SENSOR FUSION KALMAN FILTERING FOR
STABILITY AND CONTROL OF SATELLITE SWARMS

Dr. Rahul Rughani
PhD Graduate in Astronautical Engineering
University of Southern California

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Swarm Operations in Orbit

- Enables construction of complex orbital assets, and repair of existing assets.
- Redundant nature of swarm and large number of spacecraft allow for higher autonomy and reliability
On-Orbit Construction
Current State-of-the-Art

- MEV-1 successfully docked to a retired GEO spacecraft to provide mission extension services [1]
Research Goal

Advance the state-of-the-art for spacecraft swarm operations to enable large-scale in-space manufacturing in the not-too-distant future.
Swarm Example (10 Spacecraft)

- Trajectory on right shows example of 10-spacecraft swarm for in-space manufacturing
- Swarm roles split up into the staging area, a comm relay, and close-quarters robotic operations
Trajectory Generation

- Free-flight trajectories, combined with conjunction analysis, used to build safe swarms
- Optimization performed using genetic algorithms to find solutions satisfying a set of criteria [2,3]
  - Minimize insertion $\Delta v$
  - Trajectories with no collision risk for a set period of time
Swarm Sensor Fusion

• Sensor Fusion combines inputs from multiple sensors, spread across the swarm

• Using a Kalman filter, this shared data can be used to pinpoint the relative positions of each spacecraft more accurately, reducing their covariances
Sensor-Fusion Kalman Filtering

- Sensor fusion can be applied to Kalman filters
  - Simulation uses the Unscented Kalman Filter since the perturbed 2-body problem is a non-linear problem
- Similar to a standard Kalman filter, except the update step is repeated for each sensor in the shared swarm sensor net
  - Adds very little computational overhead, as most of the wall-time is spent on the propagation step of the UKF
Example of Real-Time Kalman Filtering

Kalman Filtering over One Orbit
Greedy Optimization

• Not all sensors will be useful to improve the covariance at a given point in time

• Choosing the right ones is a complex problem, similar to the classic “Knapsack problem”
  – Greedy optimization is used to find a quick solution that is not necessarily the most optimal solution, but will satisfy the required parameters
  – This is done by sequentially selecting the measurement with the largest improvement (discard those that do not improve the state)
Sensor Usage over Time

Number of Sensors Used in SFKF vs Time

- Number of sensors (spacecraft) polled for update
- Time (hours)
A Sensor Fusion Kalman Filter can be used to maintain GA generated swarm trajectories over time by tracking deviations from the initial trajectory and compensating with periodic correction burns.

- Each spacecraft is assigned a corridor and can deviate within that corridor without risk of collision with other SC (50m in these simulations).
Results

• Simulation shows SFKF can provide position estimates with 10m accuracy
  – Significant improvement over GPS alone, which is limited to 25m accuracy in LEO
Conclusion

• With swarms of spacecraft, there is an abundance of data available
  – It’s necessary to build autonomous systems to sort and analyze this data in real-time, such as the SFKF

• Future research will test this system on a hardware testbed, such as an Air Bearing Platform