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OPTIMAL TRAJECTORY DESIGN FOR HUMAN OUTER PLANET EXPLORATION

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ABSTRACT

An optimal interplanetary trajectory is presented for Human Outer Planet Exploration (HOPE) by using an advanced magnetoplasma spacecraft. A detailed optimization approach is formulated to utilize Variable Specific Impulse Magnetoplasma Rocket (VASIMR) engine with capabilities of variable specific impulse, variable engine efficiency, and engine on-off control. To design a round-trip trajectory for the mission, the characteristics of the spacecraft and its trajectories are analyzed. It is mainly illustrated that 30 MW powered spacecraft can make the mission possible in five-year round trip constraint around year 2045. The trajectories obtained in this study can be used for formulating an overall concept for the mission

Keywords: optimal trajectory, interplanetary human mission

1. INTRODUCTION

Human exploration missions to various destinations have been studied during the past decades. The previous studies have mainly focused on sending humans to Mars (Casalino et al. 1998). In support of NASA's Revolutionary Aerospace Systems Concepts (RASC), HOPE study has been started to send human beyond Mars (Troutman et al. 2003). The HOPE study has attempted to develop aerospace systems concepts and technology requirements for a human mission to the outer planets. For the HOPE mission, Callisto, one of Jupiter's moons, was chosen as the exploration place for various science goals. HOPE mission would be launched around year of 2045 or later, and six humans would stay on the surface of Callisto for a minimum of 30 days and then the crew should come back to Earth. The HOPE mission to Callisto was selected based on the success of mission to Europa which will send robotic probes to investigate life forms floating in the submarine of Europa. To teleoperate robots in Europa, Callisto is an appropriate place where can avoid Europa's extreme radiation environment and unstable surface.

Many future propulsion systems have been proposed and analyzed. One potential propulsion approach is the VASIMR under development at the Johnson Space Flight Center (Chang-Díaz et al. 2000). As a new propulsion system of spacecraft has been developed, trajectory requires new

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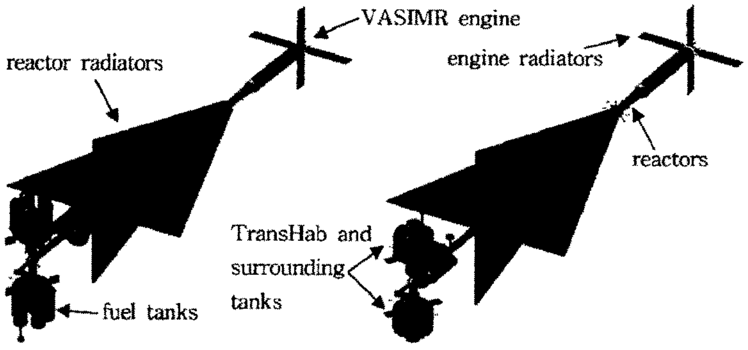

Figure 1. Configurations of the cargo spacecraft (left) and the Crewed spacecraft (right). The size is about 200 m long and about 50 m wide.

optimization formulations, because trajectory optimization is depends upon the characteristics of the spacecraft. The VASIMR propulsion system also needs a new trajectory optimization technique. Hence, it is challenged to make a contribution to utilizing the VASIMR propulsion system for the HOPE mission. The purpose of the present paper is to find optimal round trip trajectory by using the advanced engine and to investigate overall insights into the HOPE trajectory design. The spacecraft design is closely related to the spacecraft trajectory. Another goal of current paper is to determine the power level for the HOPE mission by comparing the trajectories with different levels of power.

2. PROBLEM FORMULATION

It is assumed that a space-gate is established at the L1 Earth-Moon Lagrange point for human space missions. The VARIMR spacecrafts will be assembled, and loaded propellant, and departed from the L1 point. The mission is divided into two trips: first trip is for pre-deployment of essential assets and additional fuel for piloted trip home at Callisto, and second trip is for crew transfer from Earth-Moon L1 to Callisto and return trip. Thus, two vehicles would be developed: one is cargo vehicle for the first trip, and the other is crew transfer vehicle for the second trip. The round-trip crewed mission should be finished in a maximum five years because of limitation on life sustain system. The crew transfer vehicle has artificial gravity capability for more than four years. The cargo spacecraft must deploy essential assets such as surface habitat, crew lander, and in-situ resource utilization plant to the surface, before the crew vehicle arrives at Callisto. The crew transfer vehicle has artificial gravity capability for long duration space flight, and 2 TransHabs included in dry mass that helps with artificial gravity spinning as also acts as a spare. The two spacecraft will be docked at Callisto parking orbit. For return trip, the crew transfer vehicle will be refueled with the propellant carried by the cargo vehicle at Callisto parking orbit.

The cargo and crewed spacecraft are based on VASIMR concepts proposed by NASA Johnson ace Center. A Closed Brayton Thermodynamic Heat Engine is coupled with VASIMR plasma pulsion system to supply enough electrical power for the VASIMR engine. VASIMR is a high er magnetoplasma rocket that gives continuous and variable thrust at constant power (Chang- et al. 2000). Hydrogen plasma is heated by radio frequency power to increase exhaust velocity 300 km/sec. The power output of the engine is kept constant, thus thrust and specific impulse ersely related. Thrust is increased proportional to the power level. The engine can optimize nt usage and deliver a maximum payload in minimum time by varying thrust and specific

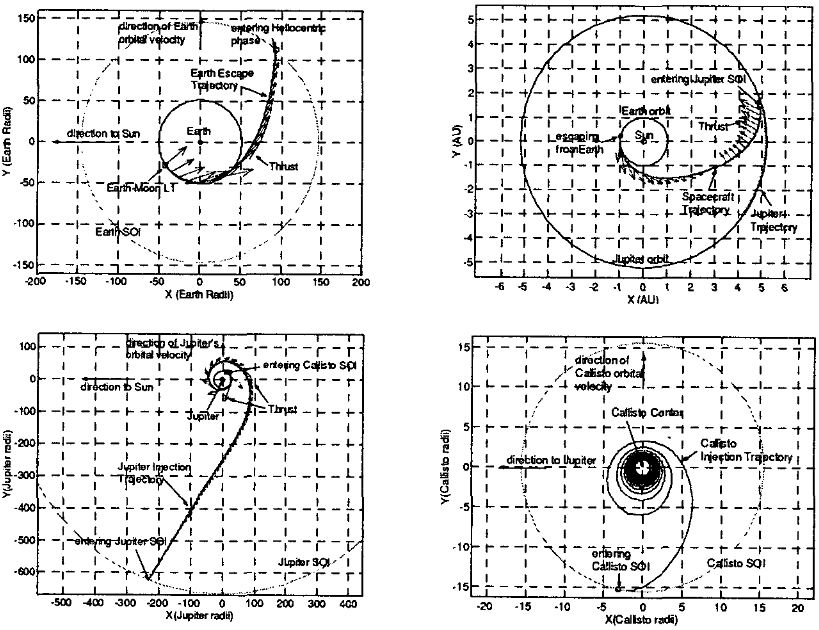

Figure 2. Outbound trajectories of the crewed spacecraft, Earth escape (upper left), heliocentric (upper right), Jupiter capture (lower left), Callisto capture (lower right).

impulse. Therefore, VASIMR can yield the fastest possible trip time with a given amount of propellant by using constant power throttling. The specific impulse range of the engine will be 3,000 sec - 30,000 sec, and the corresponding thrust range would be approximately 5,000 N - 500 N (assuming 100% power efficiency). The efficiency of VASIMR engine will vary as high at high specific impulse and lower at low specific impulse. A 10 kW space demonstrator experiment has been completed (Petro et al. 2000), and a VASIMR engine with 200 MW power could be available around the year 2050. The dimensions of the cargo and crewed vehicles are about 200 m long and about 50 m wide. Figure 1 configures the cargo and crewed spacecrafts. For the problem at hand, it is required to find the optimal trajectory that maximizes the final mass of spacecraft or minimizes the propellant usage. The optimal problem is to find thrust direction and specific impulse and engine on-off history, satisfying the necessary optimality conditions. In this paper, a shooting method is used to solve the HOPE trajectory problems, by utilizing the Pontryagin's Minimum Principle (Bryson 1999). An appropriate power level is also found for the HOPE mission. The open-loop optimal trajectory can be used as a reference trajectory for the HOPE mission.

3. NUMERICALSIMULATIONS AND RESULTS

By using appropriate spacecraft architecture of HOPE mission, a detailed trajectory analysis is performed by using the patched method. Hence, the whole trajectory is divided into individual sub-trajectories such as Earth escape leg, heliocentric leg, Jupiter capture leg, Callisto capture leg, and reversed four legs for crew return trip. Each leg has been individually developed to include gravitational effects of only the central body. Each leg is separated by the central body's Sphere of Influence (SOI), while the position and velocity and mass of spacecraft are continuous through

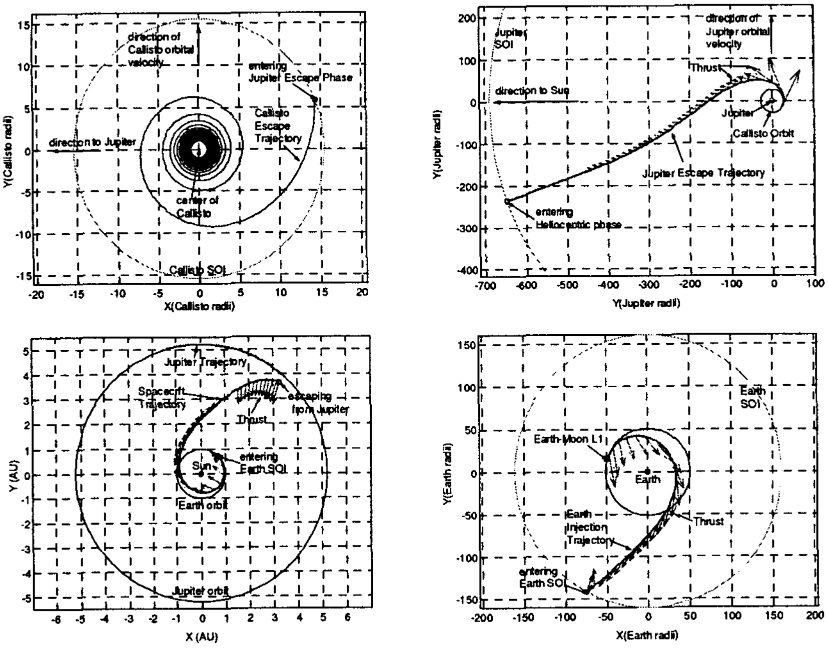

Figure 3. Inbound trajectories of the crewed spacecraft, Callisto escape (upper left), heliocentric (upper right), Jupiter escape (lower left), Earth capture (lower right).

each leg. The trajectory obtained in each leg is satisfied with the necessary conditions of optimality. The results would be good approximations of whole trajectory, by combining trajectories of all the eight legs. Different departure time yields different trajectory, hence, different fuel usage. Generally, shorter travel time requires more fuel usage. For a fixed travel time, there is a departure time giving minimum fuel usage. Because of the geometry relationship between Earth position and Jupiter (Callisto) position, it is apparent that different departure time and different total flight time would yield interplanetary trajectory whose required fuel is different. As total flight time increases, the specific impulse history is increased to its maximum value (i.e., minimum value of thrust magnitude) during the flight time; thus, the trajectory can have a coast arc created by engine-off duration. The outbound trip consists of first four legs that can be applied to both the cargo and crewed spacecraft (Figure 2). The inbound trip consists of last four legs that are applied to only the crewed spacecraft (Figure 3). For each leg, a flight time is appropriately given to avoid a meaningless fuel minimization solution with an infinite flight time. For the HOPE mission, trial-error approach is used to find an appropriate mission starting time and a proper power level of the engine. To design a preliminary optimal trajectory, the patched trajectories are found for the cargo mission and the crewed mission. Combining each patched trajectory yields whole outbound and inbound trajectories. A 30 MW power of VASIMR engine equipped with Brayton reactors is an optimal spacecraft architecture for the five-year round trip for the HOPE mission. Table 1 summarizes the characteristics of the trajectories for the cargo and crewed 30 MW VASIMR spacecraft.

Table 1. Trajectory characteristics the Cargo and the Crewed Spacecraft.

Characteristics	Cargo Spacecraft	Crewed Spacecraft
Departure Time for outbound Trip	12/6/2043	2/19/2045
Fuel Loaded for outbound Trip	82.8 MT	118.3 MT
Initial S/C Mass for outbound Trip	506.3 MT	430.7 MT
Flight time, Fuel used for Leg 1	15days (2.7MT)	15 days(2.8MT)
Flight time, Fuel used for Leg 2	950days (47.0MT)	680days (72.8MT)
Flight time, Fuel used for Leg 3	232days (22.4MT)	170days (25.1MT)
Flight time, Fuel used for Leg 4	17days (8.7MT)	7days (15.6MT)
Arrival Time for outbound Trip	3/29/2047	7/5/2047
Total Flight Time for outbound Trip	1214 days	872 days
Fuel Used for outbound Trip	80.9 MT	116.4 MT
Departure Time for inbound Trip		8/6/2047
Fuel Loaded for inbound Trip		118.3 MT
Initial S/C Mass for inbound Trip		421.0 MT
Flight time, Fuel used for Leg 5		9days (12.4 MT)
Flight time, Fuel used for Leg 6		140days (48.6MT)
Flight time, Fuel used for Leg 7		670days (53.4MT)
Flight time, Fuel used for Leg 8		20days (1.3MT)
Arrival Time for inbound Trip		11/27/2049
Total Flight Time for inbound Trip		839 days
Fuel Used for inbound Trip		115.7 MT
Total Flight Time for Round Trip		1741days(4.77year)

4. CONCLUSIONS

For the HOPE mission, preliminary round-trip trajectories and spacecraft are designed by using an advanced VASIMR engine concept. The formulations in this paper can be used to generate outbound and inbound trajectories for any human interplanetary missions with VASIMR type propulsion system. Optimal trajectories are significantly depend upon relative geometric positions and distances between the Earth and a targeted planet. It is found that a 30 MW VASIMR spacecraft with Brayton fission reactor would be optimistic for the HOPE mission around year 2045. If a powerful engine and more advanced reactor are feasible, the round trip time and fuel required can be reduced. The required propellant and flight time of the trajectories described in this paper can be used to design an overall mission concept for the HOPE space mission.

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