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Co-Apsidal Autonomous Terminal Rendezvous in Mars Orbit

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Introduction

ONE major conclusion of the studies on the proposed Mars sample return mission for a 1988 launch has been the identification of the Mars orbit rendezvous (MOR) mode as clearly superior to the direct return mode in terms of overall mission performance. For operational purposes, the unmanned or autonomous MOR may be segmented into four consecutive phases: approach, terminal, stationkeeping, and docking. This paper describes a new concept for the terminal rendezvous phase.

The approach phase of the MOR starts with the assumption that the ascent vehicle (AV) carrying samples from Mars is already injected into a slightly elliptical orbit (e.g., 400- ×600-km alt) about Mars. Since the rendezvous orbiter (RO) is initially inserted in a suitable higher orbit about Mars, from the energy point of view the rendezvous should be designed to take place at the apoapsis of the AV. At the start of the terminal phase, the RO has been maneuvered into an almost coplanar elliptical orbit of slightly higher periapsis (e.g., 406- ×600-km alt) than that of the AV at the time when the AV is at its apoapsis in such a way that the RO leads the AV by about 300 km (proposed maximum range of the RO laser radar). Data from the ladar (laser radar) will be used for orbit determination after the approach phase of the maneuvering RO. The AV is assumed to be a "dumb" vehicle with no maneuver capability.

The use of the AV orbit plane as the reference plane implies that the difference between the perturbing accelerations (due to third body, central oblateness, solar radiation) on the AV and the RO is negligible under the constraint that the distance between the two vehicles is much smaller than that between the central body and the vehicles. It is assumed for the purposes of generalization that, at the time of RO delivery, the inclination angle i is within a degree, and the angle ϕ between the lines of apsides is within a few degrees. An initial maneuver nulling the inclination is followed by another maneuver to align the lines of apsides. A proper phasing maneuver is then executed at the co-apsidal point, and the final braking maneuver is performed at the same co-apsidal point to complete the terminal rendezvous transfer.

Illustrative Examples

Cases are shown in the order of complexity in order to illustrate the basic concept of the new rendezvous technique.

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Case 1: The Simplest Basic Case with $i=\phi=0$

To simplify further, the apoapses of the two vehicles are assumed to be identical (in actuality, the apoapses should be slightly different to avoid a possible premature encounter, see case 5). In this case, only two very small maneuvers are necessary to transfer the RO into the AV orbit. By using the Mars radius $R=3397.2$ km and the Mars gravitational constant $\mu=42828.287$ km^3/s^2, the AV orbit has, as assumed earlier, an apoapsis of $r_{aA}=3997.2$ km and a periapsis of $r_{pA}=3797.2$ km, resulting in an eccentricity of $e_A=0.0256594$, a semimajor axis of $a_A=3897.2$ km, and a period of $P_A=7386.58$ s.

Since the RO orbit is assumed to have the same apoapsis as the AV orbit but a slightly higher periapsis, the RO position at the end of the approach phase must lead the AV at the apoapsis of the AV by an angle θ_0 of, for example, 4.3 deg in the RO true anomaly (approximating the maximum RO ladar range of about 300 km), as depicted in Fig. 1. The required length of the RO semimajor axis is intimately related to the number of desired AV revolutions before RO transfer at the apoapsis into the AV orbit. The time needed for the RO to regress through the phase angle $\theta_0=4.3$ deg gives a measure of the number of revolutions desired. If a minimum of about ten revolutions is desired (about 20 h), it is estimated that the required RO periapsis distance should be about 6 km longer (resulting in a RO semimajor axis $a_R=3900.2$ km, eccentricity $e_R=0.0248705$, and period $P_R=7395.11$ s) than the AV periapsis distance. With this targeted a_R, the exact time t_R for the RO to regress through the angle θ_0 during a desired consecutive number of revolutions can be calculated with the aid of Kepler's equation. For the preceding a_R and e_R, and $\theta_0=4.3$ deg in Fig. 1, we obtain $t_R=92.83$ s. The exact number of AV revolutions before closure of the phase angle

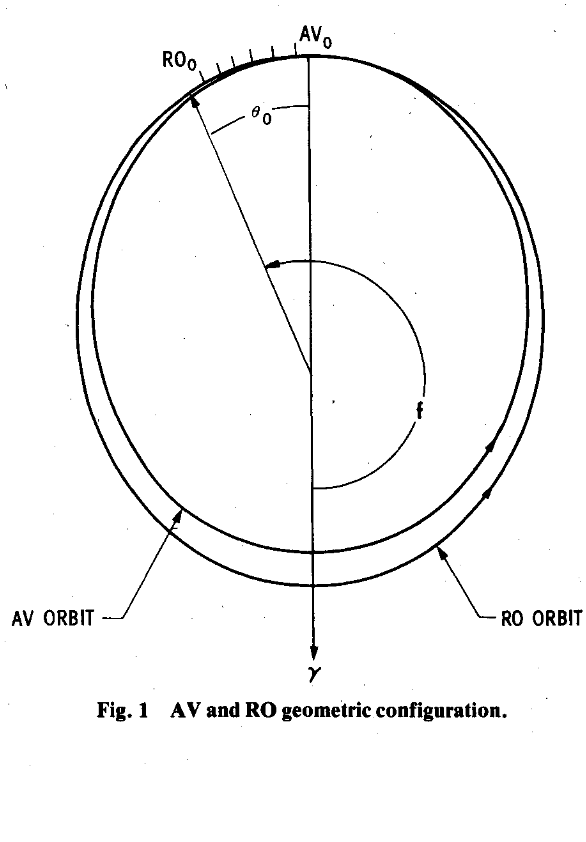

Fig. 1 AV and RO geometric configuration.

θ_0 is

$$t_R/(P_R-P_A)=10.882\,\text{rev} \tag{1}$$

Note from Eq. (1) that the number of revolutions is not an integer. It is feasible now to require that the terminal rendezvous phase be completed by the end of the 11th revolution of the AV. To accomplish this, the first impulsive phasing maneuver ΔV_1 should be executed at the nth RO apoapsis in order to reduce the a_R so slightly that the RO and AV will arrive at this common apsidal point simultaneously on the 11th revolution of the AV. To evaluate the magnitude ΔV_1 at the nth RO apoapsis passage, the following condition must be satisfied:

$$11\,\text{rev}-n\,\text{rev}=\frac{t_R-(n-1)(P_R-P_A)-C_{na}(P_R-P_A)}{P_R'-P_A} \tag{2}$$

where $n=1,2,3,...10$, P_R' is the required new period of the RO, and C_{na} is a parameter (slightly less than unity) to be determined as a function of n.

The presence of the parameter C_{na} is a consequence of the fact that the phasing maneuver ΔV_1 is to be executed at the time of nth RO apoapsis passage, i.e., at the time when the AV has not quite completed the nth revolution. Solving for P_R' from Eq. (2), we have

$$P_R'=\frac{t_R-(n-1+C_{na})(P_R-P_A)}{11-n}+P_A$$

For a given n, C_{na} can be determined by the following procedure. Referring to Fig. 1, we note that RO_0 (at θ_0) is the initial position of the RO when the AV is at its initial apoapsis AV_0. Let θ_n be the position of the RO when the AV completes its nth revolution. Since the initial position $(\theta_0+\pi)$ and its associated time $(t_R+P_R/2)$ are known, θ_n can be determined by Kepler's equation

$$M_n=\frac{2\pi}{P_R}t_n-q\cdot 2\pi$$

$$=\sin^{-1}\left[\frac{\sqrt{1-e_R^2}\sin(\theta_n+\pi)}{1+e_R\cos(\theta_n+\pi)}\right]-e_R\frac{\sqrt{1-e_R^2}\sin(\theta_n+\pi)}{1+e_R\cos(\theta_n+\pi)}$$

where $t_n=t_R+P_R/2+nP_A$ and is known for a prescribed n, and q is an integer such that $0\le M_n\le 2\pi$. In turn, the time t_{na} required for the RO to propagate from θ_{n-1} to the next RO apoapsis can be calculated as

$$t_{na}=P_R-M_{n-1}(P_R/2\pi)+P_R/2$$

$$=3P_R/2-M_{n-1}(P_R/2\pi)$$

The parameter C_{na} is then the ratio of t_{na} to P_A and is always slightly less than unity for any n. Note t_{na} approaches P_A, and C_{na} approaches unity as n approaches the limit 10 for this case. For $n=2$, we have $\theta_{n-1}=\theta_1=3.9060$ deg, $t_{na}=t_{2a}=7310.81$ s, $C_{na}=C_{2a}=t_{2a}/P_A=0.98742$, and $P_R'=7395.01$ s.

The required new semimajor axis of the RO is $a_R'=3900.164$ km instead of the initial 3900.2 km, and its velocity at the apoapsis is $V_{aR}'=3.23233$ km/s. The required ΔV_1 at the second RO apoapsis passage point is -0.0156 m/s.

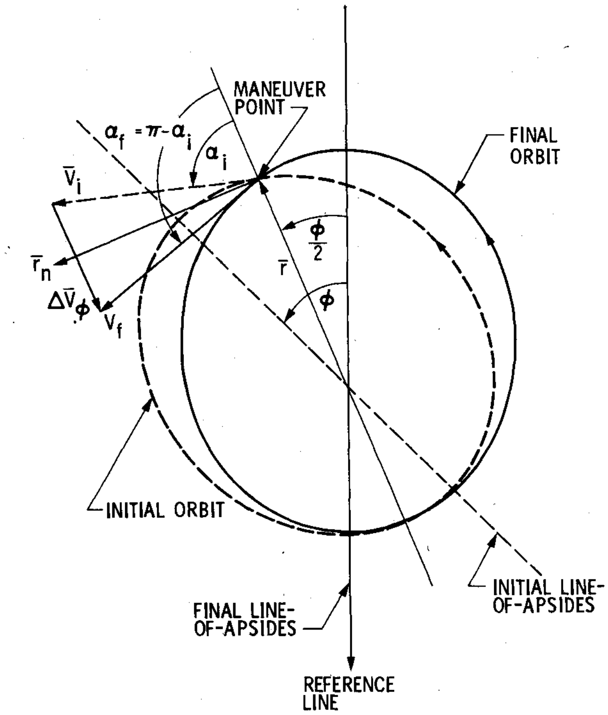

Fig. 2 Maneuver for a shift of line-of apsides.

The final braking maneuver ΔV_2 immediately before the rendezvous at the eleventh apoapsis is -1.2992 m/s for transferring the RO into the AV orbit with zero relative velocity to the AV. The total ΔV is $\Delta V_1+\Delta V_2=-1.3078$ m/s.

If the first maneuver is executed at the RO apoapsis of the sixth revolution, $t_{6a}=7344.93$, $C_{6a}=0.994361$, $P_R'=7394.92$ s, $a_R'=3900.133$ km, $V_{aR}'=3.23232$ km/s, $\Delta V_1=-0.0293$ m/s, $\Delta V_2=-1.2785$ m/s, and $\Delta V=-1.3078$ m/s, which is identical to the previous ΔV as expected from energy considerations. Accordingly, ΔV_1 can be carried out at any apoapsis between the 2nd and the next to the last. On the other hand, the operational rendezvous might decrease closing rate in a number of steps.

Case 2: Identical to Case 1, Except a Very Small Inclination Angle i

This case will be reduced to case 1 by nulling the angle i. Conventional nodal point maneuvers indicate that i can be nulled at a rate of about 56 m/s per deg for this example.

Case 3: Identical to Case 1, Except the Angle $\phi\neq 0$

This case will also be reduced to case 1 when the angle ϕ is nulled. The simplest and most efficient method to shift the line of apsides is to use a single maneuver aligned along the inward radial direction (for a positive ϕ) at $\phi/2$ near the apoapsis, as shown in Fig. 2. The magnitude of the maneuver is[1]

$$\Delta V_\phi=2e_R\sqrt{\mu/[a_R(1-e^2)]}\sin|\phi/2|$$

For $a_R=3900.2$ km, $e_R=0.0248705$, and $\phi=3$ deg, ΔV_ϕ is only 4.316 m/s. For a negative ϕ, the maneuver is aligned along the outward radial direction at $\phi/2$.

Case 4: Inclintion $i\neq 0$, and Line of Nodes and Lines of Apsides Distinct

This case can be handled easily by performing case 2 folllowed by case 3. It is clear that a combined single maneuver that could null both the inclination i and the angle ϕ would be most efficient in saving fuel consumption. Lagrange's planetary equations are useful in determining the magnitude, direction, and point of application of such a combined maneuver, but such a maneuver will not be pursued in the present paper.

Case 5: The Biased Case

The previous cases are assumed to have no dispersions from maneuver executions and orbit determinations. In reality, error dispersions are always present and error analyses are necessary. Without getting into an error analysis, we shall assume that the RO apoapsis distance is 1 km longer than the AV apoapsis distance. This 1-km bias should prevent any premature encounters of the RO and the AV (combined orbit determination and execution dispersions are assumed to be less than 1 km or its equivalent) at the start of the stationkeeping phase.

A comparison of this case with case 1 is informative since the two cases are basically identical except for the 1-km apoapsis distance bias. Calculations indicate that the $\Delta V(\Delta V_I + \Delta V_2)$ needed for the biased case (-0.696 m/s) is almost 50% smaller than that for the unbiased case. On the other hand, additional maneuvers are necessary to correct the 1-km bias during the stationkeeping phase.

Strategy in the Event of Emergency Rendezvous Abort

To complete the terminal rendezvous phase scenario, we shall mention a possible contingency strategy for continuing the mission in the event of an emergency terminal rendezvous abort in the last revolution of RO. If neither collision nor rendezvous should occur at the apoapsis at the prescribed time, the RO from then on would begin to lag behind the AV continuously. There are two ways we can restore the RO to a position suitable for a rendezvous attempt again. The first method is to let the RO lag increase with each revolution until the RO leads the AV by a few degrees again. This will involve hundreds of revolutions and therefore two to three months of delay or waiting. The second method is to use, at an appropriate RO apoapsis, a small maneuver to reduce the period of the RO to a smaller value than that of the AV, and thus reverse the successively increasing phase lag between the vehicles to a decreasing phase lag for a second rendezvous attempt. To reduce the RO period by shortening the RO periapsis by, for example, 12 km ($a_R = 3894.2$ km), a ΔV of only 2.618 m/s is needed.

Brief Comparison with Manned Rendezvous

In the "constant differential height" manned rendezvous technique[2,3] used in the Gemini and Apollo programs, the rendezvous vehicle first maneuvers into a circular orbit coplanar with the larger circular orbit of the target vehicle. During the terminal phase, the rendezvous vehicle leaves its orbit to rendezvous with the target vehicle. Immediately before the rendezvous point, it brakes to remove any differential velocity between the two vehicles. The co-apsidal autonomous terminal rendezvous technique tends to optimize the transfer of the RO into the AV orbit by utilizing long free-flight elliptical paths, and thus consumes very little rendezvous fuel. The following items show salient comparisons between techniques of the manned rendezvous and the autonomous co-apsidal rendezvous: 1) circular orbits vs elliptic orbits, 2) maneuverable target vehicle vs "dumb" target vehicle, 3) direct and "instant" Earth-based control vs onboard and/or delayed Earth-based control, 4) critical rendezvous time vs adjustable rendezvous time for operational convenience at any time, 5) relatively short terminal rendezvous duration vs any desired long rendezvous duration, 6) deviating considerably from free-flight path vs very close to free-flight path, 7) large fuel consumption vs relatively small fuel consumption, 8) proportion guidance vs phasing and braking maneuvers, 9) large fuel expenditure for a 2nd rendezvous attempt after abort vs a few m/s for a 2nd rendezvous attempt after abort, and 10) crew safety and mission success vs mission success only.

Conclusion

The co-apsidal terminal rendezvous technique takes the advantage of the aligned lines of apsides of two coplanar elliptic orbits of slightly different periods but of the same apoapsis distance. In doing so, the unmanned terminal rendezvous of the two vehicles can be chosen at any AV apoapsis passage time convenient for actual operational purposes and can be completed in two maneuvers with an extremely small fuel expenditure of only a few meters per second. In general, the rendezvous can be accomplished with four maneuvers: an initial maneuver that nulls the inclination between the orbits is followed by a second maneuver aligning the lines of apsides, and then a phasing maneuver is followed by a final braking maneuver to bring the vehicles into the stationkeeping phase.

Acknowledgments

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Maximum-Endurance Return-to-Target Gliding Trajectories

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Nomenclature

b = specific group of α parameter
B = constant = 0.5 $\rho S/m$
C_L = lift coefficient
C_D = drag coefficient

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