, we also find that initial standoff separations are most efficient (i.e., provide the greatest increase in success likelihood) when used in conjunction with low k values. These results have direct application to transfer time and velocity-cost effectiveness.

Table 3 presents data for the GEO case. We find a great general similarity between the results of the LEO and GEO data sets. The primary difference between the LEO and GEO data sets is the somewhat higher success likelihood obtained in GEO, particularly for the two large forbidden zones. In data obtained by our simulations (but not presented here), we also found that longer-arc transfers were more likely to be successful in GEO than in LEO; indeed, the greater number of

Table 2 Transfer success likelihood for LEO orbits

FZ configuration	TS-1	TS-II	TS-III	TS-IV	TS-V	TS-VI	TS-VII
Small sphere ($R=500$ m)	0.00	0.05	0.20	0.40	0.60	0.65	0.75
Large sphere ($R=5000$ m)	0.00	0.35	0.10	0.15	0.25	0.10	0.70
Small straw[a] ($R=50$ m)	0.04	0.08	0.29	0.54	0.71	0.71	0.79
Large straw[a] ($R=500$ m)	0.00	0.00	0.12	0.12	0.17	0.21	0.24

[a] $R:H=1:10$ for all straw configurations.

Table 3 Transfer success likelihood for GEO orbits

FZ configuration	TS-1	TS-II	TS-III	TS-IV	TS-V	TS-VI	TS-VII
Small sphere ($R=500$ m)	0.00	0.05	0.35	0.65	0.75	0.95	0.95
Large sphere ($R=5000$ m)	0.00	0.00	0.20	0.40	0.65	0.40	0.70
Small straw[a] ($R=50$ m)	0.04	0.08	0.50	0.75	0.79	0.79	0.89
Large straw[a] ($R=500$ m)	0.00	0.04	0.33	0.54	0.71	0.67	0.92

[a] $R:H=1:10$ for all straw configurations.

successful long-arc transfers accounted for almost all of the increase in the success ratios at GEO. We point out, however, that these results were obtained for equal transfer times at LEO and GEO; when the problem is transformed into one of constant transfer angle (i.e., $\omega\tau$), the LEO-to-GEO dependence falls away, since Eqs. (1-3) may be normalized by the quantity $1/\omega$. We stress that for operational purposes, transfer time *is* of importance; therefore LEO-to-GEO success likelihood probabilities will indeed appear.

The results of our data indicate a preference for LSS operations at higher orbits, particularly GEO; although most envisioned large space structures are intended for such orbits, planners have often relied upon LEO construction sites prior to boost to the GEO operational orbit. The results of this study bear direct importance on the advisability of LEO construction.

V. Concerning the Generalized Path-Constrained Rendezvous Problem

Here, we will briefly discuss the inherent difficulties incurred by relaxing the restricted problem by allowing forbidden zones that are either 1) not oriented favorably to the CW coordinate frame or 2) rotating with respect to the CW frame at some rate other than orbital rate. These discussions, although qualitative, serve to illuminate the results of numerical simulations not presented above in the interest of brevity.

In order to examine the difficulties incurred by FZs not favorably aligned with the CW coordinate frame, consider the cylindrical plate FZ introduced in Sec. III. Numerous stable on-orbit attitudes exist for platelike forbidden zones. Assuming that dynamical considerations (i.e., gravity gradient torques) restrain a plate radius to lie in the orbital plane, then the range of possible attitudes will lie between those depicted in Figs. 5 and 6. Transfers restricted to one plate face, as well as the plate rim, and from face to face are possible.

In the configuration illustrated in Fig. 5, the plane of symmetry lies in the orbital plane. Transfers restricted to translation in the orbital plane are equivalent to maneuvers on a simple face or about the cylinder rim. Such transfers are relatively easy to accomplish, since in-plane CW motion is both uncoupled from out-of-plane motion and free of FZ obstructions. For transfers from face to face, one must either complete the out-of-plane translation while clear of the in-plane boundaries (else violation of the FZ is assured), or maneuver through passageways in the LSS to the other side where in-plane motion can again be accomplished without restriction.

The configuration depicted in Fig. 6 is more difficult to deal with because the plane of FZ symmetry corresponds to the CW-z-plane. Simulations conducted with each of the seven targeting strategies developed above have failed to identify any successful transfers. This is due to the strongly coupled nature of the x and y motion. Invariably, transfer attempts that involve any x axis translation violate the FZ due to y axis motion prior to reaching the destination. Similar difficulties will arise for any platelike FZ with a symmetry plane not strictly coincident with the orbital plane.

Consider now the generalization described under case 2 above: forbidden zones rotating relative to the CW frame. Some large space structure applications require nonorbital rate attitude maneuvers (e.g., solar pointing). For such applications, the forbidden zone orientation (in CW coordinates) would be time dependent. Any such rotation of the forbidden zone relative to the CW coordinate frame complicate maneuvering since the path constraint is no longer scleronomic. There are two cases of interest.

If the structural rotation is purely about an axis of symmetry fixed with respect to the CW frame then the problem is greatly reduced. In this case, the FZ surface is still static (ie., time invariant) relative to the CW frame and the complication is reduced to a moving final-state problem. If the rotational motion of the structure can be predicted during the interval of the transfer, then a relatively simple calculation will lead to the destination coordinates in the CW frame at the desired intercept time τ. It may even be possible to choose the transfer initiation maneuver time in order to improve transfer cost and/or transfer time. Nonzero initial and final-state velocity components will affect the maneuver cost in a unique way for each maneuver, attitude configuration, and attitude rate history.

Alternatively, if either some component of the rotation with respect to the Clohessy-Wiltshire frame is not about an axis of symmetry, or if the axis of rotation is not fixed with respect to the CW frame, then transfers will suffer the additional complication of a FZ dynamically varying in time relative to the CW frame. This could greatly reduce the likelihood of locating a successful transfer and will dictate the development of unique targeting techniques for such circumstances. For very low rotation rates on moderately large structures, however, a simple solution is available. Enlarging the FZ uniformly by an amount sufficient to encompass the rotating FZ would completely account for the rotation while preserving the FZ geometry. Of course, this procedure would make transfer slightly more difficult due to the slight FZ size increase. The investigation of dynamic forbidden zones is an important area of investigation for future studies.

A final observation concerning the generalized problem is in order. The path-constrained rendezvous problem for LSSs can be easily seen to be analogous to the problem of maneuvering over the surface of small asteroids. In this case, the problem may be somewhat complicated by both a disturbing function representing the small gravitational attraction of the asteroid

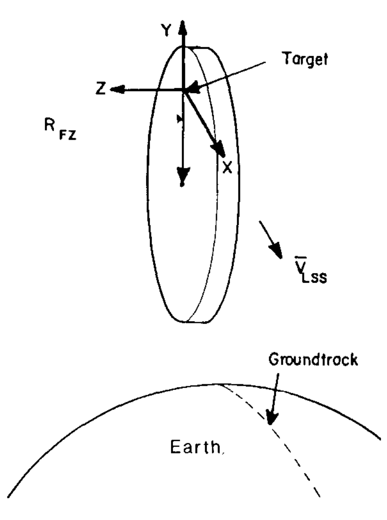

Fig. 5 Platelike large space structure in gravity gradient stabilized attitude with the plate lying entirely in the orbital plane.

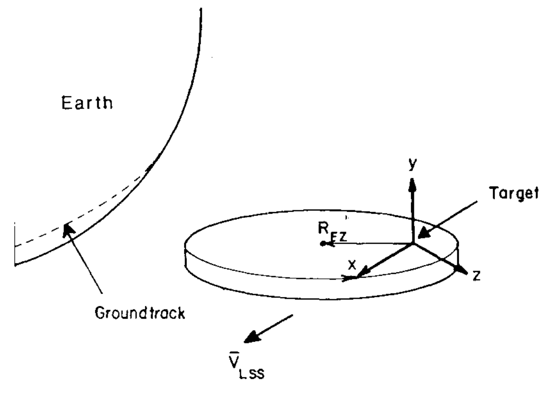

Fig. 6 Platelike large space structure in gravity gradient stabilized attitude with the plate lying perpendicular to the orbital plane.

(relative to the solar attraction), as well as the axial rotation of the asteroid itself. Research into this uniquely intriguing (and someday commercially relevant) aspect of the problem awaits only the efforts of interested investigators.

VI. Conclusions

In this study we have introduced the importance of the path-constrained transfer problem for operations in the vicinity of large space structures. A general discussion of the problem has been given. Through the use of numerical simulations, we have demonstrated that path constraint avoidance is critical to the successful accomplishment of point-to-point transfers on or near an LSS. Our simulations provided information on the importance of orbital altitude and LSS size/geometry variations on the difficulty of achieving nonpenetrating (i.e., successful) path-constrained orbital transfers. By conducting numerical simulations of approximately 2500 test cases, we have found that the most successful path constraint avoidance strategy is a combination of a small initial standoff separation combined with an intermediate target point exterior to the contraint surface. By comparing the likelihood of transfer success at LEO and GEO with equal transfer times, we found that such success is more probable at higher altitudes; for this reason, we recommend that LSS construction site planners reconsider the advisability of LEO assembly sites.

Our final contribution to the discussion of this new topic concerned the difficulties inherent to obtaining solutions to the fully generalized path-constrained rendezvous problem. Here we have qualitatively demonstrated that proper and relative placement of LSS axes of symmetry and rotation are crucial to the successful accomplishment of transfers around the LSS.

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