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Spacecraft Formation Flight on Quasi-periodic Invariant Tori

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Since the successful rendezvous of the Gemini VI and VII spacecraft in 1965, spacecraft formation flying has attracted the interest of many researchers in the field. Yet, existing methodologies do not currently account for the oblateness of a central body when the distance between the satellites exceeds the reach of standard analytical techniques such as Brouwer-Lyddane theory and thereof.

In this dissertation, the problem of designing bounded relative orbits is approached with a dynamical systems theory perspective in order to overcome the limitations imposed by mean-to-osculating orbit element mappings and linearization errors. We find that the dynamics of satellites in the Earth zonal problem can be fundamentally described by three periods, whose averaged values can be accurately computed through numerical integration. To ensure long-term bounded relative motion between the satellites in a formation, at least two of their fundamental periods need to be matched on average. This condition is enforced by including additional constraints into existing techniques for calculating families of quasi-periodic invariant tori. The result is a numerical procedure that searches for the invariant curves of a stroboscopic mapping while changing the polar component of the angular momentum vector for each of the quasi-periodic tori within the family. Upon convergence, the algorithm outputs several curves that can be interpolated to obtain an entire surface of bounded relative motion. That is, by selecting arbitrary initial conditions on this surface, bounded relative motion can be established, regardless of the number of zonal harmonics terms that are included in the geopotential.

Given this encouraging result, we move beyond Earth's orbit and investigate the problem of designing bounded relative orbits about small irregular bodies. First, we consider the case of asteroid (4179) Toutatis, and build on previous research to identify periodic and quasi-periodic

orbits that ensure boundedness in spite of the complex shape and rotational state of the target asteroid. Next, we move to the Martian system and design spacecraft formations near Phobos. Once again, we aim at improving the realism of previous simulations found in the literature by modeling the nonspherical shape and nonzero eccentricity of the Martian moon. The resulting higher fidelity model causes entire families of periodic orbits to become quasi-periodic invariant tori that eventually serve as initial conditions for bounded spacecraft formations.

The last part of this thesis is dedicated to assessing the robustness of the relative trajectories computed throughout the manuscript. Although atmospheric drag and solar radiation pressure have catastrophic effects on the relative dynamics of satellites in LEO and near Toutatis, it is found that spacecraft formations in MEO, GEO, and about Phobos are quite resilient to mismodeled dynamics, making quasi-periodic invariant tori a robust option for flying satellite clusters in these complex dynamical environments.