State Estimation and Targeting for Autonomous Spacecraft Rendezvous and Proximity Operations

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Introduction

- Historical Rendezvous and Proximity Operations
- Autonomous Rendezvous and Proximity Operations
- Kalman Filters
- Rendezvous Targeting

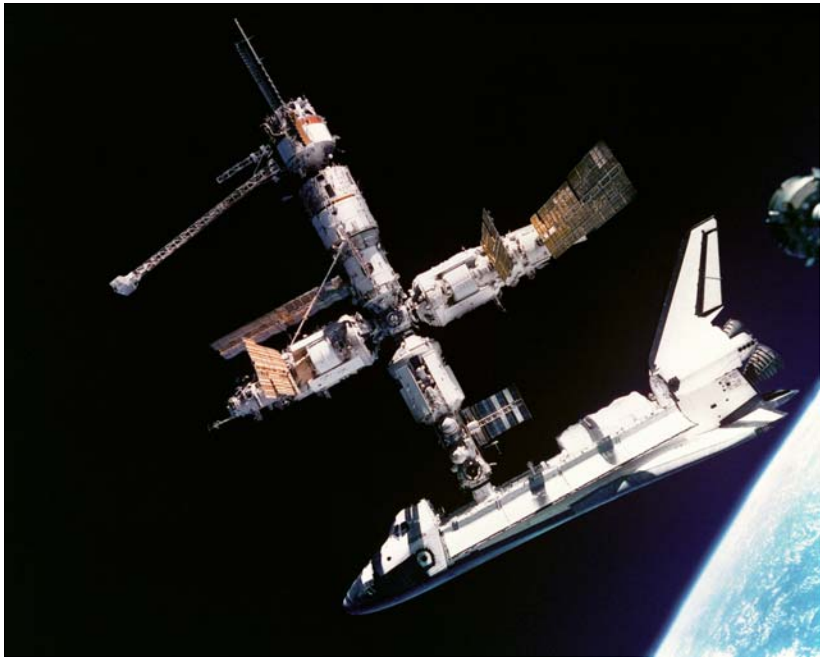
Research

- Scope of Research (Inertial vs. Relative)
- Measurements
- Scenario
- Simulation/Status

Spacecraft Rendezvous and Proximity Operations require some of the most important and challenging maneuvers in spacecraft GN&C.

Required for
- Docking
- Servicing (ISS)
- Inspection and diagnosis
- Spacecraft Reconnaissance
- Formation flying

Examples
- Gemini
- Apollo
- Space Shuttle
- ISS, Mir



Space Shuttle and MIR, APOD Oct, 20 2002

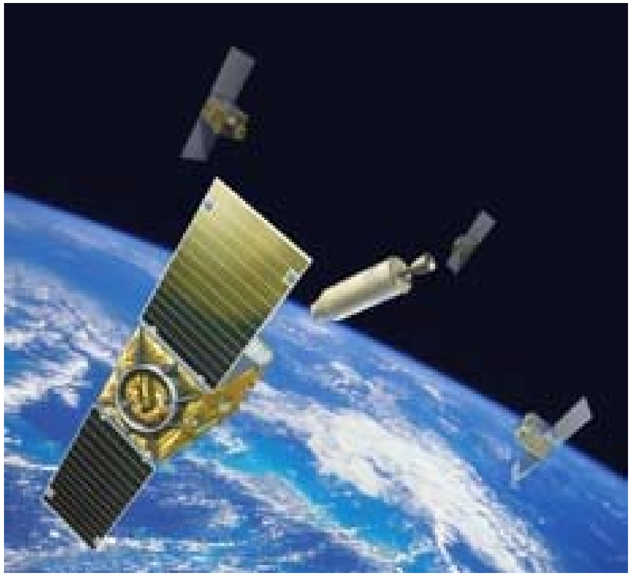
Traditionally accomplished with humans in the loop

Autonomous Rendezvous and Proximity Operations

- •Eliminates the risk associated with manned spaceflight
- •Reduces the need for ground station support
  - – Reduced ground station commands
  - – Reduced need for telemetry downlink
- •Step toward unmanned spacecraft servicing and repair
- •Small vehicles in a formation can replace large vehicles

Examples

- •XSS-11
- •DART
- •ETS-VII
- •Progress
- •Orbital Express
- •CEV/Orion



XSS-11 (LMSS photo)

Common Vehicle Distinctions

- Chaser Vehicle: Maneuvering
- Target Vehicle: Non-Maneuvering
  - Operable or Non-Operable
  - Spacecraft or Object

Chaser Vehicle Must

- Precisely determine relative position of target
- Plan and execute minimal targeting maneuvers “on the fly”
- Stay within mission relative attitude, position, and velocity constraints

These Requirements necessitate

- On board sequential state estimation
- On board maneuver targeting
- Accurate Relative Position estimation
- Accurate Attitude estimation

The dynamic models used to calculate position and velocity of a spacecraft are not perfect. Some aspects of the dynamics are not modeled. Those that are modeled, are not modeled completely.

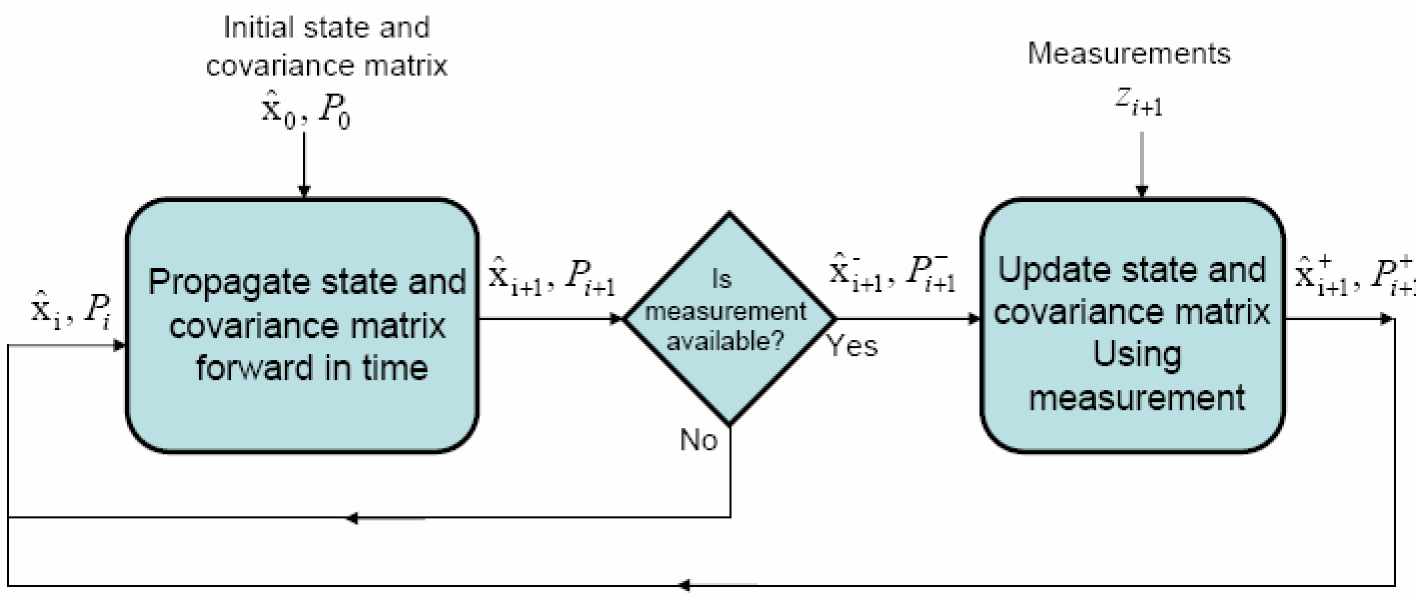
Sensor measurements are not perfect and are subject to random error. (noise, biases, etc)

Therefore, not only does the state need to be estimated sequentially, but statistically as well

To accomplish this, the Kalman filter, which is an optimal sequential state estimation tool, is used. The Kalman filter is derived from stochastic models of dynamic system and stochastic models of the sensor measurements.

The Two Steps of a Kalman Filter

1. Propagate the states and state covariance matrix using dynamic models
2. Update the states and state covariance matrix using measurements



$$\hat{x}_i = \text{"Best" estimate of } x \text{ at time } t_i$$

$$P_i = \text{Covariance of } x \text{ at time } t_i$$

The state dynamics and measurement model for an extended Kalman filter:

$$
\begin{aligned}
\dot{\mathbf{x}}(t) &= \mathbf{f}(\mathbf{x}(t)) + \mathbf{G}\mathbf{w}(t) \\
\tilde{\mathbf{z}}_i &= \mathbf{h}(\mathbf{x}_i) + \mathbf{v}_i \\
\mathbf{w}(t) &\sim N(\mathbf{0}, \mathbf{Q}(t)) \\
\mathbf{v}_i &\sim N(\mathbf{0}, \mathbf{R}_i)
\end{aligned}
$$

The states and state covariance matrix updates:

$$
\begin{aligned}
\hat{\mathbf{x}}_i^+ &= \hat{\mathbf{x}}_i^- + \mathbf{K}_i(\tilde{\mathbf{z}}_i - \hat{\mathbf{z}}_i) \\
\mathbf{P}_i^+ &= [\mathbf{I} - \mathbf{K}_i\mathbf{H}_i(\hat{\mathbf{x}}_i^-)]\mathbf{P}_i^-
\end{aligned}
$$

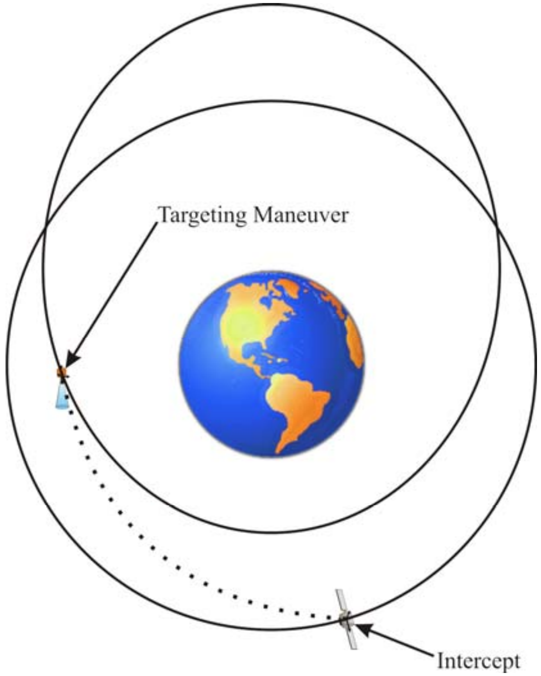
The Kalman gain ***K*** optimally weighs the measurements and estimated state.

On board targeting algorithms are needed to calculate the required ΔV maneuvers.

Given the position of a spacecraft at time t_1 what is the ΔV that must be imparted in order for the spacecraft to be at a desired position at time t_2.

Common Types

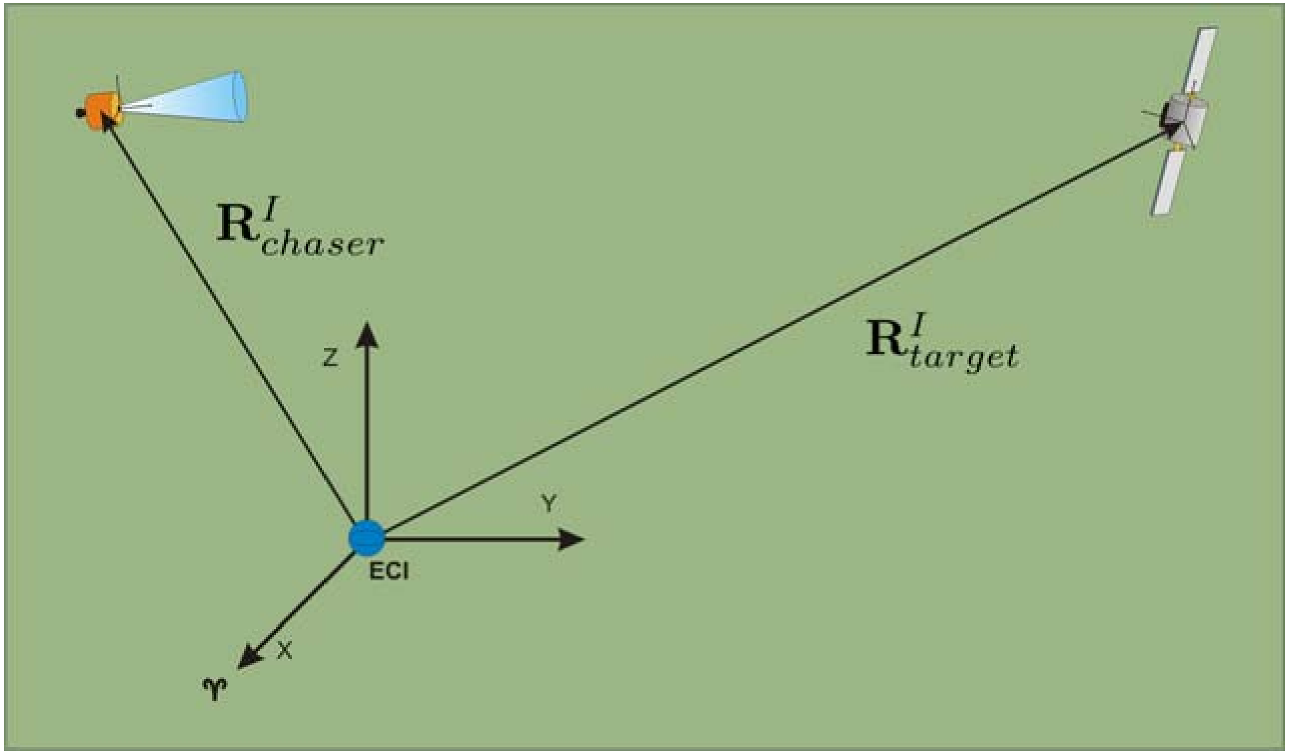
- Lambert Targeting
  - Inertial position and velocity
  - Non-linear dynamics (2-Body w/o J2)
  - Iterative process
- CWH Targeting
  - Relative position and velocity
  - Linear dynamics (CWH equations)
  - No iterations required



It is proposed, that an inertial based navigation and maneuver targeting system will provide better navigation and trajectory control performance than a relative LVLH based system.

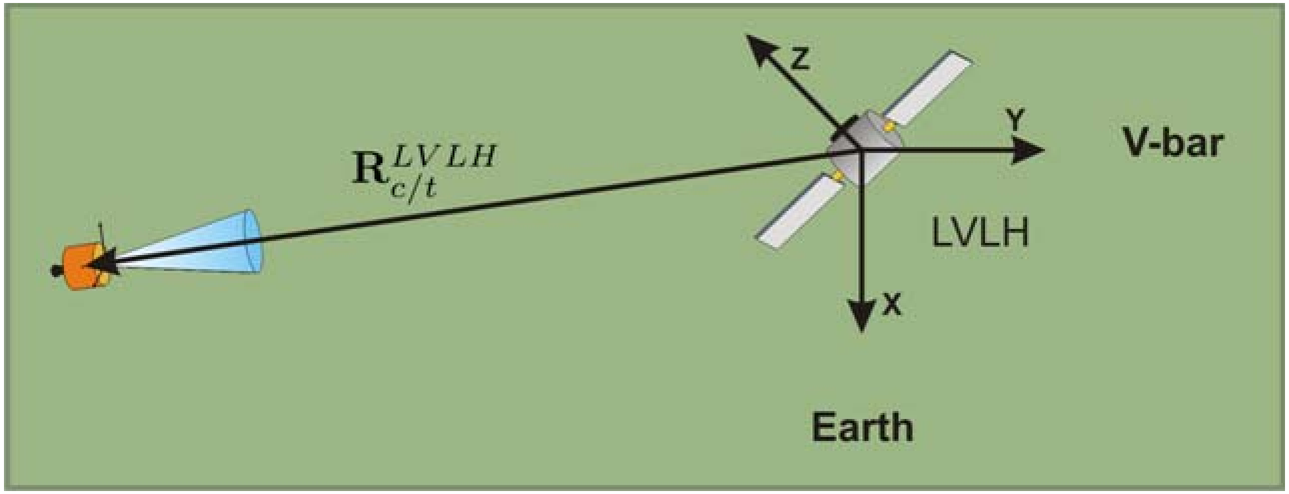
Objective: Comparison of two navigation and targeting systems

- Inertial System
  - Kalman filter estimates Inertial position and velocity in Inertial frame
  - Lambert Targeting



Objective: Comparison of two navigation and targeting systems

- Inertial System
  - Kalman filter estimates Inertial position and velocity in Inertial frame
  - Lambert Targeting
- Relative System
  - Kalman filter estimates relative position and velocity in LVLH frame
  - CWH targeting



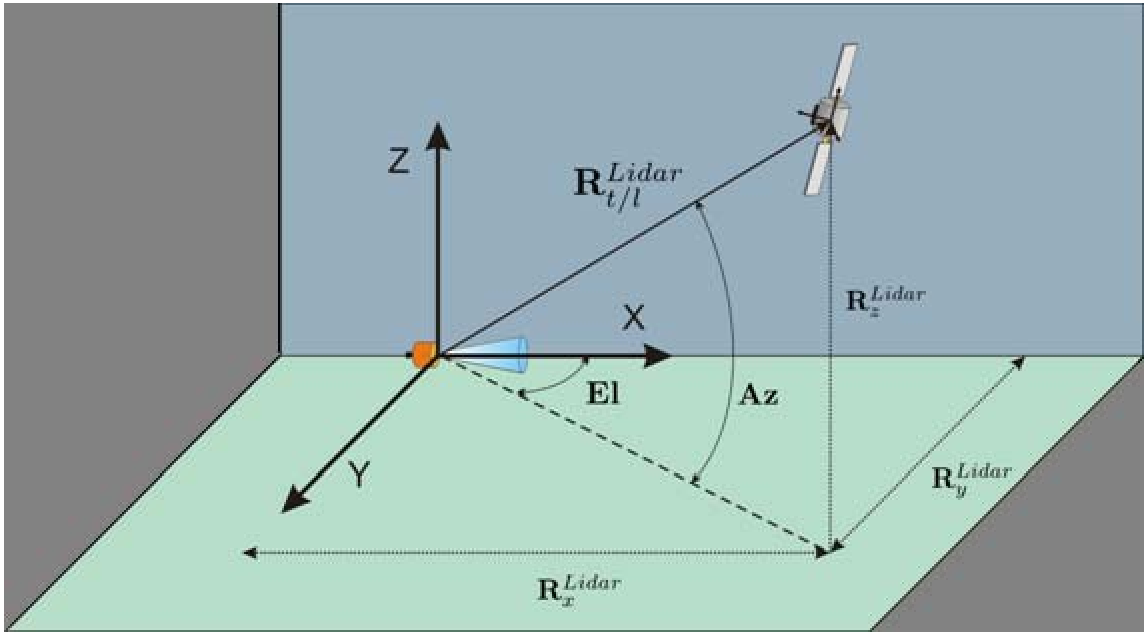
Objective: Comparison of two navigation and targeting systems

- Inertial System
  - Kalman filter estimates Inertial position and velocity in Inertial frame
  - Lambert Targeting
- Relative System
  - Kalman filter estimates relative position and velocity in LVLH frame
  - CWH targeting

Under what situations will one system estimate the relative position and perform the required proximity operation more accurately than the other?

What will the trade off between system performance and CPU time be?

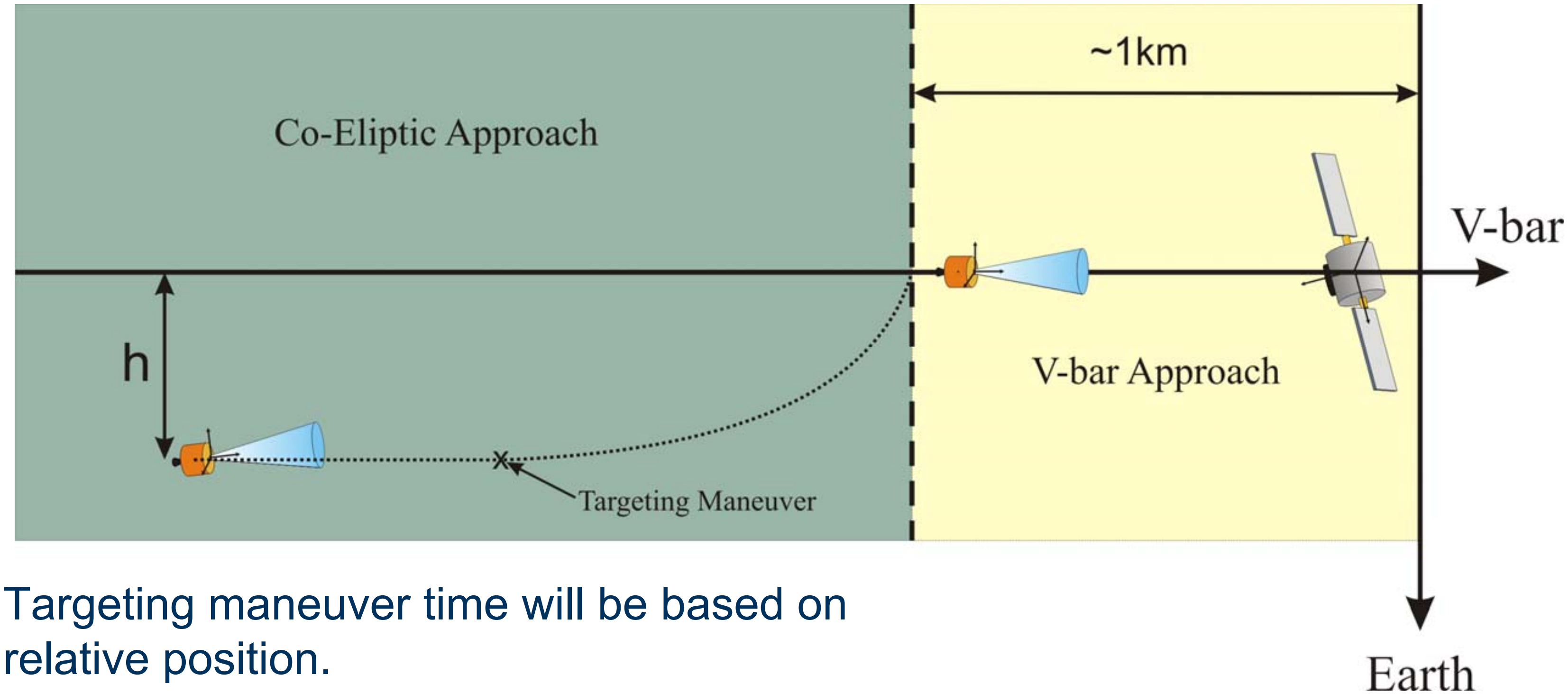
A simulated chaser LIDAR system is used to generate relative range, azimuth, and elevation measurements. The LIDAR measurements are processed by the filters.



Simulated star tracker and gyro measurements are used to determine the attitude of the chaser. They are also used to provide the inertial to body coordinate frame transformations.

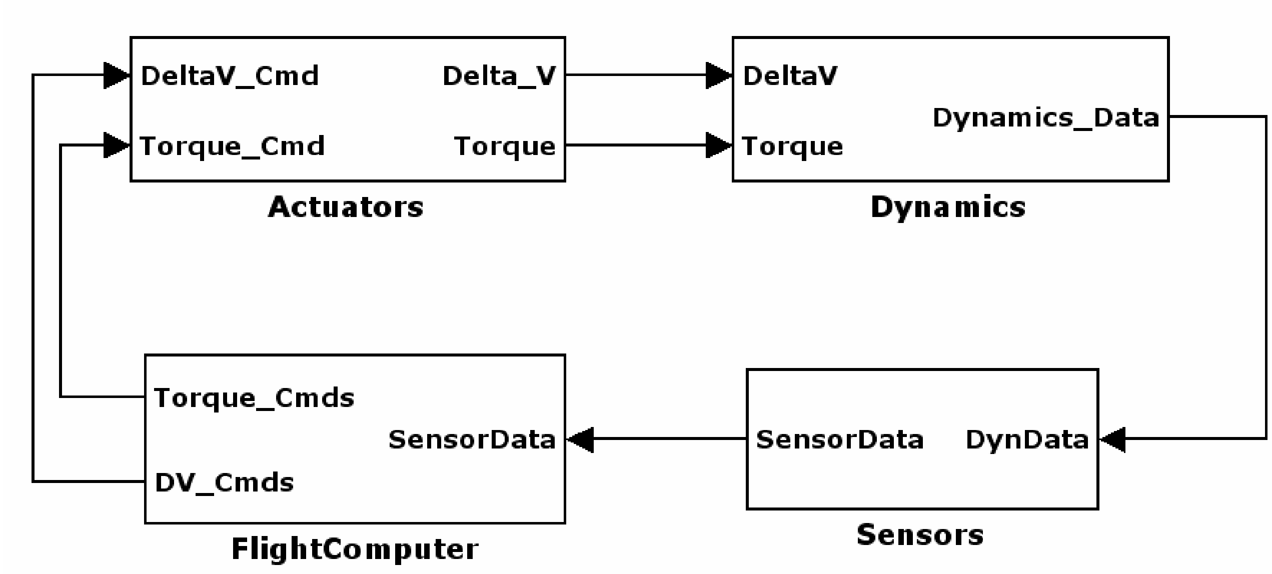
Example scenario

- Initial approach – Co-Elliptic
- Final approach – V-bar



Targeting maneuver time will be based on relative position.

Chaser attitude control will be used to keep the LIDAR pointed in the direction of the target.



Simulation Status

- Sensors/Actuators/Dynamics: Developed and integrated
- Inertial filter: developed and integrated – needs validation
- Relative filter: Coming soon
- Lambert Targeting Algorithm: Developed – needs integration
- CWH Targeting: Developed and integrated
- V-bar approach: Developed and integrated
- Co-Elliptic approach: Developed and integrated


THE END