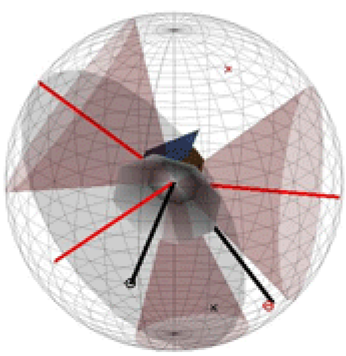
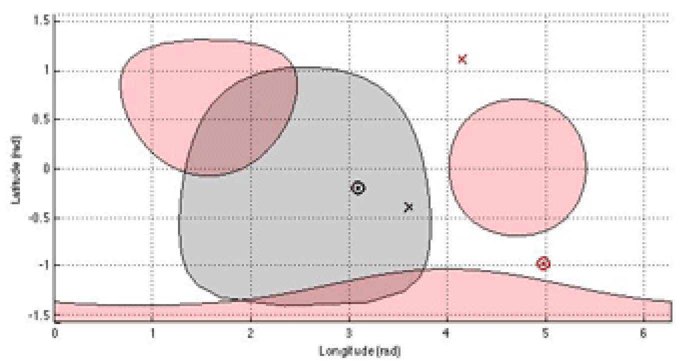
Spacecraft dynamics and control is one of the areas in which our lab has been active for a number of years. Some of the problems that we have been particularly interested in pertain to problems studied by our Principal Investigator, Dr. Mehran Mesbahi, while at the Jet Propulsion Laboratory, related to spacecraft GN&C, autonomous constraint avoidance, and distributed spacecraft control. At JPL, Dr. Mesbahi was involved in attitude control design and analysis, as well as Saturn orbital insertion for the Cassini spacecraft , distributed space systems, and the Shuttle Radar Topography Mission. Since Dr. Mesbahi's arrival at the University of Washington, our group has contributed to various facets of guidance, navigation, control, optimization, and estimation problems related to space systems. This includes recent work in which we adopt quaternion and dual quaternion representations to provide convex optimization-based solutions to a number of outstanding problems in spacecraft autonomy, both for monolithic and distributed space systems.

Funding Acknowledgements: *NASA, Aerojet Rocketdyne*

Some of our recent works include:

Spacecraft Large Angle Reorientation Under Multiple Attitude-Constrained Zones





This problem considers an autonomous maneuver planning algorithm for three-axis attitude reorientation in the presence of multiple types of attitude-constrained zones. This is inspired by the finding that the subgroup of the unit quaternions corresponding to attitude-constrained zones can be represented by a ***convex set.*** Along with this, two types of attitude-constrained zones are defined, namely, the **attitude-forbidden** and **mandatory zones.** The successful formulation of a ***strictly convex logarithmic barrier potential*** enables the synthesis of an almost globally stabilizing feedback control law using unit quaternions.

Two types of feedback controllers were examined: **model-independent** and **model-dependent** control laws. We have also simulated time/fuel optimal maneuvering using a pseudo-spectral method.

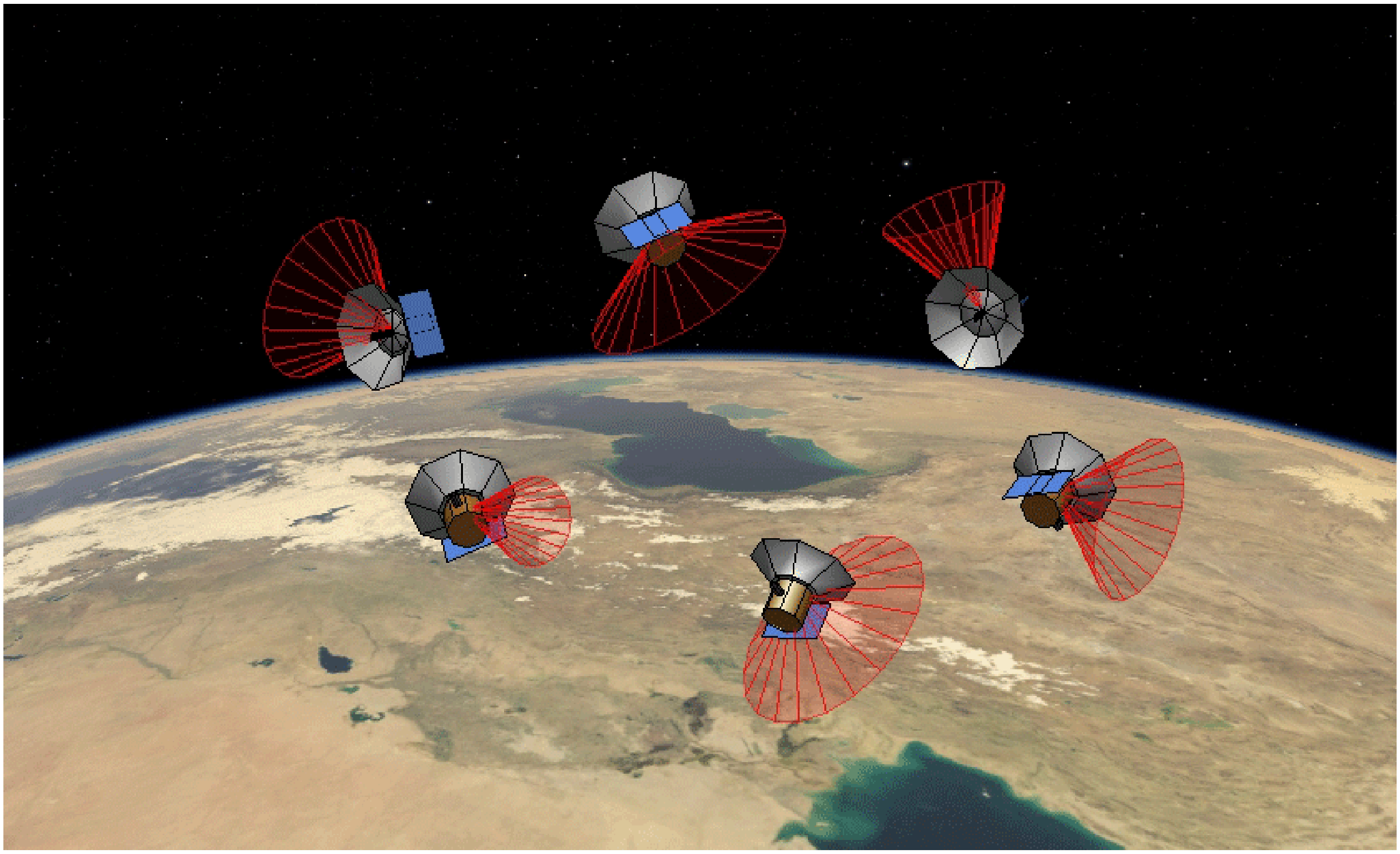
References:

[1] Unsik Lee and Mehran Mesbahi, "Spacecraft Reorientation in Presence of Attitude Constraints via Logarithmic Barrier Potentials," In Proc. of the IEEE American Control Conference, 2011.

[2] Unsik Lee and Mehran Mesbahi, "Optimal Spacecraft Reorientation under complex attitude constrained zones", AAS/AIAA Astrodynamics Specialist Conference, 2013.

[3] Unsik Lee and Mehran Mesbahi, "Feedback Control for Spacecraft Reorientation under attitude constraints via Convex Potentials ", IEEE Transactions on Aerospace and Electronic Systems, 2014.

Attitude and Position Synchronization with Pointing Constraints



This problem considers the consensus algorithm for a group of spacecraft to achieve identical orientations in the presence of attitude-forbidden zones. The algorithm allows attitude-forbidden zones to be identically defined over the group of spacecraft, or to be defined independently. The quadratic convex parameterization for the attitude-forbidden zones using unit quaternions is embedded into a convex auxiliary system, whose output is shared among the spacecraft through a communication network. The auxiliary system's output plays the role of an indicator function for the spacecraft dynamics, such that it does not violate the attitude-forbidden zones while attempting to reach consensus.

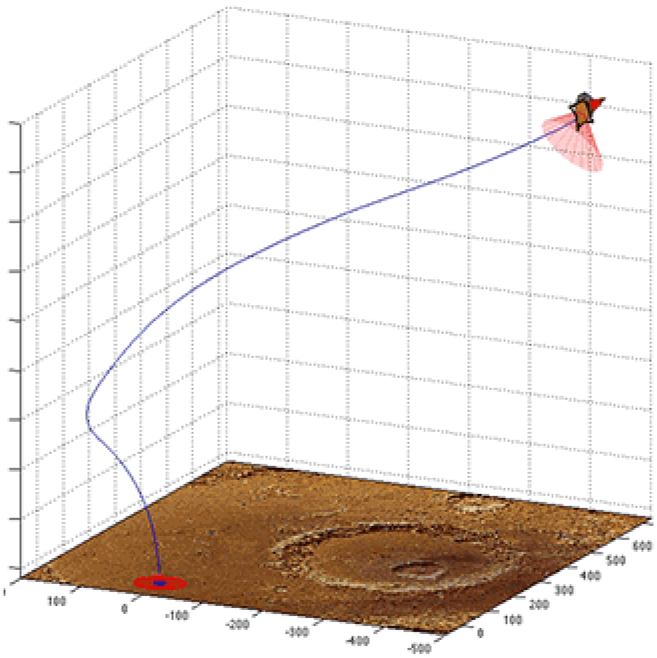
The above figure illustrates the orientations of a set of six spacecraft being synchronized to identical orientations, while avoiding individual constrained zones.

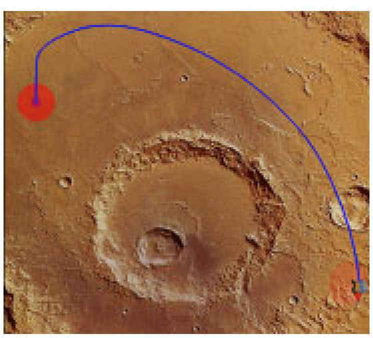
References:

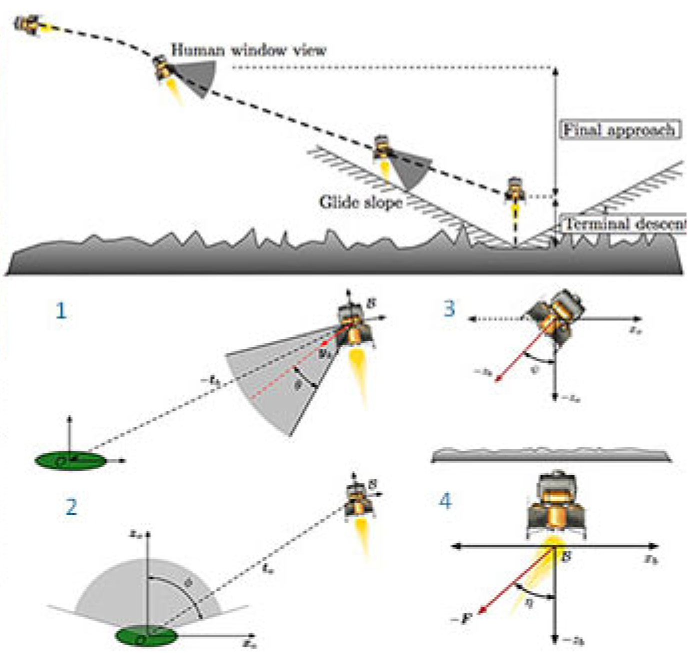
[1] Unsik Lee and Mehran Mesbahi, "Constrained Consensus via Log Barrier function", 50th IEEE Conference on Decision and Control and European Control Conference, 2011.

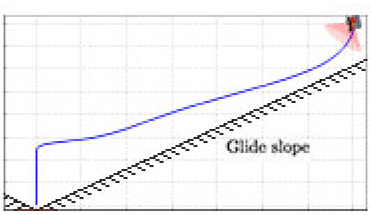
[2] Unsik Lee and Mehran Mesbahi, "Spacecraft Attitude Synchronization in presence of Constrained zones" In Proc. of the IEEE American Control Conference, 2012.

Constrained Powered-Descent Guidance Control









This problem considers a convex programming approach, based on model predictive control, for the numerical solution to a Mars powered-descent guidance problem in the presence of motion constraints. Specifically for the case of a Mars lander spacecraft, we consider the following constraints:

- Line of sight constraint (window view constraint)
- Glide slope constraint
- General attitude constraint
- Thrust vector angle constraint

It is challenging to design an autonomous control algorithm for such a problem, due to the fact that coupled rotational and translational motions affect the required constraints. In our approach, utilizing a unit dual quaternion parameterization, the general motion dynamics for a rigid body are first represented using unit dual quaternions. Subsequently, an almost globally stable feedback control law, based on nonlinear control techniques, is developed for simultaneous rotational and translational motion control.

We then develop a novel convex-representable subset of unit dual quaternions that correspond to translational and rotational states, satisfying predefined constraints with respect to a moving body frame.

Finally, we construct an LTV model predictive control problem, using a convex quadratically constrained quadratic program (QCQP) to serve as the real time powered-descent guidance algorithm for a Mars lander. The resulting guidance algorithm has shown potential to be implemented onboard a spacecraft for real-time applications.

References:

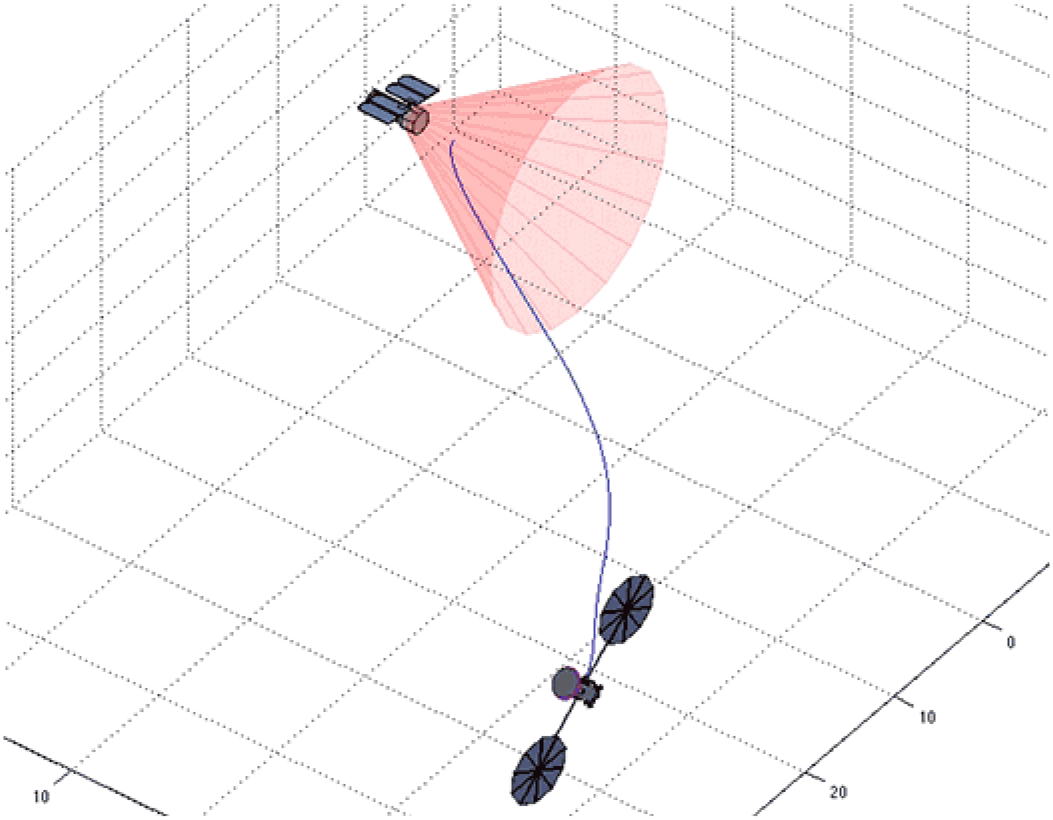
[1] Unsik Lee and Mehran Mesbahi, "Dual quaternions, Rigid Body Mechanics, and Powered-Descent Guidance", 51th IEEE Conference on Decision and Control, 2012.

[2] Unsik Lee and Mehran Mesbahi, "6 DOF Power-descent Guidance with Line of Sight Constraint via Unit Dual Quaternions," AIAA Guidance, Navigation, and Control Conference and Exhibit, 2015

Advanced Attitude Control for Solar Electric Propulsion Spacecraft

This research studies the advanced attitude control system for a solar electric propulsion (SEP) spacecraft. In the research, three algorithms related to attitude control have been developed as follows:

1. Algorithm for constrained proximity to and rendezvous with a tumbling object



This research addresses spacecraft rendezvous with tumbling objects in circular Earth orbit or in deep space. Such tumbling objects are exemplified by potentially unpowered satellites, space debris from launch vehicles, or near-Earth asteroids. Since the object is assumed to be tumbling, any approach toward the object will necessitate constrained motions. This is because the object’s rotational motion restricts the direction of approach toward the target, but the chasing spacecraft’s sensors must also lock on to the object en-route. This constitutes a challenging coupled rotationally- and translationally-constrained motion. To approach this problem, we take advantage of a unit dual quaternion parameterization to compactly represent relative motion dynamics in circular Earth orbit, as well as rotational dynamics.

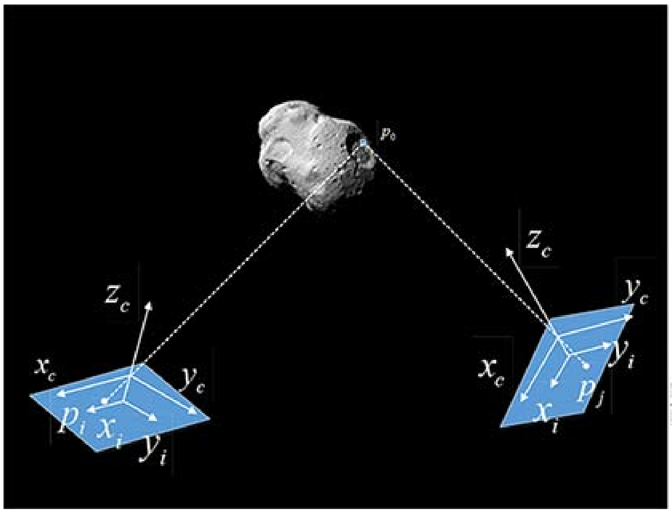
We proceed to construct a convex representable subset to represent all feasible translational and rotational motions. Convex QCQP programming is used to find the model predictive control law for the chasing spacecraft over this proposed convex subset. Our extensive simulation results, covering typical scenarios as well as more complex ones, has exhibited the viability of the proposed methodology.

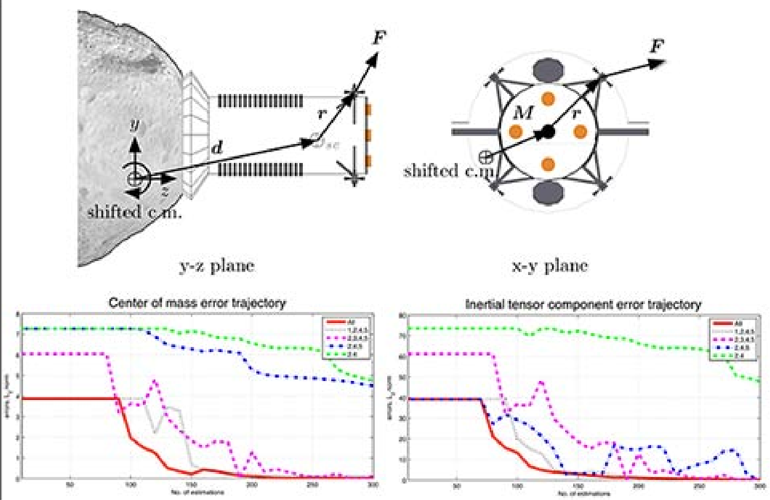
References:

[1] Unsik Lee and Mehran Mesbahi, "Dual Quaternion based Spacecraft Control for Constrained Rendezvous in Earth Circular Orbit," AIAA/AAS Astrodynamics Specialist Conference, San Diego, California, 2014.

2. Distributed motion estimation / Fast mass property estimation for a space object

This research examines the motion estimation problem for space objects using multiple image sensors in a connected network. The objective is to increase the estimation precision of relative translational and rotational motions based on integrated dual quaternion dynamics and cooperation between connected sensors. The relative motion of space objects was firstly formulated using dual elements to express kinematic relationships and translational constraints. We apply an optimization decomposition method to decompose the cooperative estimation task into a series of suboptimal problems, and then solve them individually for each image sensor in order to achieve global optimality.





Accurate inertial property estimation is critical to the success of NASA's upcoming asteroid retrieval mission. The inertia tensor, center of mass, and total mass of the spacecraft-asteroid combined rigid body must be accurately estimated so that solar electric propulsion can be used to return the asteroid to Earth. This study develops an efficient algorithm to solve for those properties. The estimation is framed as a least squares minimization problem, subject to convex constraints that improve convergence rates. Simulations are performed in MATLAB R2013B using the CVX 2.1 convex optimization solver to assess the algorithm's performance in a typical mission scenario. With only limited data measurements, the proposed algorithm quickly and accurately determines the combined body's inertial properties.

References:

[1] Yue Zu, Unsik Lee, Ran Dai, "Distributed Motion Estimation of Space Objects Using Dual Quaternions," AIAA/AAS Astrodynamics Specialist Conference, San Diego, California, 2014.

[2] Unsik Lee, David Besson, and Mehran Mesbahi, "Fast Inertia Estimation via Convex Optimization for the Asteroid Retrieval Mission," 53th IEEE Conference on Decision and Control, 2014.

3. Optimal trajectory design on the cognition of attitude dynamics via SEP thrusting (vector thrusting)