A Rectilinear Guidance Strategy for Short Orbital Transfers

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The solutions to Clohessy-Wiltshire equations of motion have been approximated for short transfer times. For such transfers, these solutions describe decoupled rectilinear trajectories that are easy to implement. The bounds over which this rectilinear approximation holds are explored. Separate normalized error functions then are derived for both in-plane and out-of-plane motion. From these error functions transfer time limits are derived. Further it is shown that in-plane motion diverges from straight-line paths much more rapidly than out-of-plane motion. Rectilinear guidance strategies are of importance to terminal rendezvous and extravehicular as well as satellite servicing operations.

Nomenclature

a	= orbital semimajor axis
CW	= Clohessy-Wiltshire
G	= universal gravitational constant
$\boldsymbol{H}$	= orbital angular momentum (i.e., out-of-plane) vector
LCW	= Linearized Clohessy-Wiltshire
M	= mass of the primary body (Earth) in Keplerian dynamics
n	= integer
$\boldsymbol{R}$	= instantaneous orbital radius vector
R_0	= initial in-plane separation
t	= time
V	= instantaneous orbital velocity vector
x	= Clohessy-Wiltshire coordinate directed antiparallel to the orbital velocity vector
$\dot{x}, \dot{y}, \dot{z}$	= Clohessy-Wiltshire x, y, and z coordinates, respectively, time rate of change
y	= Clohessy-Wiltshire coordinate directed parallel to the radius vector
z	= Clohessy-Wiltshire coordinate directed parallel to the orbital angular momentum vector
γ	= in-plane azimuth angle; measured from x to y
γ_0	= initial in-plane azimuth angle
Δ	= $\tan\gamma$
$\epsilon_x^*, \epsilon_y^*, \epsilon_z^*$	= normalized position error in x, y, and z, respectively, at intercept
ϵ_{spec}^*	= specified (desired) normalized in-plane position error at intercept
ϵ_{tot}^*	= normalized in-plane position error at intercept
θ	= transfer arc, given by ωt or $\omega\tau$
θ_{x-y}	= in-plane transfer arc
θ_z	= out-of-plane transfer arc
θ_z^*	= normalized out-of-plane transfer arc
θ_{x-y}^*	= normalized in-plane transfer arc
τ	= transfer interval, s
τ_{x-y}	= resulting in-plane transfer interval, as constrained by Eq. (15)
ω	= orbital angular rate

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Introduction

TERMINAL area guidance and navigation (G&N) has long been an area of operational concern. Every orbit transfer dictates the crossing of equienergy surfaces. In the terminal area, orbital mechanics transitions from large- to small-scale energy changes. In the limit, motion becomes rectilinear (i.e., straight line) and the G&N task becomes intuitive. Such a limit is evidenced by transfers within the restricted domain of spacecraft cabins.

In this report we will investigate rectilinear motion to determine the bounds within which these intuitive guidance laws can be applied. This problem is applicable to the NASA Solar Max and Palapa Repair Missions, extravehicular activity (EVA) transfers in the vicinity of large space structures (such as a space station), and routine rendezvous/inspection operations.

The Clohessy-Wiltshire (C-W) Equations of Motion

The early work on terminal rendezvous/proximity operations was done in the late 1950s and early 1960s in support of the NASA Gemini and USAF SAINT programs. Perhaps the most widely accepted terminal rendezvous technique was developed by Clohessy and Wiltshire[1] who rederived Hill's equations of 1878. The CW equations (as they are known) were achieved by linearizing the nonlinear differential equations of relative motion about a circular orbit to obtain

$$\ddot{x} - 2\omega\dot{y} = 0 \tag{1a}$$

$$\ddot{y} - 2\omega\dot{x} - 3\omega^2 y = 0 \tag{1b}$$

$$\ddot{z} + \omega^2 z = 0 \tag{1c}$$

where $\omega = \sqrt{GM/a^3}$ and a is the orbital semimajor axis. Since the orbital eccentricity is assumed negligible, the orbital angular velocity ω becomes a constant equal to the mean motion of the orbit. The coordinate system employed (as shown in Fig. 1) includes $\hat{x}$ in the orbital plane antiparallel to the velocity vector (i.e., against V), $\hat{y}$ directed radially outward from the center of the Earth through the coordinate origin (i.e., along $\boldsymbol{R}$), and $\hat{z}$ completing the right-handed triad parallel to the angular momentum vector (i.e., along $\boldsymbol{H}$). For convenience, the origin is typically located at the *target* point. One should note that this coordinate system is rotating at the orbital angular rate ω which is related to the orbital period by $\omega = 2\pi/T$. We define the in-plane azimuth angle γ as measured from the $+\hat{x}$ unit vector toward the $+\hat{y}$ unit vector. It is important to note that the z (out-of-plane) motion is decoupled from the x and y (in-plane) motion in Eqs. (1).

Solving Eqs. (1), Clohessy and Wiltshire obtained a set of time-parametric equations that describe the relative motion of some reference vehicle about the origin (target):

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

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

$$z(t) = z_0\cos(\omega t) + \frac{\dot{z}_0}{\omega}\sin(\omega t) \tag{2c}$$

These are the well-known CW equations. They can be used to target an intercept by forcing each coordinate to zero at the desired transit time $t = \tau$, and then solving for $\dot{x}_0$, $\dot{y}_0$, and $\dot{z}_0$, the initial velocities required to effect closure. The solutions are

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

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

$$\dot{z}_0(\tau) = \frac{-\omega z_0}{\tan(\omega\tau)} \tag{3c}$$

Tests reported by various authors, including Felleman,[2] have shown that a CW-directed rendezvous retains good accuracy for transfer times (i.e., τ) less than one-fourth the orbital period. Recent studies by Lutze[3] indicate that significant deviations from the nominal intercept can result from either inaccurate knowledge of the initial state or incorrect application of the intercept maneuver.

Although the CW solutions are much easier to implement than the exact differential equations of motion, they are far too cumbersome to execute without computational aids. In addition, the target-centered initial-state vector is required to solve Eqs. (2) and (3). These initial-state measurements, in effect, require radar or some other navigational equipment, which introduce additional systems requirements and operational complexity. Some researchers (e.g., Higgins[4]) have devised chart-assisted techniques that, when given accurate initial relative-state information, supply the required ΔV's to effect the rendezvous transfer.

Another investigation of the terminal rendezvous targeting problem[5] empirically demonstrated that, for short transfers, the CW paths reduce to rectilinear motion. The regime within which such rectilinear targeting schemes can be applied will be explored herein.

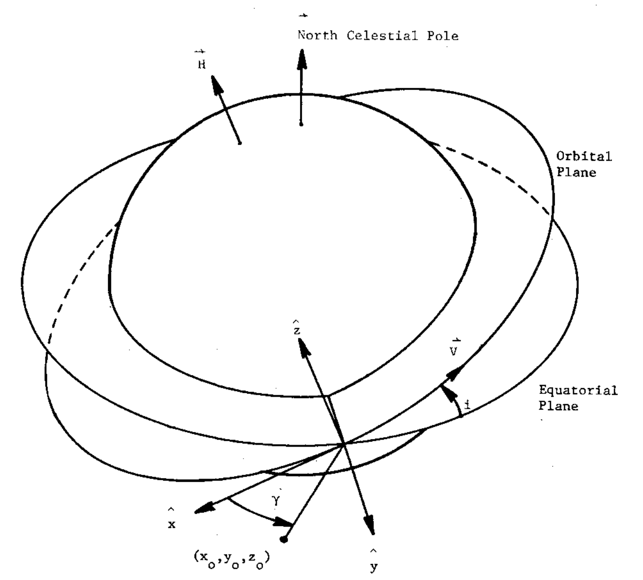

Fig. 1 CW coordinate and its relation to the orbit: The coordinate system rotates about the Earth at orbital angular rate ω.

Linearization of the Clohessy-Wiltshire Solutions

The CW equations only hold their accuracy for transfer angles $\lesssim \Pi/2$. Because first-order approximations of trigonometric functions hold for angles $\lesssim \Pi/8$, it would seem reasonable to linearize the trigonometric terms in Eqs. (2). Such a linearization would be useful for initial motion studies, as well as the investigation of "short arc" transfers.

Letting $\theta \triangleq \omega t$, $\sin\theta \equiv \theta$, and $\cos\theta \equiv 1$, and substituting into Eqs. (2), we obtain the linearized CW equations (LCWs):

$$x(t) = x_0 + \dot{x}_0 t \tag{4a}$$

$$y(t) = y_0 + \dot{y}_0 t \tag{4b}$$

$$z(t) = z_0 + \dot{z}_0 t \tag{4c}$$

Several conclusions can be drawn from examining Eqs. (4). First, the LCW equations are rectilinear; no simpler targeting scheme is possible. Further, the LCW equations exhibit completely decoupled motion in the three orthogonal axes. Solving for the initial velocities required to effect target intercept after τ s [i.e., $x(\tau) = y(\tau) = z(\tau) = 0$], we obtain,

$$\dot{x}_0(\tau) = -x_0/\tau \tag{5a}$$

$$\dot{y}_0(\tau) = -y_0/\tau \tag{5b}$$

$$\dot{z}_0(\tau) = -z_0/\tau \tag{5c}$$

Subsequently we will analytically determine (and numerically verify) the bounds for which this simple rectilinear targeting scheme holds.

Accuracy of Rectilinear Targeting in the Terminal Area

Because the CW equations retain very good accuracy for $\tau \lesssim \pi/2$, and because the CW equations will portray exact intercept at $t = \tau$, one can gage the LCW accuracy by substituting the LCW targeting equations (5) into the CW solutions (2) and evaluating the result at the intercept where $t = \tau$. If, for the given initial-state (and chosen) transfer time, the LCW equations are a good approximation of the CW equations, the target range at $t = \tau$ should be very close to zero.

By substituting Eqs. (5) into Eqs. (2), and normalizing the solution in each axis to the initial separation in that axis, we obtain the relative error at the time of intercept for an LCW-directed rendezvous. Normalization is employed so that we can study the error at intercept as a percentage of the unit initial separation in each axis (e.g., x_0), without regard to the absolute magnitude of the initial state.

Following this approach, we obtain,

$$\epsilon_x^*(\theta) = 4\left(1 - \frac{\sin\theta}{\theta}\right) + 2\Delta\left(\frac{1}{\theta}(\cos\theta - 1) + 3(\theta - \sin\theta)\right) \tag{6a}$$

$$\epsilon_y^*(\theta) = 4 - 3\cos\theta - \frac{1}{\Delta\theta}(2 - 2\cos\theta - \Delta\sin\theta) \tag{6b}$$

$$\epsilon_z^*(\theta) = \cos\theta + \frac{1}{\theta}\sin\theta \tag{6c}$$

where $\theta \triangleq \omega\tau$, $\Delta \triangleq y_0/x_0 = \tan\gamma$, and the asterisks indicate that the solutions have been normalized by their initial separations (i.e., by x_0, y_0, and z_0, respectively). It is interesting to note that the error equations in x and y remain coupled through the Δ terms as a direct result of Eqs. (2); we will take advantage of this fact in a later portion of this paper.

One should note that these error functions lose their meaning, mathematically (i.e., $\Delta \to \infty$), if $x_0 = 0$, because normalizing to zero initial separation produces infinite relative errors.

Out-of-Plane LCW Accuracy

We can determine the minimum out-of-plane error incurred by LCW targeting by setting Eq. (6c) to zero and solving for θ. This will allow us to evaluate the out-of-plane intercept error as a function of the transfer time τ. The solution gives zero error when $\theta = 0$ (i.e., $\tan\theta = 0$); naturally an instantaneous transfer suffers no error because the approximations $\sin\theta \cong \theta$ and $\cos\theta \cong 1$ hold exactly at $\theta = 0$.

In practice, intercept errors are acceptable up to some specified nonzero percentage of the initial separation. Thus, given any desired relative error ϵ_z^*, we can solve for the transfer angle that satisfies Eq. (6c); we denote this parameter θ_z. In Table 1 we have inverted Eq. (6c) and solved for θ_z as a function of the normalized out-of-plane error at intercept $\epsilon_z^*(\theta)$. Here, $\tau_{\rm LEO}$ and $\tau_{\rm GEO}$ refer to the transfer times in low Earth orbit (LEO) and geosynchronous Earth orbit (GEO) that correspond to θ_z, respectively.

These data demonstrate clearly that significant out-of-plane intercept errors (e.g., 10% initial separation), do not occur until θ_z exceeds 0.55 rad (31.5 deg). In LEO this corresponds to transfers of up to 500 s, and at GEO transfers of up to about 7700 s. The great increase in the transfer-time limit for GEO arises from the significantly lower orbital angular rate ω.

Because the motion is rectilinear, choosing an average closing rate is equivalent to choosing the initial velocity. Note, however, that the total maneuver cost (including braking) will be twice the initial impulse. For example, if an error of $\geq 5\%$ of the initial separation is desired, Eq. (6c) demonstrates that a 1 m/s initial ΔV constraint will restrict the out-of-plane radius of operations to 335 m in LEO, and 5352 m in GEO. In either case the total transfer is 2 m/s. In this manner the LCW targeting strategy can be used to plan out-of-plane short arc intercepts.

In-Plane LCW Accuracy

Since the in-plane relative error functions ϵ_x^* and ϵ_y^* remain coupled via the term $\Delta \triangleq y_0/x_0$, it would seem best to study the *total* relative in-plane error $\epsilon_{\rm tot} \triangleq (\epsilon_x^2 + \epsilon_y^2)^{\frac{1}{2}}$. Following the convention used throughout this paper, we normalize $\epsilon_{\rm tot}$ by R_0 (the total in-plane initial separation) to obtain

$$\epsilon_{\rm tot}^* = \left(\epsilon_x^2 + \epsilon_y^2\right)^{\frac{1}{2}} / R_0 \tag{7}$$

where ϵ_x and ϵ_y are *not* normalized (i.e., $\epsilon_x = x_0\epsilon_x^*$ and $\epsilon_y = y_0\epsilon_y^*$), and $R_0 = (x_0^2 + y_0^2)^{\frac{1}{2}}$. However, notice that

$$\left(x_0^2 + y_0^2\right) = x_0\left(1 + \Delta^2\right)^{\frac{1}{2}} \tag{8}$$

Table 1 Normalized out-of-plane errors for LCW targeting

$\lvert\epsilon_z^*\theta\rvert$	θ_z, rad	$\tau_{\rm LEO}$, s	$\tau_{\rm GEO}$, s
0.01	0.18	155	2,472
0.05	0.39	335	5,352
0.10	0.55	482	7,704
0.20	0.80	687	10,992

Because $\Delta = y_0/x_0$, we can transform Eq. (7) to arrive at

$$\epsilon_{\rm tot}^* = \epsilon_x^{*2} + \Delta^2\epsilon_y^{*2\frac{1}{2}}\left(1 + \Delta^2\right)^{-\frac{1}{2}} \tag{9}$$

however, $(1 + \Delta^2)^{-\frac{1}{2}} = \cos\gamma$ (because $\Delta = \tan\gamma$), so,

$$\epsilon_{\rm tot}^* = \left[\epsilon_x^{*2} + \Delta^2\epsilon_y^{*2}\right]^{\frac{1}{2}}\cos\gamma \tag{10}$$

Now, substituting Eqs. (6a) and (6b) into Eq. (10), squaring the result, and grouping like terms, gives

$$\begin{aligned}\epsilon_{\rm tot}^{*2} = \Bigg[& 16 + 4\frac{\Delta^2}{\theta^2} + 36\Delta^2\theta^2 + 48\Delta\theta - 8\Delta^2 + \frac{4}{\theta^2} \\ & + \left(16\frac{\Delta^2}{\theta} - 96\Delta - 72\Delta^2\theta - \frac{32}{\theta} + 12\frac{\Delta}{\theta^2}\right)\sin\theta \\ & + \left(-8\frac{\Delta^2}{\theta^2} - 12\frac{\Delta}{\theta} - \frac{8}{\theta^2}\right)\cos\theta \\ & + \left(\frac{16}{\theta^2} + 36\Delta^2 + 48\frac{\Delta}{\theta} + \frac{\Delta^2}{\theta^2}\right)\sin^2\theta \\ & + \left(4\frac{\Delta^2}{\theta^2} + 9\Delta^2 + 12\frac{\Delta}{\theta} + \frac{4}{\theta^2}\right)\cos^2\theta \\ & + \left(-12\frac{\Delta}{\theta} - 18\frac{\Delta^2}{\theta}\right)\sin\theta\cos\theta\Bigg]\cos^2\gamma\end{aligned} \tag{11}$$

If we approximate $\sin\theta$ by θ and $\cos\theta$ by unity, we obtain $\epsilon_{\rm tot}^* \equiv 0$, regardless of γ. Of course, this approximation only holds for $\theta = 0$ and π, so to capture higher-order effects applicable to small (but nonzero) θ, we can write

$$\sin\theta = \theta - \theta^3/6 + \theta^5/120 \tag{12}$$

$$\cos\theta = 1 - \theta^2/2 + \theta^4/24 \tag{13}$$

These approximations both hold extremely well for $\theta \leq \pi/2$.

Substituting Eqs. (12) and (13) into Eq. (11), retaining terms in θ^n where $n \leq 2$ (because $\theta \ll 1$, $\theta^3 \ll \theta^2$), and recalling the identity $\Delta^2 + 1 = \sec^2\gamma$, we eventually arrive at the following surprisingly simple result:

$$\theta_{x-y}^* = \epsilon_{\rm tot}^*/2\pi \tag{14}$$

where the subscript on θ_{x-y}^* denotes the in-plane solution. Note that θ_{x-y}^* has been normalized by 2π, so that the transfer arc is measured as a decimal percentage of a revolution.

This is a rather astonishing result. Given any desired normalized error (i.e., a percentage of the initial separation) at target intercept, a unique and directly proportional normalized transfer angle θ_{x-y}^* (hence, transfer time τ) will exist. Although the transfer times will be different for different orbits ($\omega_{\rm LEO} \gg \omega_{\rm GEO}$), θ_{x-y}^* will remain invariant. For operational convenience, we can rewrite Eq. (14) as

$$\tau_{x-y} = \epsilon_{\rm tot}^*/(2\pi\omega) \tag{15}$$

to obtain an in-plane transfer time limit which we denote τ_{x-y} any transfer time $\tau \leq \tau_{x-y}$ will thus be *assured* to meet the accuracy standards set by the desired value of $\epsilon_{\rm tot}^*$.

Let us take an example. Suppose that the largest relative intercept error one would accept in a given rectilinear in-plane transfer is 10%, then Eq. (14) gives $\theta_{x-y}^* = 0.0159$. Now, following Eq. (15), a transfer-time limit of 81 s would be imposed for a 400-km-high orbit; this constraint obviously defines a unique linear tradeoff between initial in-plane separation and the closing rate, $\dot{R}$. It is important to note that for any reasonable

Table 2 Comparison of numerical and analytic results for the in-plane targeting scheme with $\gamma = 2.5$ deg

Specified targeting error, %, $\triangleq 100\epsilon_{spec}$	Analytically predicted θ^*_{x-y} [Eq. (14)]	Numerically calculated θ^*_{x-y} [Eq. (11)]	τ_{LEO} transfer, s
2	0.32	0.31	17.1
3	0.48	0.47	25.9
5	0.80	0.79	43.5
7	1.11	1.11	61.1
9	1.43	1.43	78.7
10	1.59	1.57	86.4

targeting error, say $\epsilon^*_{tot} \le 20\%$, θ^*_{x-y} remains small enough for the trigonometric approximations in Eqs. (12) and (13) to hold.

One further note concerning the in-plane result is appropriate. In actual practice, small off-line-of-sight (i.e., nonrectilinear) errors can be nulled out routinely by small maneuvers directed against the off-line-of-sight motion. Such a technique would permit accurate transfers that exceed the time limits placed by these results, with maneuver segment limits as predicted by Eq. (14).

Computer Verification of the In-Plane Solution

To confirm the in-plane results obtained above [particularly the validity of the approximations leading to Eq. (11) and the tedious algebra leading to Eq. (14)], a Fortran program was constructed. Equation (11) was evaluated for θ^*_{x-y} with ϵ^*_{tot} and γ given; γ was stepped at increments of 5 deg throughout the interval from 0 to 360 deg.

Table 2 allows us to compare the predictions of Eq. (14) with those of Eq. (11). ϵ^*_{spec}, the specified targeting error, is given on the left, followed by θ^*_{x-y}, as given by Eq. (14). The third column presents the numerically determined θ^*_{x-y}, required in Eq. (11) to satisfy ϵ^*_{spec}. Finally, the transfer-time limit τ_{LEO} [for a typical low Earth orbit (400 km)], as given by Eq. (15), is presented in the rightmost column.

Let us inspect Table 2. The close agreement between columns two and three confirms that the solutions obtained by substitution of small θ^*_{x-y} angles into Eq. (11) are in excellent agreement with the predictions of Eq. (14). The residuals are at the 1% level and are directly attributable to unmodeled effects introduced by the truncation of higher terms in the trigonometric series used to obtain Eq. (14). Although the example shown in Table 2 was calculated with $\gamma = 2.5$ deg, many other in-plane azimuths were also run. Continued good agreement between the numerical calculations and Eq. (14) was found. From these data we conclude that Eq. (14), and, therefore, Eq. (15), represent accurate error functions for the in-plane rectilinear targeting problem.

Returning to Table 2 we find that maximum discrepancies were noted when $\gamma = n\pi/4$, with n odd. These remained at the 4% level and were caused by ϵ^*_x and ϵ^*_y errors acting in concert with $|\tan\gamma| = 1$. Finally, the numerical data demonstrated that, for $\gamma = n\pi/2$ with n even, the error was dominated by the ϵ^*_x component, while the componentwise targeting error in ϵ^*_y dominated for n odd. This stems directly from Eq. (10), which can be rewritten to read

$$\epsilon^*_{tot} = \left(\epsilon^{*2}_x \cos^2\gamma + \epsilon^{*2}_y \sin^2\gamma\right)^{\frac{1}{2}}$$

Some Operational Considerations

The LCW targeting technique, we conclude, works quite well for short transfers, both in-plane and out-of-plane. By comparing the ϵ^*_z (out-of-plane) solution to the ϵ^*_{tot} (in-plane) solution, however, we find that in-plane errors accrue much more rapidly than out-of-plane errors. For example, when $\epsilon^*_{tot} = 0.02$, the $\theta^*_{x-y}/\theta^*_z$ ratio is 1.45. As ϵ^*_{tot} is allowed to increase to 0.2, $\theta^*_{x-y}/\theta^*_z$ increases to 4.0. This result demonstrates that three-dimensional transfers will primarily diverge from rectilinear motion due to in-plane errors.

One distinct operational advantage of rectilinear (LCW) targeting is ease of implementation. For automatic rendezvous by remote control, only a television system is required for aiming; for EVA maneuvers, a reticle would suffice.

Given time, fuel, or distance constraints, Equation (15) sets a transfer-time constraint which guarantees control over the intercept accuracy requirements for in-plane transfers. For example, given a requirement of a 10% error at intercept (in a 300 km LEO), an 88-s transfer limit results; thus, one 100-m transfer would require one 1.14 m/s maneuver directed at the target to initiate the transfer and a braking maneuver of equal magnitude at intercept. Since out-of-plane errors accrue more slowly than in-plane errors, they can be ignored for most LCW transfers.

Conclusions and Recommendations

Rectilinear targeting, derived from the solutions to the Clohessy-Wiltshire relative motion equations, has been shown to be a simple, accurate, and easy-to-implement technique for short orbital transfers; rectilinear targeting is ideally suited to inspection, extravehicular activity, and docking operations. Error functions have been developed for both out-of-plane and in-plane solutions. From these error functions, we have produced a simple rule [Eq. (15)] which supplies the upper bound on the transfer time necessary to guarantee that any desired intercept error constraint placed upon the transfer will be achieved.

In-plane motion has been shown to diverge linearly in time from a rectilinear path; out-of-plane errors accrue at a smaller rate. Large vehicles in low Earth orbit, such as the proposed Space Operations Center, may employ gravity-gradient stabilization techniques which place the axis of least moment of inertia in the orbital plane and along ***R***. Because in-plane errors accrue most rapidly for rectilinearly directed transfers, proximity operations for large structures will be intimately affected by their architectural configuration.[6]

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