Mars Mission Design and Analysis using Nuclear Thermal Propulsion

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1. Introduction

A Nuclear Thermal Propulsion (NTP) can be used as an alternative method for deep space missions, such as Mars and asteroids, due to its relatively high specific impulse and thrust compared to traditional chemical propulsion system despite its risk. We prepare for dedicated small launch vehicle not only to mainly put a satellite into the Low Earth Orbit (LEO) but to put an explorer into the deep space missions. As the launch vehicle capability and propulsion system equipped on explorer are key elements to design Mars mission, based on these conditions, mission design is performed and then required mass and thruster level of the explorer are estimated. Simulation results shown final dry mass using NTP was 454.1 kg, but final dry mass using bi-propellant propulsion was 194.2 kg for Mars orbiter mission.

2. Mars Mission Design

Synodic period for the Mars exploration is around 2.2 years so that launch opportunities around 2030 are 2028, 2031 and 2033[1]. The launch date for Mars mission is selected as 2028 considering the urgency in this study.

2.1 Launch Site and Dedicated Small Launch Vehicle

Naro Space Center located in South Korea is launch site for mainly LEO satellites but there is possibility to launch a deep space mission such as Mars and asteroids. We have a plan to develop the dedicated small launch vehicle consist of 2nd stages. The launch vehicle aims to put a payload mass of 500 kg into a 500 km Sun-synchronous orbit [2], but payload mass of 800 kg can be put into a 300 km LEO for interplanetary exploration.

2.2 Porkchop Plot for Mars Exploration

To select the launch and arrival date for the Mars mission, Lambert's theorem is necessary and the solutions of this theorem provide "Porkchop" plot as depicted in Fig. 1 [2]. Ballistic contours for departure energy (C_3) and arrival excess velocity (V_∞) are shown as a function of departure and arrival dates. Less departure energy and low arrival velocity are required to have optimal transfer trajectory.

Four candidates can be summarized as Table I. Departure date on 12/02/28 is selected because its departure energy has a minimum value among the candidates.

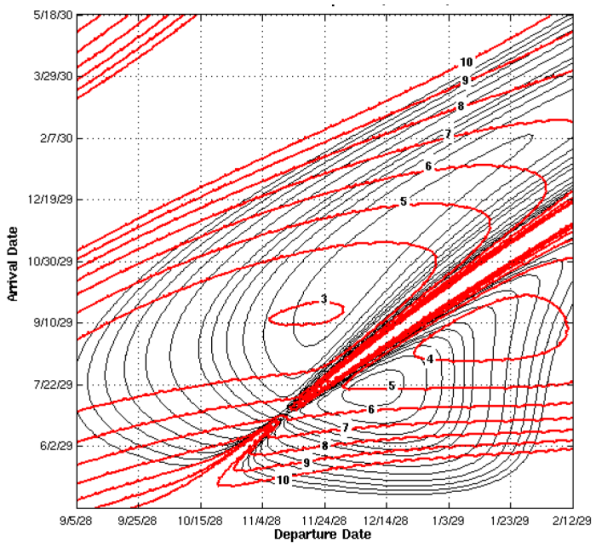

Fig. 1. Departure energy (C_3) and arrival excess velocity (V_∞) as a function of departure and arrival dates[2].

Table I: Launch Opportunity Candidates [2]

Mission Type	Departure Date	Arrival Date	C_3 (km^2/s^2)	V_∞ (km/s)
Type 1	12/10/28	07/20/29	9.048	4.892
Type 2	12/02/28	10/16/29	8.928	3.261
Type 1	01/17/29	09/02/29	24.12	3.593
Type 2	11/20/28	09/18/28	9.315	2.966

2.3 Dynamic Model and Numerical Search Method

Although results of Lambert's theorem provide basic parameters, equations of motion shown equation (1) is necessary to design a Mars explorer from launch site to the target orbit at the Mars [3].

$$\ddot{\vec{r}} = -\mu \frac{\vec{r}}{|r^3|} + \sum_{i>0} \mu_i \left(\frac{\vec{r}_{Bi} - \vec{r}}{|\vec{r}_{Bi} - \vec{r}|^3} \right) + \frac{1}{m} \vec{F}_s \qquad (1)$$

Where $\ddot{\vec{r}}$ and $\vec{r}$ are the acceleration and position of the spacecraft relative to a coordinate system with origin B_0 (reference gravitational body). μ and μ_i are the gravitational parameters for B_0 and B_i (i^{th} gravitational body, in here, Mars). $\vec{r}_{Bi}$ is the position of the B_i relative to B_0. m is the mass of the spacecraft and $\vec{F}_s$ consists of atmospheric drag and solar radiation pressure [3].

In order to solve this problem, numerical search method using Newton-Raphson algorithm shown equation (2) is used [4].

$$\vec{x}_{k+1} = \vec{x}_k + \vec{J}_n^{-1}(f(\vec{x}_k) - \vec{y}_d) \qquad (2)$$

Where $\vec{J}$ is Jacobian matrix consists of partial differential equation of $f(\vec{x}_k)$, $\vec{x}_k$ are control variables and $\vec{y}_d$ are equality constraints.

For from launch to Mars approach, control variables ($\vec{x}_k$) are launch epoch, coast duration in Earth parking orbit and Delta-V (ΔV) for Trans-Mars Injection (TMI). Equality constraints ($\vec{y}_d$) are departure date, departure energy (C_3), departure right ascension (α_∞) and declination (δ_∞). After the numerical search method converges, it is necessary to change the equality constraints ($\vec{y}_d$) to arrival date, Mars periapsis altitude and inclination and then re-run numerical search method to satisfy the targeted Mars orbit. Once the explorer approach periapsis of the Mars, ΔV for Mars orbit insertion is performed to meet the orbital period of 35 hours.

2.4 Simulation Results

Figure 2 shows the launch trajectory of dedicated small launch vehicle from Naro Space Center (red) and earth parking orbit (yellow) trajectory with respect to Earth fixed frame. Due to the safety range limitation and non-yaw maneuver during ascent, launch azimuth should be approximately 170° so that the initial inclination after separation is around 80°.

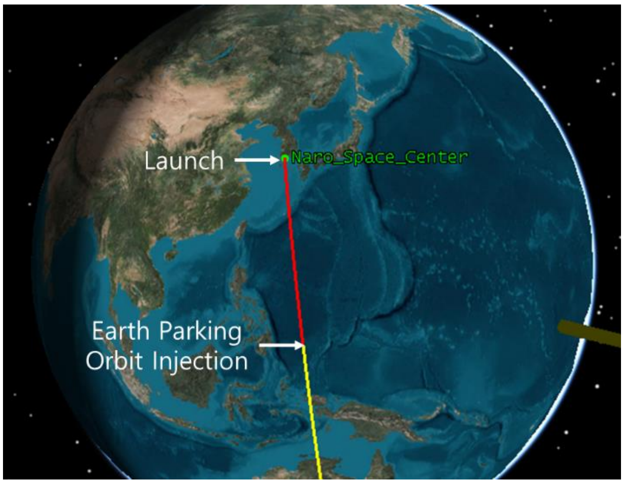

Fig. 2. Dedicated small launch vehicle trajectory from Naro Space Center (Earth Fixed Frame).

Figure 3 shows the launch (red), coast duration in LEO (from Earth parking orbit injection to trans-Mars injection, yellow) and trans-Mars trajectory (purple) with respect to Earth inertial frame. In this scenario, coast duration is less than half of the revolution which is called "short coast" option for interplanetary mission.

Figure 4 shows the Mars transfer trajectory (purple) for 289 days, which starts from Dec-01, 2028 to Sep-16, 2029, as well as Earth (green) and Mars (red) trajectory with respect to Heliocentric inertial frame.

Figure 5 shows the Mars orbit insertion and Mars mission orbit whose orbital period is around 35 hours and inclination of 90° with respect to Mars inertial frame. These target orbits were used for Mars Atmosphere and Volatile Evolution (MAVEN) mission [5].

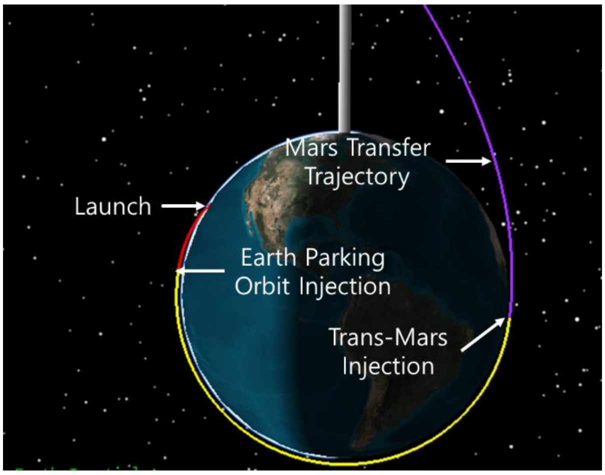

Fig. 3. Trajectory from Launch, coast duration in LEO, trans-Mars injection and Mars transfer (Earth Inertial Frame).

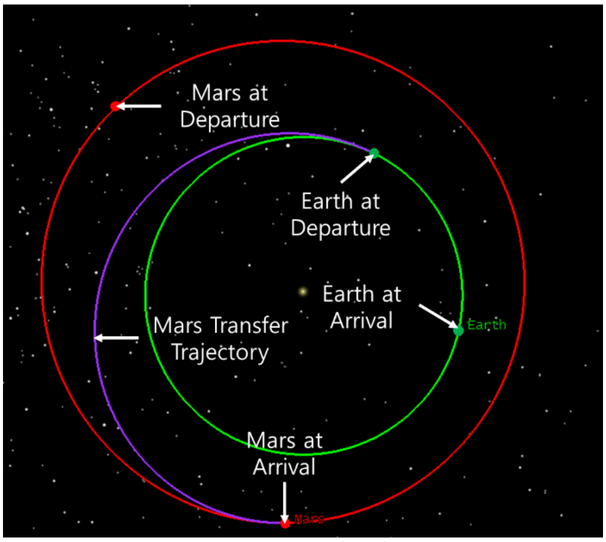

Fig. 4. Trajectory of Mars transfer for 289 days as well as Earth and Mars (Heliocentric Inertial Frame).

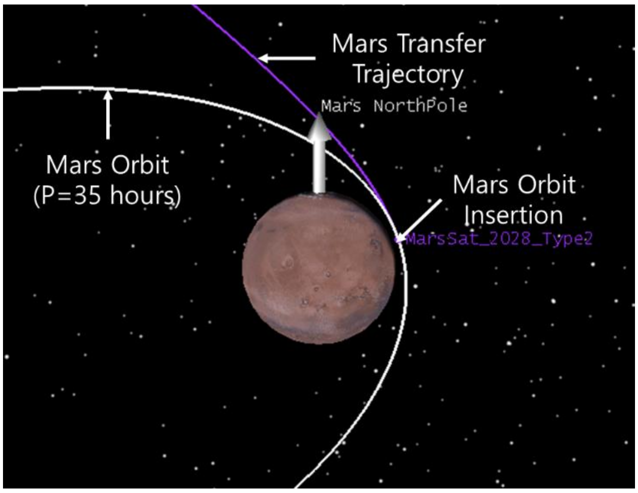

Fig. 5. Trajectory of Mars orbit insertion that orbital period is 35 hours with inclination of 90° (Mars Inertial Frame).

2.5 Mass Estimation

According to the simulation results, the ΔV for TMI was 3,642.18 m/s and the ΔV for Mars Orbit Insertion (MOI) was 1,047.6 m/s so that total ΔV is 4,689.78 m/s. To establish the ΔV budget for the Mars mission, additional maneuvers are set up such as trajectory correction maneuver, aerobraking maneuver (if this technique is applied to have circular orbit), mission orbit maintenance and etc. However, it is necessary to discuss in detailed so that we set the additional maneuver to 310.22 m/s to simply represent the total ΔV as 5,000 m/s. Equation (3) represents rocket equation to calculate propellant mass [6].

$$m_p = m_0 \left(1 - exp^{\frac{-\Delta V}{I_{sp} \cdot g_0}}\right) \tag{3}$$

Where m_p and m_0 are propellant and wet mass.

Table II: Mass Estimation of Mars Explorer

Contents	Bi-propellant	NTP
Wet Mass (kg)	800	800
Total ΔV (m/s)	5000	5000
I_{sp} (sec)	360 [2]	900 [7]
Prop. Mass (kg)	605.8	345.9
Dry Mass (kg)	194.2	454.1

Table II shown that final dry mass using Bi-propellant propulsion system (LCH4/LOX) was 194.2 kg, but final dry mass using NTP was 454.1 kg. It shown that the NTP remains more fuel after the Mars explorer arrived at the target orbit because of the high specific impulse.

Specific impulse of 900 sec and maximum thruster of 15 klbf of the NTP using hydrogen propellant were designed conceptually for round trip human mission to Mars [7]. However, in this case, thruster level should vary according to the total mass of Mars explorer while maintaining the specific impulse. In order to estimate appropriate thruster level of the propulsion system based on this condition, ballistic transfer from Earth to the mars is assumed. It means that the propulsion system should provide the total impulse required for TMI (3,642.18 m/s) at one time.

Table III: Propulsion Parameters for TMI

Contents	NTP
Initial Mass (kg)	800
TMI ΔV (m/s)	3,642.18
Prop. Mass (kg)	270.41
Remaining Mass (kg)	529.58
Total Impulse (Ns)	2,387,524.8
Burn Duration (Δt, sec)	600
Thruster Level (N)	3,979.2

Total impulse and propellant mass (270.41 kg) for TMI can be calculated using Equation (3) and Equation (4) respectively [6]. Therefore, only remaining term is the relation between thruster level (F) and burn duration (Δt). As a result of this relationship, thruster level of NTP can be 3,979.2 N or 1,989.6 N if the burn duration of the NTP is 600 sec or 1,200 sec.

$$I_{tot} = I_{sp} \cdot m_p \cdot g_0 = \mathrm{F} \cdot \Delta t \tag{4}$$

3. Conclusions

NTP provides high specific impulse and thrust compared to the traditional chemical propulsion system. Despite its risk, it is necessary to estimate its potential for Mars mission. Simulation departing on Dec 2028 was performed using dedicated small launch vehicle and NTP. Using NTP for Mars exploration, it was confirmed that the final dry mass was more than 50% of the initial mass even if small launch vehicle was used. It means that Mars exploration is possible with small launch vehicle even though it required medium or large launch vehicle until recently. This directly leads to a large reduction in launch cost and total project cost. In addition, this simulation results can derive the appropriate thrust level and burn duration of NTP required for the strategies for Mars transfer.

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