EDU Journal of International Affairs and Research (EJIAR), ISSN: 2583-9993
Volume 3, Issue 3, July-September, 2024, Available at: https://edupublications.com/index.php/ejiar

Conceptual Overview on Development of Methodologies for Direct Interplanetary

Shreya Mane

Department of Research and Development, Astroex Research Association, Deoria-274001, India

ABSTRACT

Highly effective electric propulsion systems can be employed in interplanetary missions to shorten the journey time or enhance the mass delivered to the destination compared to conventional chemical propulsion systems. Growing concerns about possible habitable environments and the possibility of Earthly species contaminating them are brought about by the rapid speed of scientific discovery of our solar system. Key approaches include gravity assist maneuvers, Hohmann Transfer Orbit, and Patched-Conic Approximation. Multiple gravity-assist trajectory preliminary design is formulated as a global optimization problem. Next, a trajectory model is described, which strikes a balance between the difficulty of the optimization problem and the completeness of the model. Investigating the final resolution space is carried out using a unique global search strategy. The spacecraft travels from the departure planet's parking orbit to the arrival planet's parking orbit during a direct interplanetary transfer. It is necessary to construct the transfer trajectory in a way that ensures the stated arrival parking orbit criteria are met. For a predetermined departure in a direct transfer, four different transfer trajectory design alternatives are depending on the period and flight time. These design choices are not identified by the most popular analytical trajectory design method, the standard patched pop method.

Keywords: Trajectory Model Analysis, Hohmann Transfer Orbit, Gravity-Assist Free Direct Transfers, Patched-Conic Approximation.

INTRODUCTION

Robotic planetary exploration development costs are often exorbitant since a significant amount of new technology, hardware, and software development is inadequately applied to the mission. One of the recurring concerns to be addressed early in the conceptual design process is the relevant payoffs of various new technologies to the system. Acquisitions are frequently used to push the boundaries of current technology in important domains. The introduction or advancement of technologies frequently needed to accomplish program goals typically results in higher expenses and schedule concerns. As a result, their employment should be limited. As a result, the options for utilizing particular hardware for a mission might also be influenced by the needs of the task.

The ambition to study far-off planets, moons, and other celestial bodies has long motivated space exploration efforts to pursue direct interplanetary travel. To reduce fuel consumption, traditional approaches frequently rely on multi-step missions using orbital slingshots and gravity aids. However new approaches to more direct and efficient routes have been spurred by developments in navigation systems, trajectory planning, and propulsion technology. The utilization of continuous-thrust propulsion technologies, such as electric or ion engines, and optimized flight paths that reduce trip time while taking gravitational forces and planetary motions into consideration are some examples of these advancements. Furthermore, advancements in artificial intelligence and spaceship autonomy enable more accurate in-flight corrections, minimizing the need for human intervention. To examine their potential to revolutionize space exploration and permit expeditions to outer planets with never-before-seen speed and efficiency, this study examines the key approaches emerging in the field of direct interplanetary transport.

Highly effective electric propulsion systems have the potential to outperform conventional chemical propulsion systems in terms of mass delivered to the destination and/or travel time for interplanetary missions [1, 2]. There hasn't been a more sincere attempt to land men on a far-off planet since the Apollo Program in the late 1960s and early 1970s. This is mostly because President George W. Bush announced in 2004 that a permanent Moon base would be used for Mars exploration [3].

Trajectory Model Analysis

An optimization process is frequently used to depict the search for a solution in the two-stage process of problem modeling and problem-solving that is always applicable to engineering design problems. The process of translating a physical phenomenon into a mathematical representation is known as modeling. Since there is always a trade-off between the accuracy of the needed solution and the computational cost associated with its search, the modeling stage has a special impact on the definition and development of preliminary design methodologies [4]. Different models by nature contain different kinds of solutions and can favor or not their identification.

When a large number of effective first-guess solutions must be created for a thorough preliminary examination of complicated engineering issues, this issue becomes of substantial importance. Here, efficiency is measured as the ratio of the number of workable solutions to the corresponding computational time. Of course, trajectory design is likewise subject to these considerations. Therefore, when creating an efficient design tool for the initial study of complex interplanetary transfers, the two aforementioned stages—which are mutually dependent—must be specified.

Trajectory model selection and analysis are essential for direct interplanetary missions to maximize mission success, energy consumption, and trip duration. There are several models available to forecast and fine-tune the spacecraft's trajectory, each corresponding to distinct mission goals and propulsion capacities. Generally speaking, trajectory models fall into two categories: impulsive and continuous-thrust models. Each has a unique strategy for fuel optimization and navigation.

Hohmann Transfer Orbit

The Hohmann transfer orbit is a well-known orbital mechanic's orbit that entails two impulsive burns: one to leave the departure orbit and another to join the orbit of the target planet. Because of its lengthy journey times and dependence on exact planetary alignment, this model is less suitable for direct interplanetary trips, even though it is fuel-efficient for brief transfers between planetary orbits. Therefore, other models are required for deep-space missions to shorten the transit time.

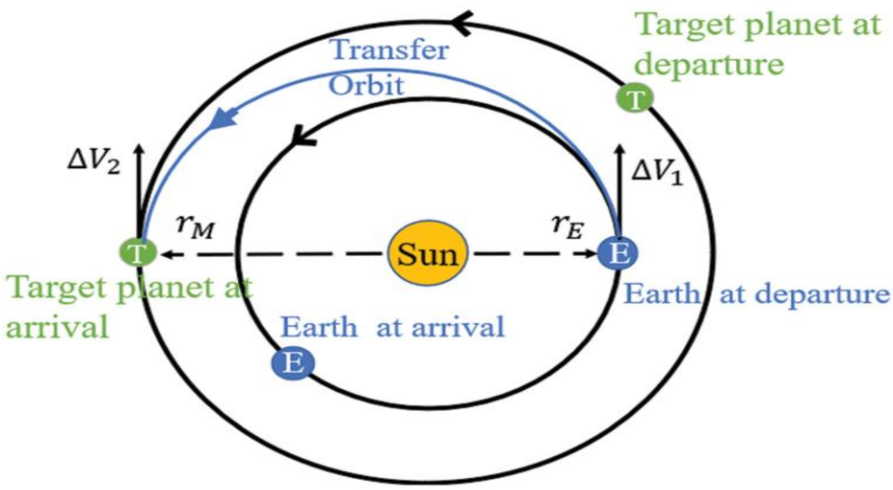

Fig. 1. Hohmann Transfer Orbit [4]

The most cost-effective model is the Hohmann transfer ellipse, provided that the planets' orbits are circular and coplanar. It is the ellipse that is precisely at perihelion and apohelion in contact with the circular orbits of Earth and the destination planet. That means that the transfer angle between the heliocentric locations of Earth on the departure date and the destination planet on the minimal energy transfer trajectory must arrival time is supposed to be 1800. The years that show such a positional approximation are considered to present a launch opportunity.

The Hohmann transfer geometry between Earth and Mars is shown in Fig. 1.1. The position of Earth at departure (rE) is the periapsis of the transfer orbit; this is opposed to the position of Mars at arrival (RM), which is the apoapsis of the transfer orbit. The velocity change needed to launch a spacecraft from Earth's orbit into a transfer orbit is denoted by ΔV1, while the velocity change needed to launch a spacecraft from a transfer orbit into Mars' orbit is denoted by ΔV2.

Gravity-Assist Free Direct Transfers

Direct interplanetary missions aim to skip these detours, but many classical missions rely on planetary flybys to gather velocity (gravity aids). Accurate trajectory modeling that accounts for the lack of gravitational boosts is necessary for this. Similar to the Lambert-based or continuous-thrust models, these models also have to minimize the requirement for in-flight corrections while taking into consideration the spacecraft's propulsion restrictions.

Here, a connected conic approximation is used to describe gravity-assist moves in three dimensions. The movement is immediate, and the sphere of influence is condensed into a single point. Aerogravity-assist is a maneuver in which a spaceship leaves the atmosphere to a modified hyperbolic approach after entering a planetary atmosphere during a hyperbolicorbit. The distinction between aerogravity-assist and gravity-assist is depicted in Figure 1.3.A larger turn angle (~AGA) is obtained with traditional aerogravity-assist maneuvers by using aerodynamic forces, resulting in an increased acceleration boost over gravity-assist (GA) [5, 6].

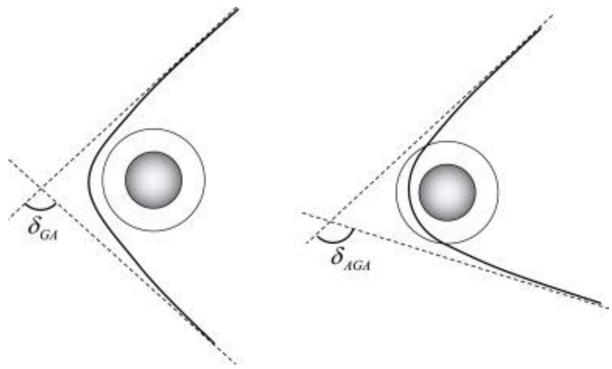

Fig. 2. An Aerogravity – Assist [5, 6]

The literature's depiction of traditional aerogravity-assist maneuvers uses an atmosphere-bearing body to produce a larger turn angle than gravity-assist and may call for a vehicle with an L/D of 3.0 or higher [7]. These maneuvers have the same application as gravity-assist. This type of vehicle maximizes AGA turn angles while minimizing aerodynamic drag forces [8]. Hypersonic Technology, or prototype hypersonic cars, exists in automobiles [9] although none of them are operational; most are for military use. The aerogravity-assist turn angle is computed analytically in the literature using a formula predicated on the idea of hypersonic wave riders (L/D > 1:0), or vehicles with a high L/D [10].

Aerobraking

By flying the spacecraft through the atmosphere at the periapsis and employing drag to limit its velocity, aerobraking is a spaceflight maneuver that lowers the apoapsis of an elliptical orbit. In situations where the spaceship needs to enter a low orbit after reaching a planet with an atmosphere, aerobraking is a more fuel-efficient method than using a rocket engine directly. Aerobraking is the process by which an object approaching a planet or other body with an atmosphere slows down due to atmospheric drag. Alternatively referred to as atmospheric breaking, it is a purposeful technique that can be employed in situations where there is sufficient atmosphere to change a spacecraft's orbit or slow a vehicle down before landing. To accomplish this, the high-orbiting spacecraft propels itself into an elliptical orbit with a periapsis (lowest point) inside the atmosphere. At periapsis, air drag lowers velocity, lowering the apoapsis, or the highest point of the orbit. A propulsive burn is done at apoapsis after one or more trips through the atmosphere lowering the apoapsis to the desired height. As a result, the orbit becomes circular and the periapsis rises out of the atmosphere.

Aerocapture

This method uses the planet's atmospheric drag to lower an incoming spacecraft's hyperbolic velocity and cause it to be trapped in an orbit around that planet. Unlike aerobraking, this technique just requires a single pass through the atmosphere. During the Manoeuvre, it needs precise closed-loop guidance and substantial heat shielding.

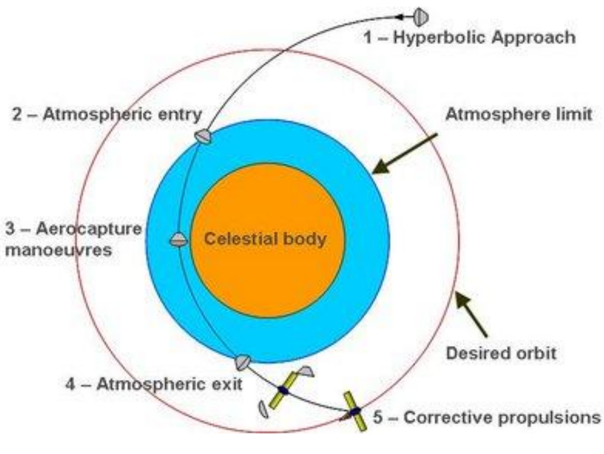

Fig. 3. Representation of Aerocapture

Aerocapture and aerobraking are similar techniques, but they differ in that the former is used to lower a spacecraft's velocity as it passes a planet to put it into orbit in a single atmospheric pass. Planetary orbiters could benefit greatly from aerocapture since it would enable a spacecraft to be launched from Earth at a high speed, leading to a short trip time, and subsequently descend at the target solely due to aerodynamic drag. In the absence of aerocapture, a sizable propulsion system is required to achieve the same velocity reduction, which lowers the deliverable payload. However, due to its higher velocities and deeper penetration of a planet's atmosphere, aerocapture is a more drastic maneuver than aerobraking.

A shallow approach to the planet would be the first step of an aerocapture maneuver, after which a descent to comparatively dense levels of the atmosphere would occur. The spaceship would maneuver to exit the atmosphere once the majority of the necessary deceleration had been accomplished. To account for atmospheric uncertainties and entry condition inaccuracies, the vehicle would require its own guidance and control system in addition to maneuvering capabilities. using the vehicle's aerodynamic design providing lift, most of the movement would be accomplished using it. The heat shield would be removed upon departure, and a brief propellant burn would be performed to elevate the orbit's lowest point or periapsis. The car would have to drive itself the entire time it was inside the planet's atmosphere.

To date, aerocapture has not been used on a space mission. When Zond-6 and Zond-7 returned to the moon, their re-entry skip was an aerocapture maneuver. Aerobraking was eventually chosen over aerocapture for the Mars Odyssey orbiter because to cost and mission-wide compatibility concerns. It has been suggested that aerocapture be used to reach Titan, Saturn's moon.

Patched-Conic Approximation

The spacecraft's trajectory is divided into several conic sections by the approximation known as the "patched-conic approximation," which is a popular technique for planning interplanetary missions. Each of these parts is affected by the gravitational field of a different celestial body. By considering each segment as a two-body problem, it simplifies the intricate three-body problem. Although this model works well for missions involving gravity assistance, it is less suitable for direct missions that eschew intermediate planetary flybys.

A popular technique for simulating spacecraft trajectories in orbital mechanics and interplanetary mission design is the patched-conic approximation. By breaking down the spacecraft's path into discrete gravitational forces and treating each segment as a two-body problem, it simplifies the difficult n-body problem. By breaking down interplanetary paths into smaller segments, mission planners can streamline the calculations needed to transit between different celestial bodies.

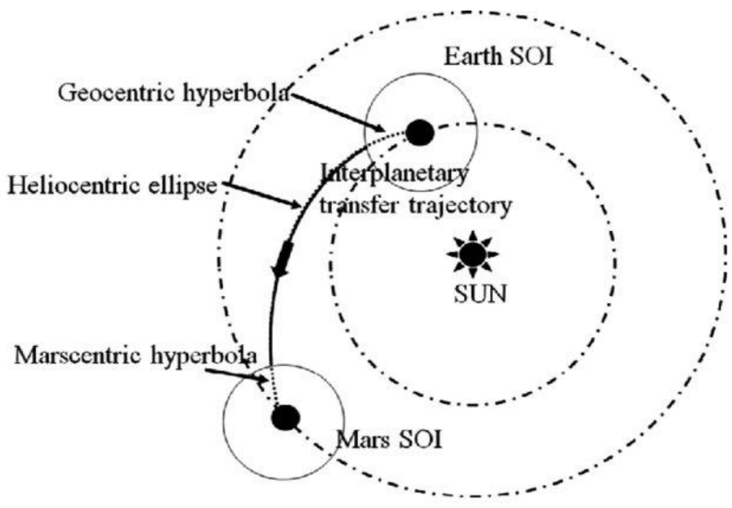

Fig. 4. Patched-Conic Approximation

In order for the patched-conic approximation to work, the spacecraft's trajectory is divided into multiple sections, each of which is subject to the gravitational pull of a single central body, such as the Sun or a planet. Kepler's rules of motion for two-body systems are used to approximate the trajectory as a conic section (such as an ellipse, parabola, or hyperbola) inside each region.

The trajectories "patched" together at boundary points, where the gravitational attraction of one celestial body starts to outweigh that of another, are indicative of the transition between these regions. Usually, these places are at the celestial bodies' sphere of influence.

While keeping the simplicity of the traditional patched conic technique, the iterative patched conic method identifies the various transfer trajectory design alternatives accessible for an interplanetary orbiter mission. The suggested approach can be used for direct transmission to every planet. Fig. 4 shows the three parts of a typical Earth-to-Mars transfer originating from patched conic assumptions for demonstration purposes.

The heliocentric Lambert conic is first used to connect the position vectors of the target planets, Earth and Mars, at the arrival and departure epochs, respectively. It is assumed that the spacecraft's heliocentric velocities in the transfer conic at the target point and the SOI are equal. Consequently, the difference between the heliocentric velocity vector of the planet at the departure epoch and the heliocentric velocity vector in the transfer conic is used to compute the initial asymptotic excess velocity vector.

To reach the asymptotic excess velocity vector at the SOI, the initial hyperbolic orbit characteristics are calculated from the excess velocity vector and then adjusted using the analytical tuning technique. The adjusted hyperbolic orbit characteristics are propagated by Keplerian to produce the planetocentric position vectors at the SOI. The patch points are the names given to these places. A heliocentric Lambert conic is used to connect the patch points once the planetocentric position vectors of the patch points are converted to the heliocentric frame.

REGIONS IN THE PATCH-CONIC APPROXIMATION

Departure Phase

During this stage, the spacecraft starts under the gravitational pull of the planet or body it is leaving behind, such as Earth. The path is interpreted as a conic segment, usually involving an elliptical orbit around the main body. A Hohmann transfer or other impulsive maneuver is commonly used to apply a velocity boost (Δv) to propel the spacecraft into a high-energy orbit that intersects with the central body's sphere of influence, such as Earth's escape velocity.

Interplanetary Phase

The spacecraft enters the heliocentric (Sun-cantered) phase once it leaves the departing planet's area of influence. Here, the spacecraft's trajectory is described as a two-body issue between the spacecraft and the Sun, with the trajectory being determined by the gravity of the Sun. This phase lasts until the spacecraft gets close to the target planet's zone of influence. The course is typically an elliptical orbit around the Sun.

Arrival Phase

The spacecraft enters the destination planet's area of influence as it gets closer to the target planet. The planet's gravity is now the main factor affecting the spacecraft's motion. The spacecraft orbits the target planet, and the trajectory is again modeled as a two-body system. To get the spacecraft into a stable orbit around the planet or to start the atmospheric entry or landing processes, an arrival burn (an additional Δv) may be carried out.

CONCLUSION

Conclusively, the advancement of techniques for designing direct interplanetary missions signifies a noteworthy progression in space research, offering quicker and more effective routes between celestial planets without requiring intricate gravity supports. Direct transfer methods provide greater mission planning freedom and shorter travel durations by combining cutting-edge propulsion technologies—such as electric and nuclear propulsion—with precise trajectory optimization techniques. These benefits are critical for both robotic and crewed missions. The next phase of interplanetary exploration will be made possible by these evolving approaches, which will be crucial in helping us explore the solar system and beyond.

REFERENCES

[1]. Williams, Steven N., and Coverstone-Carroll, Victoria, "Benefits of Solar Electric Propulsion for the Next Generation of Planetary Exploration Missions," *Journal of theAstronautical Sciences*, Vol. 45, No. 2, April-June 1997, pp. 143-159.

[2]. Palak Raina, Hitali Shah. (2017). A New Transmission Scheme for MIMO - OFDM using V Blast Architecture.Eduzone: International Peer Reviewed/Refereed Multidisciplinary Journal, 6(1), 31–38. Retrieved from https://www.eduzonejournal.com/index.php/eiprmj/article/view/628

[3]. Raina, Palak, and Hitali Shah."Security in Networks." International Journal of Business Management and Visuals, ISSN: 3006-2705 1.2 (2018): 30-48.

[4]. Sauer, Carl G., Jr., and Yen, Chen-Wan L., "Planetary Mission Capability of Small Low Power Solar Electric Propulsion Systems," IAA-L-0706, IAA International Conference on Low-Cost Planetary Missions, Laurel, MD, April 12-15, 1994.

[5]. Kulkarni, Amol. "Enhancing Customer Experience with AI-Powered Recommendations in SAP HANA." International Journal of Business Management and Visuals, ISSN: 3006-2705 7.1 (2024): 1-8.

[6]. Bush, G. "A Renewed Spirit of Discovery," The White House, Office of the Press Sec, 14 Jan 04.

[7]. Vasile, M., "A Global Approach to Optimal Space Trajectory Design". AAS/AIAA Space Flight Mechanics Meeting, AAS Paper 03-141, Ponce, Porto Rico, Feb 2003.

[8]. Nathan J Strange and James M Longuski. Graphical Method for Gravity-Assist Trajectory Design. Journal of Spacecraft and Rockets, 39(1):9{16, 2002.

[9]. Neha Yadav,Vivek Singh, "Probabilistic Modeling of Workload Patterns for Capacity Planning in Data Center Environments" (2022). International Journal of Business Management and Visuals, ISSN: 3006-2705, 5(1), 42-48. https://ijbmv.com/index.php/home/article/view/73

[10]. Vivek Singh, Neha Yadav. (2023). Optimizing Resource Allocation in Containerized Environments with AI-driven Performance Engineering. International Journal of Research Radicals in Multidisciplinary Fields, ISSN: 2960-043X, 2(2), 58–69. Retrieved from https://www.researchradicals.com/index.php/rr/article/view/83

[11]. Jon A Sims, James M Longuski, and Moonish R Patel. Aerogravity-Assist Trajectories to the Outer Planets and the E_ect of Drag. Journal of Spacecraft and Rockets, 37(1):49{55, 2000.

[12]. Gregory A. Henning, Peter J. Edelman, and James M. Longuski. Design and Optimization of Interplanetary Aerogravity-Assist Tours. Journal of Spacecraft and Rockets, 51(6):1849{1856, 2014.

[13]. Shah, Hitali. "Ripple Routing Protocol (RPL) for routing in Internet of Things." International Journal of Research Radicals in Multidisciplinary Fields, ISSN: 2960-043X 1, no. 2 (2022): 105-111.

[14]. Hitali Shah.(2017). Built-in Testing for Component-Based Software Development. International Journal of New Media Studies: International Peer Reviewed Scholarly Indexed Journal, 4(2), 104–107. Retrieved from https://ijnms.com/index.php/ijnms/article/view/259

[15]. Eugene P. Bon_glio, James M. Longuski, and Nguyen X. Vinh. Automated Design of Aerogravity-Assist Trajectories. Journal of Spacecraft and Rockets, 37(6):768{775, 2000}.

[16]. Steven Walker, Je_rey Sherk, Dale Shell, Ronald Schena, John Bergmann, and Jonathan Gladbach. The DARPA/AF Falcon Program: The Hypersonic Tech- nology Vehicle #2 (HTV-2) Flight Demonstration Phase. In 15th AIAA Inter- National Space Planes and Hypersonic Systems and Technologies Conference, Dayton, OH, 2008. AIAA

[17]. Hitali Shah."Millimeter-Wave Mobile Communication for 5G". International Journal of Transcontinental Discoveries, ISSN: 3006-628X, vol. 5, no. 1, July 2018, pp. 68-74, https://internationaljournals.org/index.php/ijtd/article/view/102.

[18]. Bharath Kumar Nagaraj, SivabalaselvamaniDhandapani, "Leveraging Natural Language Processing to Identify Relationships between Two Brain Regions such as Pre-Frontal Cortex and Posterior Cortex", Science Direct, Neuropsychologia, 28, 2023.

[19]. Mark J. Lewis and Angus D. McRonald. Design of hypersonic wave riders for aeroassisted interplanetary trajectories. Journal of Spacecraft and Rockets, 29(5):653{660, 1992.