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Engineering Notes

Mars Surface Exploration Caching from an Orbiting Logistics Depot

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Nomenclature

$D_{\mathrm{crs,eq}}$ = worst-case cross-track error, km
h_{orb} = orbit altitude, km
m_f = final (burnout) mass, kg
m_0 = initial (with propellant) mass, kg
R_{Mars} = radius of Mars, km
R_{orb} = orbit radius, km
T_{orb} = orbit period, s
T_{sol} = Martian day, s
β = ballistic coefficient, $\mathrm{kg/m^2}$
ΔV = (required/provided) velocity change, m/s
$\Delta\phi$ = longitude shift for consecutive ground tracks, deg

I. Introduction

EXPLORATION missions on Earth have used the principle of caching for centuries. Caching involves prepositioning discrete quantities of supplies at specific locations along a route in order to lighten the burden or extend the range of an exploring party. Historical missions that made use of caching on Earth are the Lewis and Clark expedition in 1803–1806 [1] and the ill-fated Imperial Trans-Antarctic Expedition of 1914–1917 [2]. Caching may play an important role in the future of manned planetary exploration as well. Without it, exploration sorties are inherently limited to a specific distance from a base or landing location given by the type of transportation vehicles used, the size of the crew, the mix and quantity of consumables, operational rules, and the nature of the terrain. For manned lunar missions, for example, this distance has been estimated at 3 km for exploration on foot, 5–15 km with unpressurized rovers, and up to 30 km with pressurized rovers [3]. In part, exploration range is determined by the quantity of consumables that can be carried along, limiting the amount of useful exploration that can be done at distances greater than 30 km from the landing site or base. Similar issues exist for manned Mars exploration.

This Note explores the concept of storing caches in a logistics depot on orbit and deliberately deploying them to the surface to extend human exploration range. We will use Mars as the motivating context, but the idea may apply to other situations as well. We first introduce the concept and then perform initial sizing of such a depot. This Note does not explore the full tradespace of orbital depots and caching architectures. Caching in space exploration can be implemented as two different architectures: direct entry from in-space trajectory and orbital entry from a low Mars orbit. While the direct entry does not contain the Martian orbit insertion maneuver and can be more efficient in terms of required ΔV, this Note only considers the orbital entry because of the following two reasons. First, the short time gap between deployment decision and actual landing of the supply unit provides meaningful flexibility to operate on orbit. Secondly, advanced propulsion systems such as a nuclear electric propulsion system (NEP) and solar electric propulsion can significantly reduce the cost resulting from the orbit insertion, and the efficiency gap gets very small.

Let us consider an orbiting logistics depot that is composed of a cluster of supply units deployed to a Martian orbit. Each prepackaged supply unit contains supply items (fuel and consumables) that allow extending the range of humans exploring the surface of Mars. Figure 1 shows the orbiting depot concept and its concept of operations. Typically, one or more surface vehicles start exploration from a base and return to the base before all fuel and consumables (e.g., fuel, food, water, and oxygen) have been expended. This is the case of an unassisted surface route, yielding a total distance D. In this case, the amount of fuel and consumables that can be used during a single route is determined by the capacity of the surface exploration vehicle. Now suppose that there is a logistics depot in Martian orbit and it is possible to command the depot to drop a supply unit (pod) filled with a known mix and quantity of consumables corresponding approximately to a vehicle's capacity. If the supply unit lands at such a location that the surface exploration vehicle can reach the unit before it runs out of consumables, the vehicle's range can effectively be doubled to $2D$. This is the case of the depot-assisted surface route shown in Fig. 1 (right) along with a simulated pod landing error ellipse. In the following sections we discuss the most important design decisions for such an orbiting depot, including orbit selection, individual supply unit design, and depot operations. These calculations are meant to establish a realistic "strawman" for the concept. Studies regarding detailed design in the context of specific surface exploration campaign strategies are left for future work.

II. Conceptual Design of a Mars Orbiting Logistics Depot

A. Orbit Selection

We first select relevant orbital elements that should be specified for the logistics depot orbit. It is assumed that the orbit is circular and the eccentricity e of the orbit is therefore zero. Also, the inclination of the orbit is set to be 90 deg so that the supply units can access the full latitude range.

The radius of the orbit (R_{orb}) is determined with consideration of atmospheric drag and ground track of the orbit. It is assumed that the orbiting depot is placed in low Mars orbit and can support 3–4 consecutive missions, each of which is related to the opportunity to visit Mars that comes approximately every 2.2 years (every 1 synodic period), and the orbit should be operational for about 10 years. Keating et al. [4] predicted that Mars atmospheric density at the altitude of 160 km ranges between $0.45 \times 10^{-10}\ \mathrm{kg/km^3}$ and $1.0 \times 10^{-10}\ \mathrm{kg/km^3}$ based on Mars Global Surveyor experimental data. This level of atmospheric density is small enough for orbit maintenance to not require significant propellant over this long period. Thus, a constraint that the altitude of the logistics depot orbit should be larger than 160 km is imposed.

For each orbit the ground track of the depot sweeps all latitudes, but the ground track may not exactly pass over longitudes that have scientific interest and are within range of the base. To access a specific

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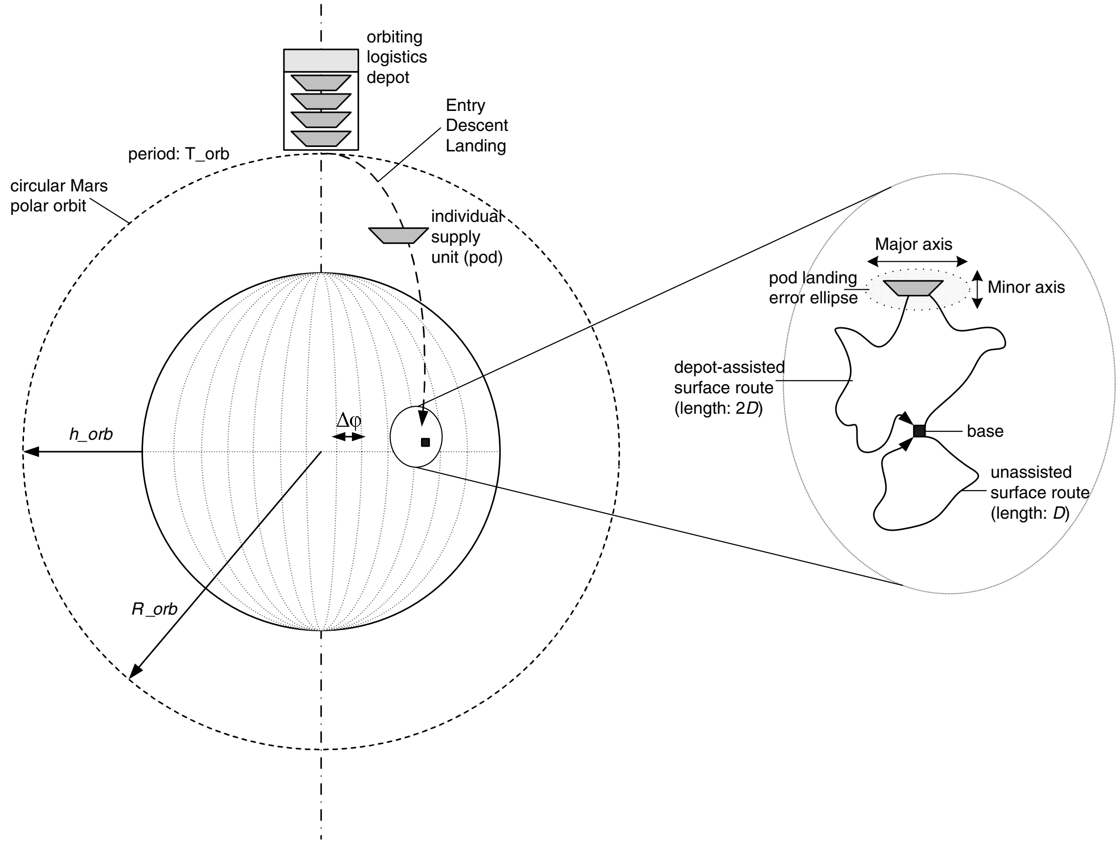

Fig. 1 Orbiting logistics depot: (left) concept diagram with logistics depot in Mars polar orbit and (right) surface exploration.

target point on the surface, the orbiting depot waits until its ground track is closest to the target point and releases the supply unit at the right time with proper initial cross-track velocity. The release time controls the along-track landing position and the initial cross-track velocity controls the cross-track landing position. The worst-case cross-track position difference takes place at the equator. It is known that the shift in the crossover longitude value of the ground track at the equator can be expressed as follows [5]:

$$\Delta\phi = T_{\mathrm{orb}}/T_{\mathrm{sol}} \cdot 360 \tag{1}$$

Considering that there are two chances for accessing a specific landing location (descending and ascending) in an orbit, the worst-case error is expressed as follows:

$$D_{\mathrm{crs,eq}} = 0.25 \cdot R_{\mathrm{Mars}} \cdot \Delta\phi \cdot (\pi/180) \tag{2}$$

This Engineering Note proposes the family of orbits that follow the same ground track each Martian day be used for the logistics depot. These orbits guarantee that, every day, any location on Mars surface can be approached within cross range expressed in Eq. (2). If the ΔV supplied by the pod is capable of generating the cross range in Eq. (2), daily accessibility of any Mars surface location is also guaranteed globally, which enables the on-demand operation of the pod. In this case, the descending ground track crosses the target latitude exactly at the center of the two consecutive ascending ground tracks. This situation can be achieved when the orbit has a period of the following form:

$$T_{\mathrm{orb}} = T_{\mathrm{sol}}/(2k) \qquad (k = 1, 2, \ldots) \tag{3}$$

Table 1 shows the family of orbits whose periods satisfy Eq. (3). The orbit with a k value of 6 is chosen so that its orbital altitude is higher than 160 km. In this case, the radius of the orbit is 3904 km and the altitude of the orbit is 494 km.

Other orbital elements such as the longitude of node Ω or the argument of pericenter ω are irrelevant to the operation of the orbiting depot and are not discussed in this Note.

B. Individual Supply Unit Design

An individual supply unit is designed to approximately double the exploration range by providing the same amount of fuel and consumables as the surface vehicle's capacity. The capacity is determined so that the vehicle can support the scenario proposed by Hong [6]. It is a 7-day excursion scenario designed for an

Table 1 Possible Mars orbits for a logistics depot

k	T_{orb}, s	R_{orb}, km	h_{orb}, km	$\Delta\phi$, deg	$D_{\mathrm{crs,eq}}$, km
3	14,798	6,198	2,788	60	893
4	11,097	5,116	1,706	45	670
5	8,878	4,409	999	36	536
6	7,398	3,904	494	30	446
7	6,341	3,523	113	26	383

Table 2 Core contents for an individual supply unit

	Mass, kg	Density, kg/m^3	Volume, m^3
Food	28	500	0.01
Water	80	998	0.14
Oxygen	9	——	——
Fuel	677	1313	0.52
Food container	3	——	0.01
Water container	8	——	0.15
Oxygen container	1	——	0.05
Fuel container	70	——	0.65
Total	876	——	0.87

unpressurized vehicle /camper surface mobility system, including 32 h of driving and 24 h of extravehicular activity. Table 2 presents the mass and volume of the fuel and consumables contained in an individual supply unit.

The supply unit should be protected from deceleration and heating during entry. The Mars Exploration Rover (MER) mission was selected as the reference case for reentry dynamics [7].

Zarchan [8] and Regan [9] identified three parameters that mainly affect the descent trajectory: initial velocity, initial altitude, and the ballistic coefficient. The ballistic coefficient $\beta = m/(S \cdot c_D)$ is interpreted as the relative magnitude of the inertial force compared to the drag. An entry body with low β is easily decelerated by atmospheric drag and has smaller terminal velocity.

The ballistic coefficient for the MER entry vehicle is estimated to be about 94 $\mathrm{kg/m^2}$ and its descent velocity at the altitude of 9.1 km was 440 m/s, where a supersonic parachute was deployed [7]. It entered the Martian atmosphere directly from its interplanetary trajectory, and the initial condition of the entry vehicle was more severe than that of our individual supply unit released from a low Martian orbit. If we design the supply unit so that the β value of the unit matches that of the MER entry vehicle, the supersonic parachute deployment condition would be sufficiently satisfied.

We carried out the sizing of the individual supply unit. The MER entry vehicle is used as the baseline design. Motors and propellant used for deorbiting and cross-track impulse are added to the core (fuel and consumables) and the weights for backshell, parachute, and heat shield are allocated so that the unit's parachute loading and aeroshell mass ratio match that of the MER. Table 3 presents the sizing results. Assuming that the I_{sp} value of the engine for the supply unit is 350 s, ΔV available from the motors and propellants is 366 m/s. Considering that 100 m/s of ΔV is required for deorbiting, the remaining 266 m/s can be used to provide cross-track maneuvering. We also obtained the maximum diameter of the entry surface (3.9 m) by matching the β value. Note that detailed packaging of the pod is not simple and many other factors (e.g., packaging elements to place the center of gravity at a proper location) should be carefully considered. These details are not within the scope of this Note and are left for future work.

C. Logistics Depot Assembly Sizing

It is assumed that 12 individual supply units are aggregated to make up a depot assembly and that the mass of all pods in the assembly equals $1781\ \mathrm{kg} \cdot 12 = 21,372\ \mathrm{kg}$. The main body of the depot assembly provides common functionalities such as holding and releasing pods, generating power, navigating, communicating, and maintaining its orbit. The structure of the main body does not require much strength and its mass would not be that heavy compared to the mass of the individual pods. A total of 20% of the pod mass is allocated to the main body of the assembly, including structure, power, avionics, and the propulsion system.

The orbiting depot can be prepositioned to Mars orbit separately from human flights and a low-thrust propulsion system can be used for a trajectory from the Earth to Mars. Landau and Longuski [10] presented a family of low-thrust trajectories between the Earth and Mars that may be suitable for such a depot. Based on the results in their paper, it is assumed that an NEP with a minimum initial acceleration trajectory and an I_{sp} value of 2050 s is used and that the required ΔV for a 270-day powered-capture low Earth orbit (LEO) to Mars trajectory is 8 km/s.

Table 3 Design of an entry body for an individual supply unit

	Supply unit	MER
Mass Allocation, kg		
Core contents	876	530
Impulse motors	100	——
Propellants	180	——
Backshell	423	194
Parachute	33	15
Heat shield	170	78
Total mass	1781	817
Dimension, m		
Max diameter	3.9	2.7
Ballistic coefficient, $\mathrm{kg/m^2}$	94	94

The orbital logistics depot must be capable of stationkeeping in Mars orbit for the duration of the mission. In LEO, the amount of ΔV required to make up the atmospheric drag is approximately 50 m/s/year [5], depending on orbital altitude and cross-sectional area. Considering that the atmospheric density of Mars is about 1/100 that of the Earth, a value of 300 m/s ΔV is assigned for stationkeeping of the depot assembly in low Mars orbit for 10 Earth years.

Using these results, the initial mass of the whole orbiting depot assembly departing from the Earth is calculated as 38,766 kg. A future heavy-lift cargo vehicle would be required to carry the initial 39 t supply depot into LEO for departure. Given the modularity of the concept a smaller or larger number of pods could be added or removed in 2 t increments to match the launch vehicle capability. Table 4 summarizes the mass calculation of the Mars orbiting depot assembly.

D. Depot Operations

There are two alternative strategies to operate the orbiting logistics depot, each of which has distinct advantages and drawbacks over the other.

The first strategy predetermines the landing location of an individual supply unit and deploys the unit before a route (the depot-assisted route in Fig. 1) begins and is similar to the push or prepositioning strategy in supply chain management (SCM) [11]. This strategy allows larger position error during the entry, descent, and landing (EDL) procedure and hence provides larger operational robustness sacrificing on the flexibility from dynamic rerouting. The communication system in the supply unit enables astronauts to identify the actual landing location of the supply unit before they start a route. Based on this information, the astronauts could partially or completely redesign the route starting from their base. Furthermore, if the landing of the unit is not successful or the landing location of the unit is too far away from nominal, they can release an additional supply unit and wait for the next successful deployment while waiting in the safety of the base.

The second strategy, analogous to the pull strategy in SCM, embeds larger flexibility in the operation than the first strategy by dynamically changing the route during the exploration. On the other hand, astronauts are out of base when the supply unit lands on the surface, and waiting is not a viable option to resolve troubles due to large landing position error. Thus, this strategy should be supported by a very reliable and accurate EDL system.

The 3-σ landing error (semimajor axis of error ellipse) for our reference mission (MER, ballistic entry) was approximately 50 km, and can be reduced to the order of 30 km by using improved approach navigation systems such as delta-differenced one-way ranging, dual spacecraft tracking, and optical navigation. In addition, hypersonic aeromaneuvering technology can place the unit within 10 km of the specified target [12–15]. Considering that the range of the pressurized exploration rover is 30 km [3], the first strategy

Table 4 Design of an entry body for an individual supply unit

Item	Calculation	Value
Calculation of arrival mass m_f		
Pod mass, kg	$1,781 \cdot 12$	21,372
Main body of the depot assembly, kg	$21,372 \cdot 20\%$	4,274
Total mass arriving Mars orbit, kg	——	25,646
Calculation of initial mass m_0		
Required ΔV, ΔV_{req}, m/s	——	8,300
I_{sp} of the propulsion system	——	2,050
Initial mass departing LEO, kg	$m_f \cdot e^{\Delta V_{\mathrm{req}}/I_{\mathrm{sp}}/g_0}$	38,766

(prerouting landing) is recommended for near-term missions adopting ballistic-type EDL. The second strategy can be selected in future missions with active maneuvering during the EDL to achieve a higher degree of operational flexibility by dynamic rerouting. In this case, the tradeoff study between the additional value from the flexibility and incremental cost to realize the advanced EDL system should be carried out to decide on the operational strategy.

III. Conclusions

This Engineering Note introduces the concept of an orbiting logistics depot designed to deploy supply caches to a planetary surface. This would allow extending the range of crewed surface exploration beyond the range and endurance of vehicles operating from a fixed base with an assumed range of 30 km without resupplying. We provide a strawman for a Mars orbiting logistics depot and generate a conceptual design of the depot. Depot orbit selection, individual supply unit and assembly sizing, and operations of the depot are discussed.

A detailed feasibility study concerning technological parameters of the depot assembly (power system; guidance, navigation, and control system; structure; propulsion system; etc.) and the individual supply units (EDL system, communication system, etc.) are suggested as future work.

In addition to the feasibility study, development of the orbiting depot should be supported by a rationale indicating that a significant amount of benefit can be achieved when the supply depot is used for Mars surface exploration [16]. In particular, the efficiency of the Mars depot concept will have to be compared with that of increasing the size and range of surface vehicles by an equivalent amount.

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