Hardware Demonstration of Starshade Formation Flying

Leonel M. Palacios   Anthony Harness

Princeton University
Mechanical & Aerospace Engineering
High Contrast Imaging Lab

Hardware Demonstration of Starshade Formation Flying

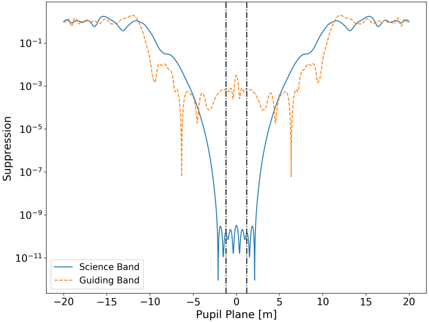
Objectives:

- To experimentally validate formation sensing and control algorithms while maintaining high contrast with a flight-like starshade

Our approach:

- Princeton starshade testbed
- Pupil image sensor of diffraction pattern
- Discrete-time control and estimation

Formation flying in starshade technology?



In science mode:

- The width of the deep of starshade's shadow depends on:
  - size of the starshade
  - separation distance
- The width can be resized but at a cost

Thus, better formation-keeping performance helps to maximize the scientific yield.

Position Sensing

- Technology development needed in position sensing
  - Need position accuracy < 10 cm
  - Centimeters over 10,000's kilometers separation is sub-mas angular measurement
- We can exploit nature of diffraction to avoid angular measurement
- Starshade's diffraction pattern moves one-to-one with starshade position over large distance
- Out-of-band light is bright and generates distinct Poisson spot – provides good guiding signal
- Pupil image is direct measurement of diffraction pattern

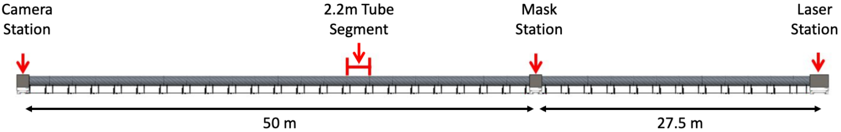
S5 Work

- Lateral Sensing technology gap at TRL 5 (as of Nov 2018)
- SLATE testbed at JPL demonstrated position sensing accuracy < 30 cm and control accuracy < 1 m (flight equivalent)
- See Milestone #4 Report by Flinois, Bottom, et al. (2018)
- Excellent work validating concept and showing robustness of sensing + control scheme
- Optical performance limited by small starshade and collimating optics

Opportunity with Princeton testbed

- Existing testbed with flight-representative starshade
- Optical performance validated to 10^{-10} contrast level
- Can validate formation sensing and high contrast simultaneously
- Realistic optical performance allows exploration of new sensing techniques
- Starshade alignment with out-of-band light already used in high-contrast experiments
- Can be used for TRL 6+ work

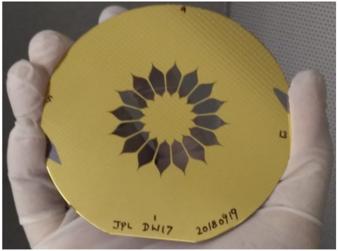
Princeton Starshade Testbed



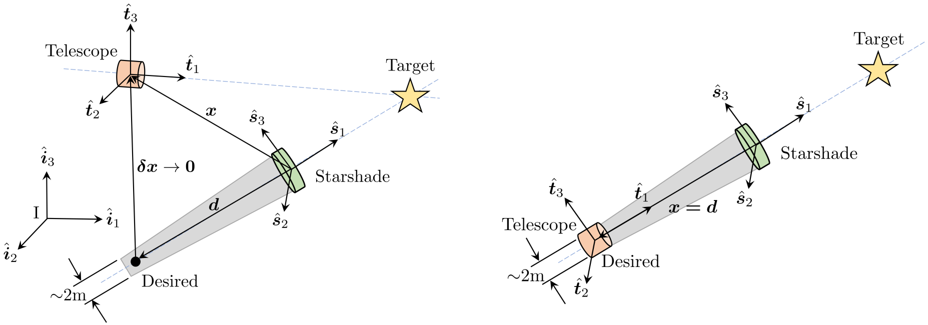
Starshade diameter: 26 mm

Science channel: $\lambda = 641$ nm

Guiding channel: $\lambda = 405$ nm



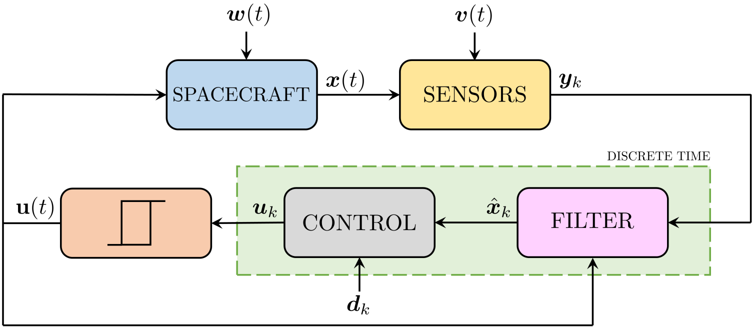
The formation flying problem



(a) Initial misalignment (b) Final alignment

Control and estimation diagram

Feedback control loop



The N-body problem for relative motion

The leader spacecraft:

$$\ddot{\boldsymbol{r}}_L = -\sum_{i=1}^{N} \mu_i \left(\frac{\boldsymbol{r}_{Li}}{\|\boldsymbol{r}_{Li}\|^3} \right) + \boldsymbol{u}_L \quad \text{for} \quad i = 1, 2, \ldots N \tag{1}$$

The follower spacecraft:

$$\ddot{\boldsymbol{r}}_F = -\sum_{i=1}^{N} \mu_i \left(\frac{\boldsymbol{r}_{Fi}}{\|\boldsymbol{r}_{Fi}\|^3} \right) + \boldsymbol{u}_F \quad \text{for} \quad i = 1, 2, \ldots N \tag{2}$$

The term $\boldsymbol{u}_X$ correspond to control inputs.

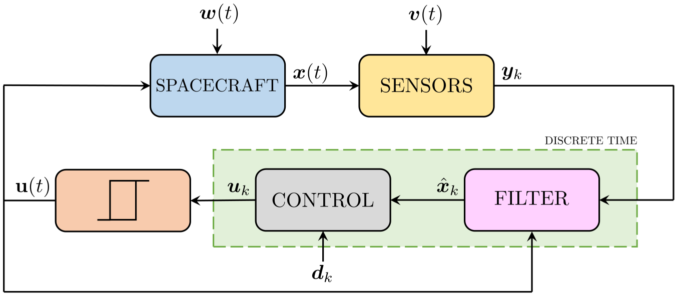
Equations of Motion

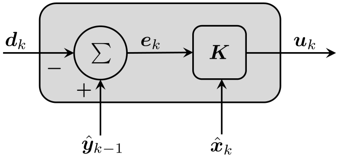
The relative motion is $\boldsymbol{x} = \boldsymbol{r}_F - \boldsymbol{r}_L$

$$\ddot{\boldsymbol{x}} = -\sum_{i=1}^{N} \mu_i \left(\frac{\boldsymbol{r}_{Fi}}{\|\boldsymbol{r}_{Fi}\|^3} - \frac{\boldsymbol{r}_{Li}}{\|\boldsymbol{r}_{Li}\|^3} \right) + \Delta \boldsymbol{u} + \boldsymbol{w} \quad \text{for} \quad i = 1, 2, \ldots N \quad (3)$$

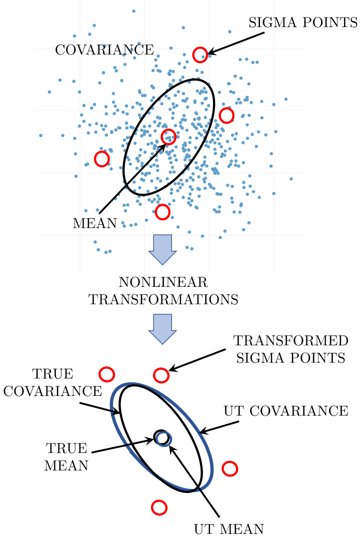
- $\boldsymbol{w} \sim \mathcal{N}\left(\mu_{SRP}, \sigma\right)$ adds uncertainty (normal random noise)
- μ_{SRP} is the average of the differential acceleration caused by the solar radiation pressure
- According to the configuration of our laboratory, we assume:
  - The starshade is the leader in free motion
  - The telescope is the follower in controlled motion
  - Therefore $\Delta \boldsymbol{u} = \boldsymbol{u}_F - \cancelto{0}{\boldsymbol{u}_L} = \boldsymbol{u}_F$

Linear quadratic regulator with integral action





Unscented Kalman filter



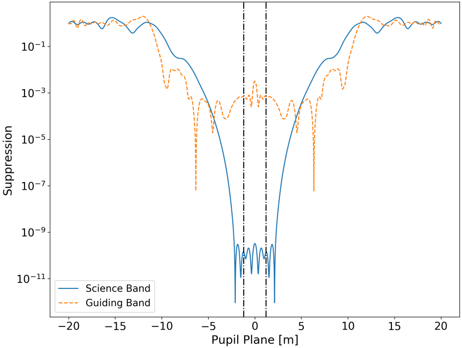
Other relevant features:

- Approximates the actual motion as:

$$\ddot{\boldsymbol{x}} = -\sum_{i=1}^{N} \mu_i \left(\frac{\boldsymbol{r}_{Fi}}{\|\boldsymbol{r}_{Fi}\|^3} - \frac{\boldsymbol{r}_{Li}}{\|\boldsymbol{r}_{Li}\|^3} \right) + \Delta \boldsymbol{u} + \cancelto{0}{\boldsymbol{w}}$$

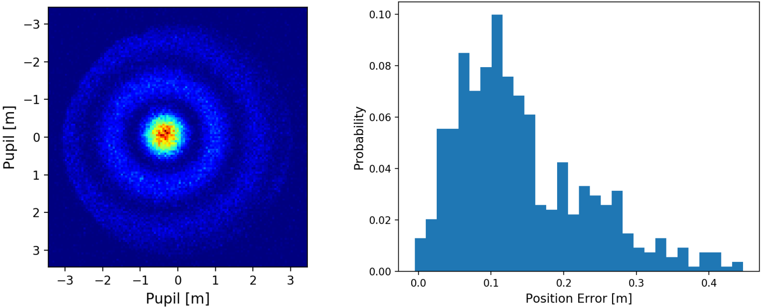
- Fed by the sensors and the controller

Some background



- Deep shadow ∼1m larger than telescope (in radius)
- Formation-keeping needs lateral position error $\lesssim$ 10 cm
- For 1000's km of separation it means milliarcsec measurement
- Direct sampling the one-to-one diffraction pattern of the starshade

Pupil Sensor



- Starshade's diffraction pattern approximated by a Bessel function:

$$I(x,y) \approx J_0^2\left(\frac{2\pi R\sqrt{(x-x_s)^2+(y-y_s)^2}}{\lambda z}\right) \tag{4}$$

- x_s and y_s solved via non-linear least squares

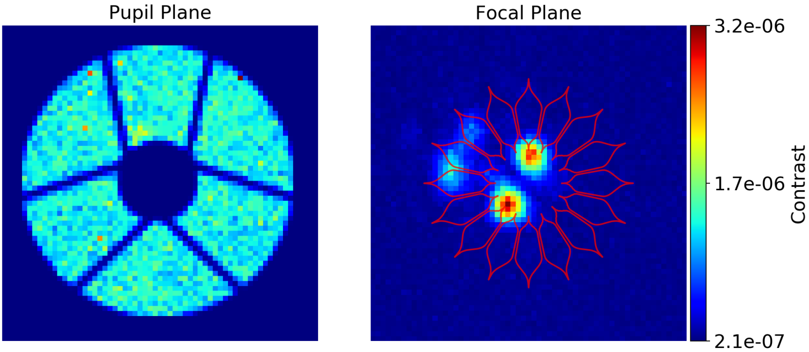
Hardware-in-the-loop simulation features

- Intersatellite separation 26,000km
- For in-plane readings < 1m use pupil sensor
- For intersatellite separation and in-plane readings > 1m:
  - Star-tracking sensor
  - Normal distributed random signal with a ±5m error
- Target star is Epsilon Eridani
- Maximum thrust firing of 1N
- Simulation time 2 hour
- 10 celestial bodies from JPL's ephemeris DE432

Experiment Procedure

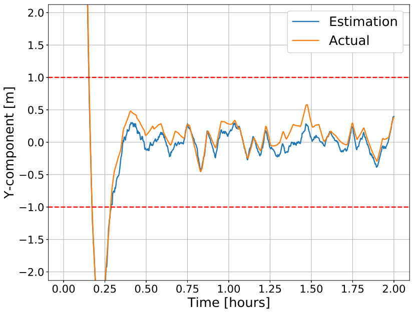
- Start camera with initial misalignment
- Begin control loop...
  - Switch to pupil plane camera
  - Switch to out-of-band wavelength channel
  - Take pupil image and extract position
    - Or get position from noisy star tracker if at large offset
  - Generate control signal + move camera
  - Switch to focal plane camera
  - Switch to science-band wavelength channel
  - Take contrast image with focal plane camera

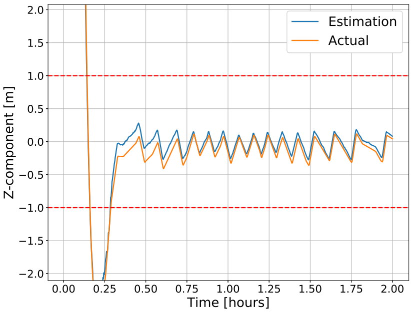
Results



Position error in the line-of-sight frame

- Starting offset: 50 m
- Median pupil sensor error: 16 cm

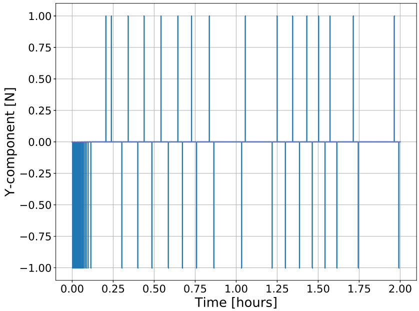


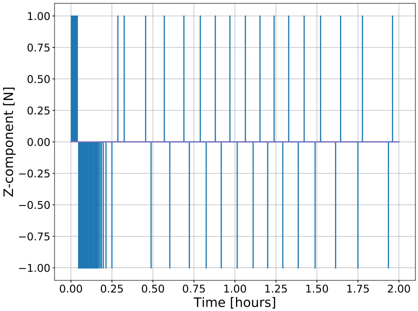


Results

Control signals

- Total $\Delta v = 0.89$ m/s





Conclusions

- Combination of an LQR+i and UKF
- High precision position sensing using a pupil image sensor
- Favorable performance includes:
  - Position error convergence within tolerances
  - Robust steady-state
  - Low values of total Δv
- Initial results suggest the validity of formation flying approach in starshade technology

Future Work

- Implement control scheme that maximizes observing time (minimizes thruster firings)
- Add beacon on starshade to do focal plane “retargeting” control
- Add control in “putting” region and implement proper sensor handoff
- Investigate position sensing in “putting” region
- Investigate other position extraction schemes (e.g., neural net)

THANK YOU

FOR YOUR ATTENTION

lmmoreno@princeton.edu