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Multi-Spacecraft Cooperative and Non-Cooperative Trajectory Optimization

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Multi-spacecraft systems can provide enhanced capability and robustness of space missions as compared to their single-spacecraft counterparts. This improvement, however, comes at the cost of a more complex mission design and optimization process. Spacecraft operators must also contend with space becoming increasingly congested and contested. Both cooperative and non-cooperative spacecraft interactions must be managed as an increasing number of spacecraft and spacecraft operators populate space. While these opportunities and needs exist for multi-spacecraft systems, trajectory optimization methods for them are relatively underdeveloped. Finding optimal trajectories can be critical in enabling enhanced performance of these missions.

In this dissertation, optimization theory is employed to develop methods that can simultaneously optimize the trajectories of multiple, dynamically connected spacecraft to analyze both cooperative and non-cooperative scenarios of interest. Several multi-spacecraft optimization methods are developed that cover varying applications as well as mathematical formulations. Applications explored in this work include: fuel-optimal multi-spacecraft rendezvous/deployment with unconstrained rendezvous/deployment orbits (e.g. constellation deployment), single and multiple spacecraft traveling salesman problems, cooperative and non-cooperative spacecraft collision avoidance, Pareto-optimal single spacecraft low-thrust interplanetary trajectories that are robust to missed thrust events (using a spacecraft swarm transcription), and fuel-optimal spacecraft pursuit-evasion games with terminal rendezvous. The solutions provided to these problems provide additional insight into each of these areas.

The mathematical techniques used in this work cover both single and multiple decision maker scenarios. If it can be reasonably assumed that a single decision maker decides the controls for all spacecraft, the multi-spacecraft optimization problem is formulated and solved as a mathematical

programming (MPP) or optimal control problem (OCP). However, because multi-spacecraft problems are higher-dimensional than single-spacecraft optimization problems, solution methods that use MPP or OCP formulations must be carefully constructed to manage this additional complexity. When multiple decision makers must be accounted for, a differential game perspective is used to find optimal trajectories. This includes both zero-sum and general-sum games. The methods developed in this work provide additional tools to design improved spacecraft systems and trajectories.