FY23 Innovative Spontaneous Concepts Research and Technology Development (ISC)

New Class of Low Energy Flyby, Capture & Landing Orbits Around Small Moons

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Objectives: Our objective is to explore, discover, and map out classes of orbits that are sufficiently stable and with long enough period that they can provide the desired scientific coverage while being successfully navigated. We want to explore the instability of orbits due to 3rd body gravity, the spherical harmonics, and the eccentricity of the orbit of the moon and planet. Due to the perturbations, standard approach for analyzing unstable periodic orbits by computing theri invariant manifolds are no longer applicable directly. We want to explore new approaches to analyze the instability of these orbits, using different methods to compute flow structures around the unstable orbits replacing the invariant manifolds of standard periodic orbits.

Background: Missions that approach, orbit, and/or land on scientifically-rich small, inner moons (e.g., Enceladus) of the Outer Planets are a high priority for NASA and JPL. Recent work on these types of missions has revealed complicated dynamics that make them extremely difficult and risky to fly. As small, inner moons, the orbital dynamics near them are heavily influenced by the thirdbody effects of the giant planet, making the region around them incredibly unstable and chaotic. In addition, their orbital periods can be less than a week long. This combination of instability and short period necessitates a frequency of trajectory correction maneuvers that is unprecedented and beyond our current navigational capabilities.

Approach and Results: Orbits with half the period of the moon are unstable and can easily escape the moon via L1 or L2 to orbit the planet. Typically, at these energies, there is a substantial Forbidden Region which prevents the spacecraft from a quick return to the moon. However, the ellipticity of the orbits of the moons causes the Forbidden Region to shrink and grow. In the case of Enceladus, the Forbidden Region can disappear entirely when Enceladus is the furthest away from Saturn. Preliminary explorations have shown that during the period when the Forbidden Region is at its smallest, it is possible for the spacecraft to cross the Forbidden Region and make a quick return to the moon. In our recent work, we have discovered some elusive orbits with a period around 10 days. They can have close approaches to the moon suitable for capture orbits or close flybys to sample the plumes. Our approach will start by identifying and characterizing this new class of innovative orbits. We will then expand this research to construct quasi-stable orbits with periods of 5 to 30 days, thereby avoiding the need for station keeping maneuvers in less than 24 hours for missions to the small, inner moons of the Outer Planets. We attempted to analyze the instability of orbits in JPL ephemeris model with gravity harmonics. We were interested in Near Rectilinear Halo Orbits (NRHO) around Enceladus (see Figure 1). Since NRHOs are not periodic orbits, the use of monodromy matrix doesn't make sense since "monodromy matrix" refers to the state transition matrix around 1 period of the periodic orbit. A trivial attempt is to look at the linearized differential equation and study the eigenstructure of the Jacobian matrix, A, where $x'=Ax$ is the linearization of the nonlinear $x'=f(x,t)$ equation of motion. Using the eigenvectors of A as initial conditions on the NRHO X(t) produced interesting results that seem to shadow the unstable manifold of halo orbits. In fact, trying random directions produced the same manifold structure with shifted timing information. At this point, the Spontaneous R&TD project reached its end. We continued the analysis in the SURP project. In the SURP project we completed the research and discovered that any random vector will produce the unstable manifold. This became NTR 52884.

Significance/Benefits to JPL and NASA: Orbits around the small moons of the Solar System like Europa, Ganymede are difficult to compute and analyze due to their instability. Operationally, the are extremely difficult to navigate due to their small size and weak gravity field and often their very short periods. This research would contribute to a deeper understanding of the nature of the instability of orbits around the small moons. This knowledge will help us compute and analyze these orbits and develop new approaches to navigate these orbits.

New Technology:
NTR 52884 - The Las Vegas Algorithm for Computing Invariant Manifolds (Pending)
This NTR is for the new method to compute invariant manifolds with a random vector without computing the eigenvectors of the monodromy matrix. This research project was initiated first in the Spontaneous R&TD Project New Class of Low Energy Flyby, Capture & Landing Orbits Around Small Moons. Once the Spontaneous R&TD project ended, the research was continued in the SURP project Rapid GPU Trajectory Optimization With New ALTRO Constrained Trajectory Optimizer. We were able to complete the solution of this problem in the SURP project.

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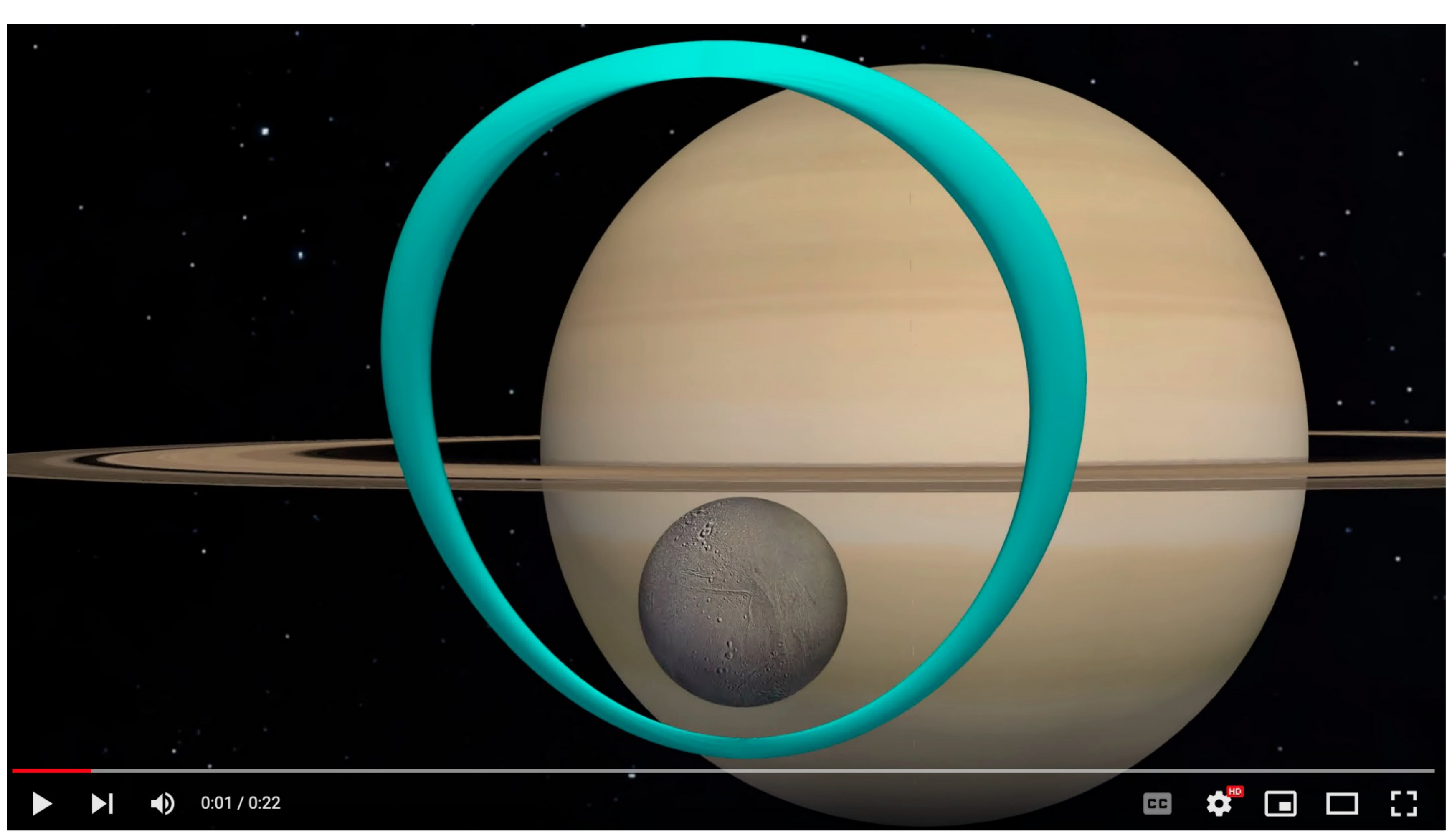

Figure 1. Visualization of Near Rectilinear Halo Orbit around Enceladus around Saturn. Generated using VTK visualization tool developed by Prof. Xavier Tricoche, applied in Paraview visualization with data and animation produced by Jared Blanchard.

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