End-to-End Trajectory Design and Optimization of a Twin Atmospheric Entry Probe and Satellite Tour Orbiter to the Ice Giant Planets

Introduction and Background

The ice giant planets, Uranus and Neptune, have only been observed directly during flybys of the Voyager 2 probe in 1986 and 1989. As it stands, the ice giants are two of the most under explored objects in our solar system, and raise many of the most important questions about planetary and solar system evolution. In order to complete a thorough survey of the outer planets, the Ice Giants Pre-Decadal Survey (IGPDS) decided on two areas of interest to pursue in the first flagship missions: the atmospheric composition of the ice giants, including the tropospheric 3-D flow, heat balance, and meteorology, and the composition, structure, and evolution of the ice giant satellites[1]. To accomplish both objectives, a flagship mission to either system would require a complex trajectory that takes into account both an atmospheric entry probe and a satellite tour of the system. Due to the lengthy flight time involved in such a mission, it would be beneficial to consider a pair of twin atmospheric entry probes in the interest of ensuring that the scientific objectives are met. Two atmospheric probes would allow for a greater spatial resolution as well as a second sampling of the atmosphere, which decreases the chances of the atmospheric probe landing in an unrepresentative region, as the Jovian Galileo atmospheric entry probe experienced in 1995[2]. A flagship mission with twin atmospheric entry probes and a satellite tour brings forth a complex trajectory design problem when factoring in the vehicle weights, atmospheric entry locations, and launch windows of each planet.

Proposal

To further investigate the feasibility of a flagship mission to either Uranus or Neptune including two atmospheric entry probes and a satellite tour, I propose using two NASA trajectory design and optimization softwares, the Copernicus Trajectory Design and Optimization System and the Program to Optimize Simulated Trajectories II (POST2), in order to systematically test combinations of spacecraft weights, atmospheric probe weights, and separate atmospheric probe latitudinal/longitudinal entrances alongside traditional ballistic (chemical) trajectories and solar electric propulsion (SEP) trajectories.

Methods

In order to design and evaluate the various mission combinations with end-to-end optimization, I will utilize POST2 alongside the Copernicus software. Copernicus serves as the primary trajectory optimization tool for mission design at NASA, and as such, has many degrees of customizability in terms of low and high thrust trajectories.[3] This will allow for the testing of various combinations of SEP in the inner solar system flight with a later transition to chemical propulsion. POST2 gives the ability to introduce multiple vehicles at any point in the simulation- these “child” vehicles inherit the state of their “parent” vehicle, and will be vital in further analyzing the trajectories of the two atmospheric entry probes once they begin separation from the parent spacecraft.[4] I plan to utilize the Copernicus API in order to rapidly test various configurations for the launch stage up to the entry probe separation stage of the mission, including the transition from SEP to chemical propulsion. I will then push this output into the POST2 software, which will complete the trajectory design by simulating the separation of the atmospheric entry probes, the atmospheric entrances, and the satellite tour of the remaining orbiter. I plan

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[1] Ice Giants Pre-Decadal Survey Mission Study Report., 2017. (JPLD-100520) https://www.lpi.usra.edu/icegiants/mission_study/

[2] Irwin, P. G. J.,2009. Giant Planets of Our Solar System. Giant Planets of Our Solar System: Atmospheres, Composition, and Structure, Springer Praxis Books. ISBN 978-3-540-85157-8. Springer Berlin Heidelberg, 2009.

[3] Williams, J. et al. “Overview and Software Architecture of the Copernicus Trajectory Design and Optimization System.” (2010).

[4] NASA Langley Research Center, “Overview of the Program to Optimize Simulated Trajectories II (POST2)”, https://post2.larc.nasa.gov/overview/

to write the data interchange software in either Python or Julia, a new programming software used for trajectory design, depending on the requirements of the two trajectory design softwares.

The outputs of these combinations can then be compared in terms of the fastest route, the most cost-efficient route, and the lightest route. The combinations explored will be constrained by the following scientific considerations outlined in the IGPDS report [5].

Uranus

The flight length and severe axial tilt of the Uranus brings forth many constraints to the mission: A combination of SEP and chemical trajectory could deliver a basic probe and orbiter combination to Uranus in ~11 years of interplanetary time, when considering an average vehicle, such as the Atlas V 551. Due to the axial tilt, the planet's seasons last ~21 years. In order to observe a different season than that of Voyager 2's observations, we must launch before the end of the 2030 decadal window so that the mission is completed before the 2049 equinox. Due to the alignment of the planets during this window, a gas giant flyby and/or gravity assist can only be considered with Jupiter. As such, the best gravity-assist sequence for this window is Venus-Earth-Earth-Jupiter (VEEJ).

Neptune

The flight length of a Neptune flagship mission would require covering a much larger inter-planetary distance than that of a Uranus flagship mission, and would in turn require a stronger launch vehicle. The Delta-IV Heavy or the SLS Block 1-B would lend itself better to a Neptunian system mission than the Atlas V 551, and would allow the spacecraft to complete only an Earth-Jupiter (EJ) gravity assist in order to reach Neptune. Neptune's largest satellite, Triton, raises many questions about satellite evolution due to its retrograde orbit, and thus it may also be beneficial to explore multiple flybys of this moon during the satellite tour.

Intellectual Merit

Though the Uranian and Neptunian systems were briefly analyzed in the Voyager 2 flybys, there have been no further missions to these systems. Furthermore, the only scientific data regarding these systems are from remote telescopic observations and the limited Voyager 2 observations.[6] As the IGPDS report stressed the importance of a flagship mission with an optimal launch window in the 2030 decade, we must prepare a mission as soon as possible. Due to the extreme inter-planetary distances, we must optimize the mission to ensure that all scientific goals are met in both a timely and efficient manner. The inclusion of twin atmospheric entry probes would ensure that the in-situ atmospheric readings are precise and representative of the planet, while the satellite tour would allow for further exploration of the system and its evolutionary path. This proposed study will explore the trajectory design and optimization of a mission with twin atmospheric entry probes and a satellite tour, ensuring that the decades of preparation and execution involved in an ice giants mission will be as fruitful as possible.

Broader Impacts

A flagship mission to the ice giants would constitute a new age in space exploration, particularly if the mission included a set of twin atmospheric entry probes. As a twin probe setup has never been executed, this would revolutionize the future of in-situ atmospheric measurements, while also providing precise results for a relatively unknown part of our solar system. The trajectory considerations of a satellite tour could also result in the discovery of new satellites, as well as previously unknown chemical signatures and geographical landscapes. This study would allow for the exploration of a brand-new spacecraft and probe configuration as well as the potential for a flagship mission to one of the most under-explored areas of our solar system, allowing for technological and scientific research for decades to come.

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[5] Ice Giants Pre-Decadal Survey Mission Study Report., 2017. (JPLD-100520) https://www.lpi.usra.edu/icegiants/mission_study/

[6] Irwin, P. G. J.,2009. Giant Planets of Our Solar System. Giant Planets of Our Solar System: Atmospheres, Composition, and Structure, Springer Praxis Books. ISBN 978-3-540-85157-8. Springer Berlin Heidelberg, 2009.