Cubic-Centimeter Star Imager

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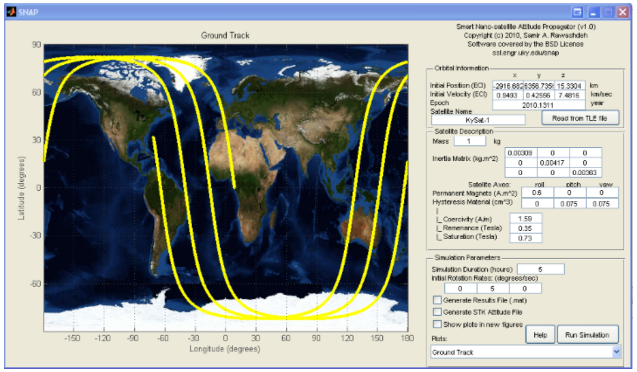
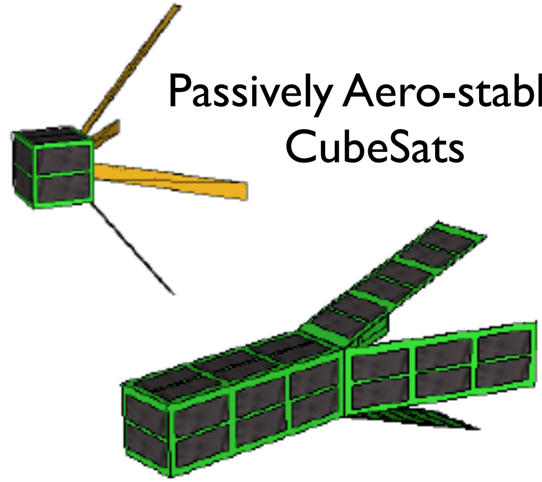
August 8, 2015

Brief Personal Introduction

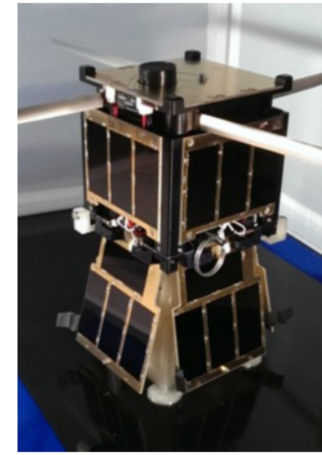
At Kentucky Space Systems Lab



Smart Nanosatellite Attitude Propagator (SNAP)

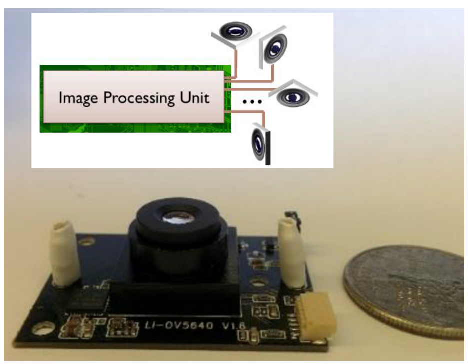


Passively Aero-stable CubeSats

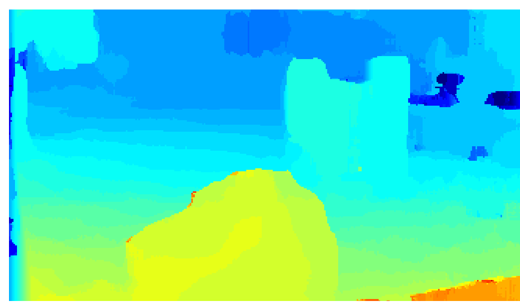


KySat-2 ADCS (Star Imaging)

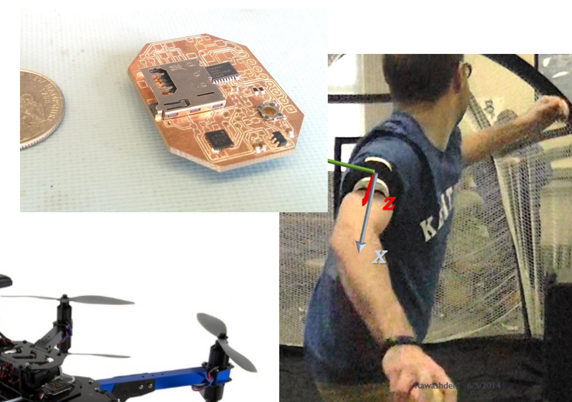
At Univ. of Michigan Dearborn (since Aug 2014)



Distributed Star Imaging for CubeSats



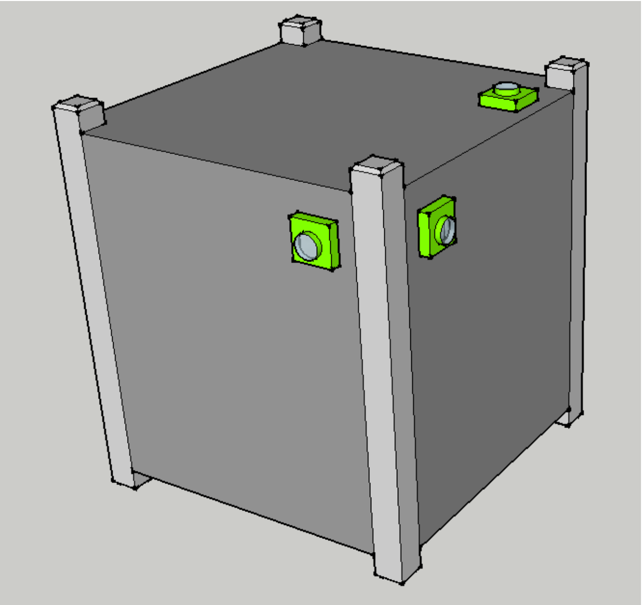
Visual Sense and Avoid for Micro Aerial Vehicles



Wearable Motion Capture for Shoulder Health

Objective

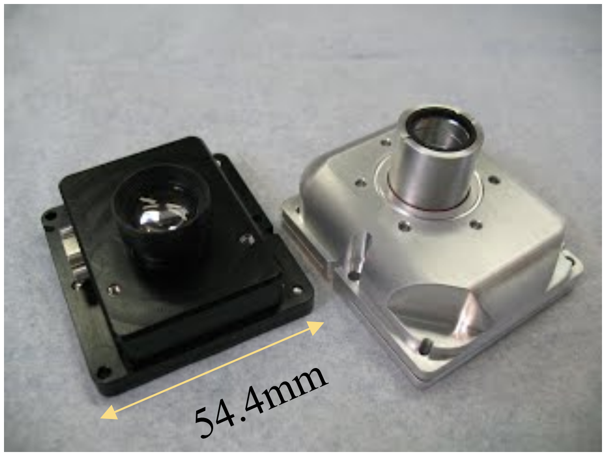
Develop a star imager at the smart-phone scale.

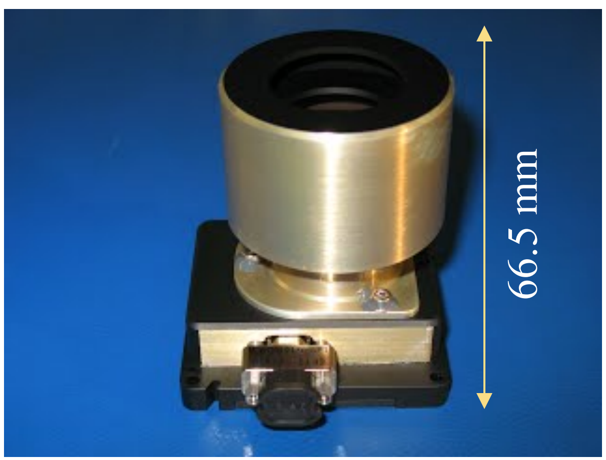


- Major challenges:
  - Physically small sensor: less **light** sensitivity
  - Small Lens: small aperture (less **light** enters the sensor)
  - Small Lens: typically short focal length (wide **field of view**)

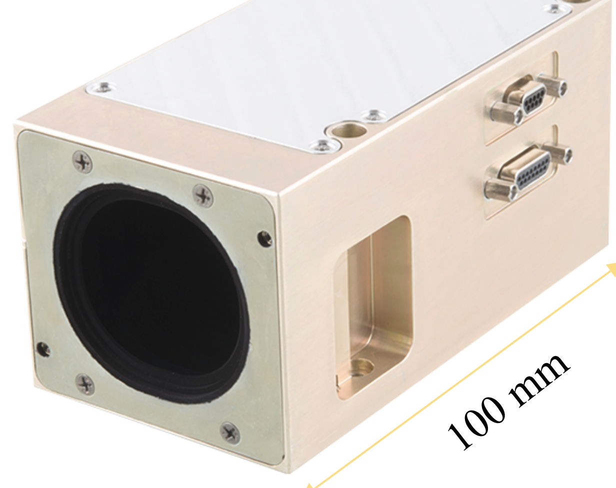
Introduction: Off-The-Shelf Star Trackers

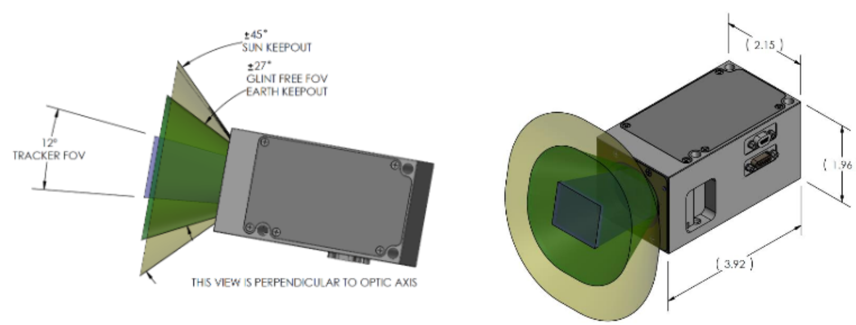
Sinclair Interplanetary





Blue Canyon Technologies XACT ADCS

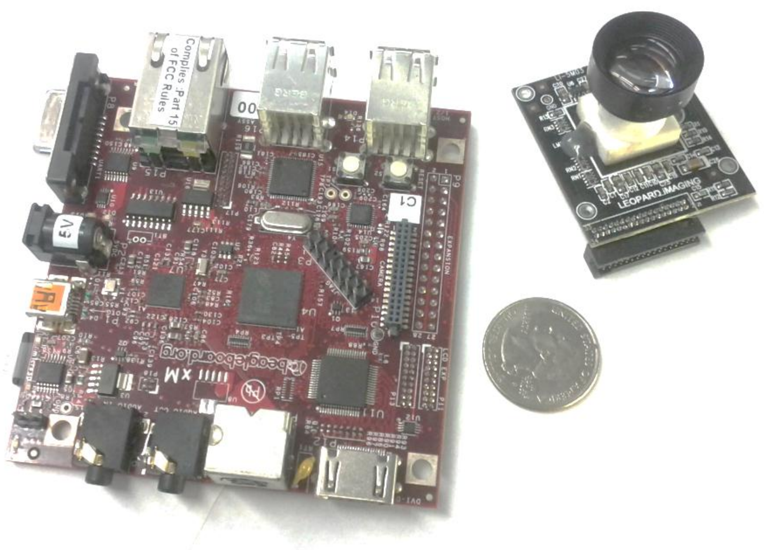


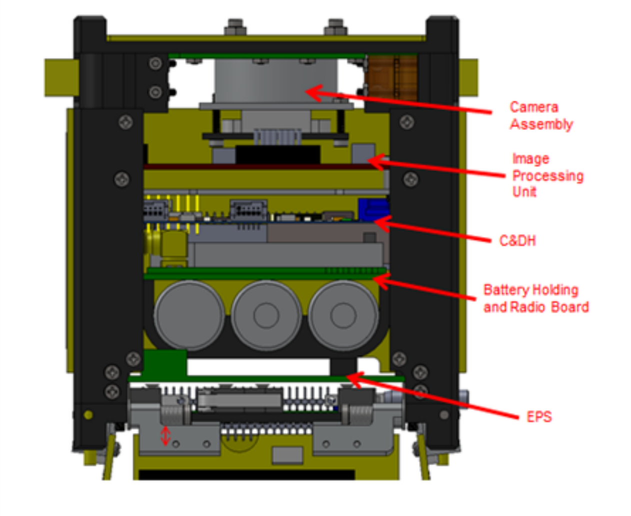


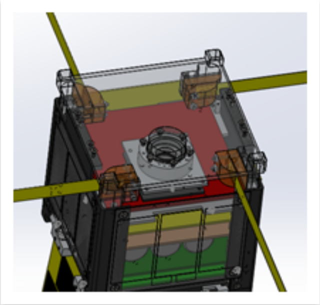
Mechanical Layout (Inches)

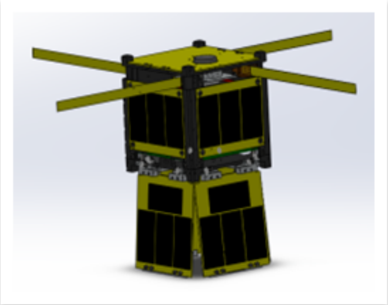
Star Imager on KySat-2

- 5 Megapixel Sensor (MT9P031)
- BeagleBoard-xM Linux single-board computer

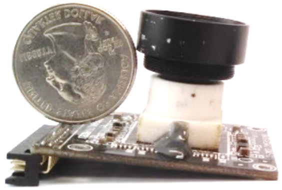








Rawashdeh, Samir, "VISUAL ATTITUDE PROPAGATION FOR SMALL SATELLITES" (2013). PhD Dissertations--Electrical and Computer Engineering, University of Kentucky

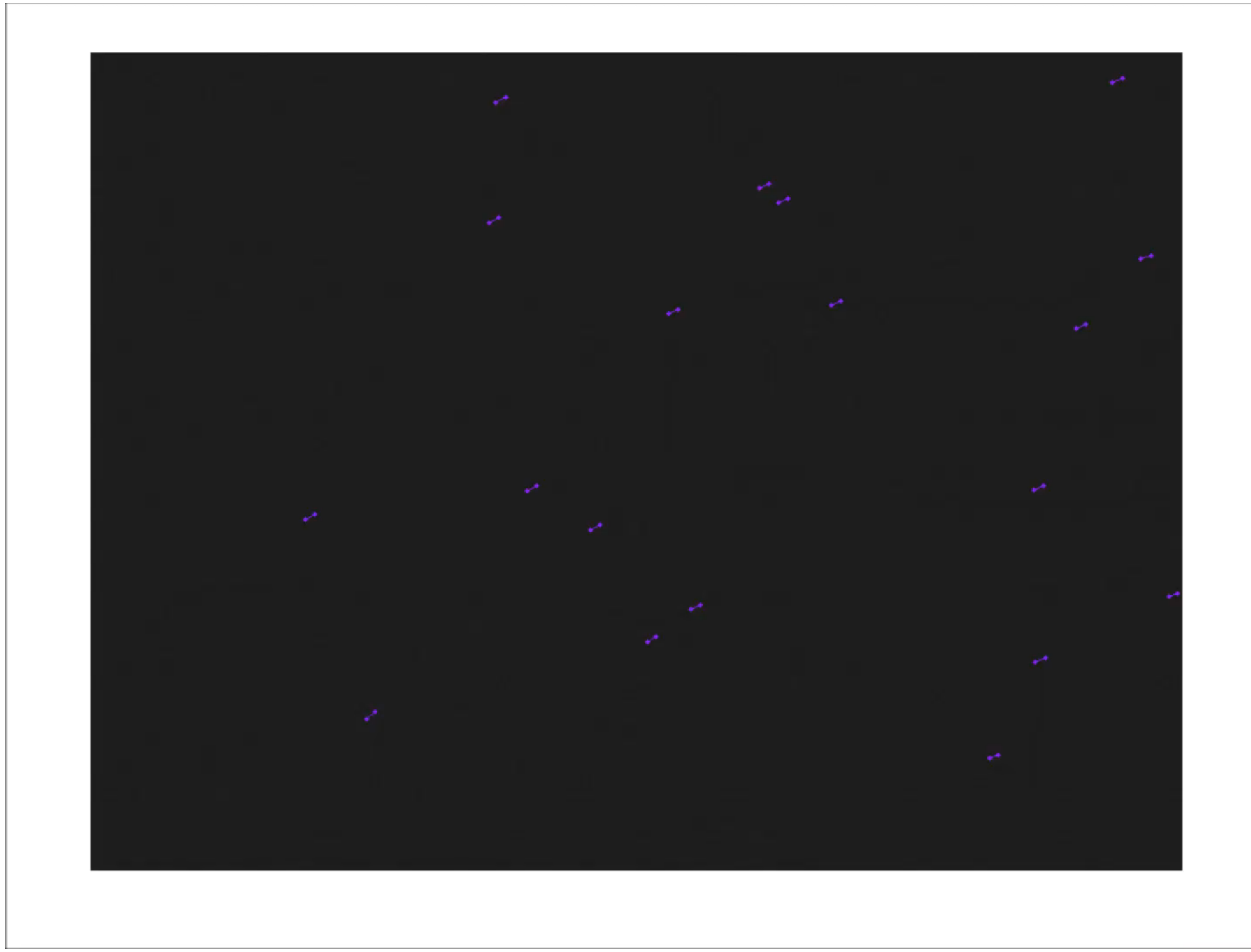


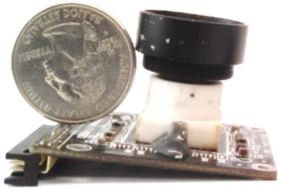
Stellar Gyroscope - Panning

Essentially: For two images of a star field, produce rotation estimates

(three degree-of-freedom / quaternion).

- Estimation bias: within 0.005°
- Standard deviation: below 0.02°
- Dimmest Star: magnitude 5.7

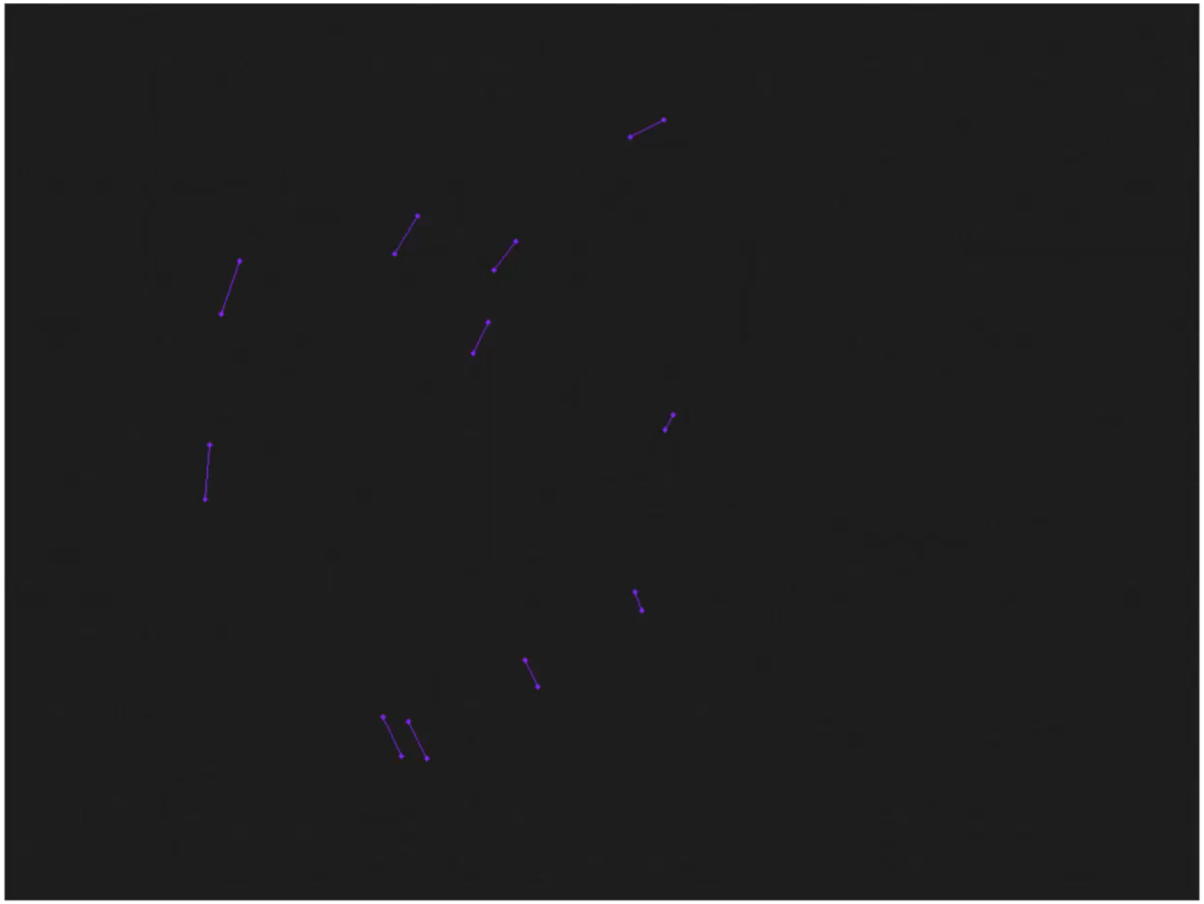




Stellar Gyroscope - Rotating

Essentially: For two images of a star field, produce rotation estimates

(three degree-of-freedom / quaternion).



- Estimation bias: within 0.005°
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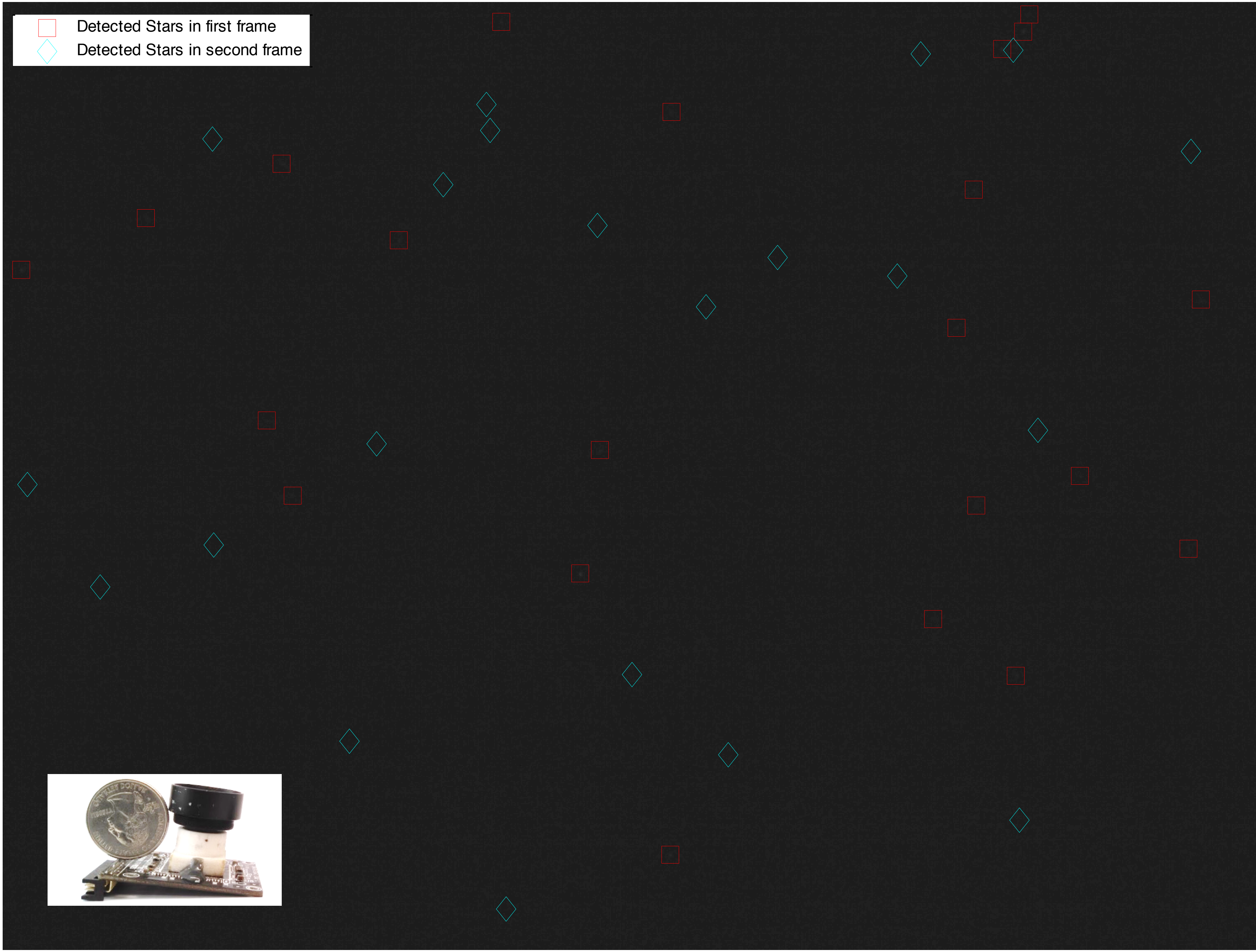
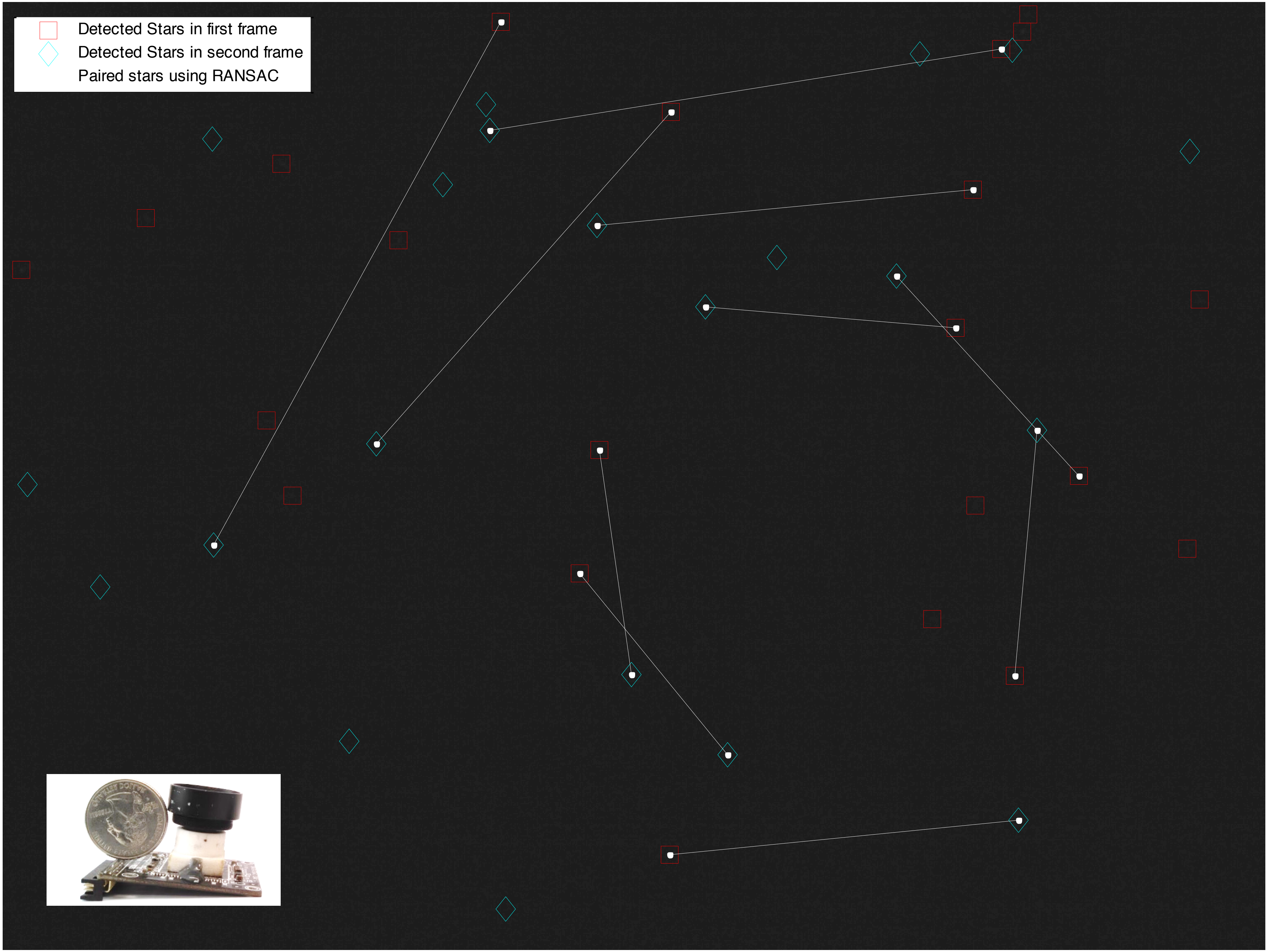
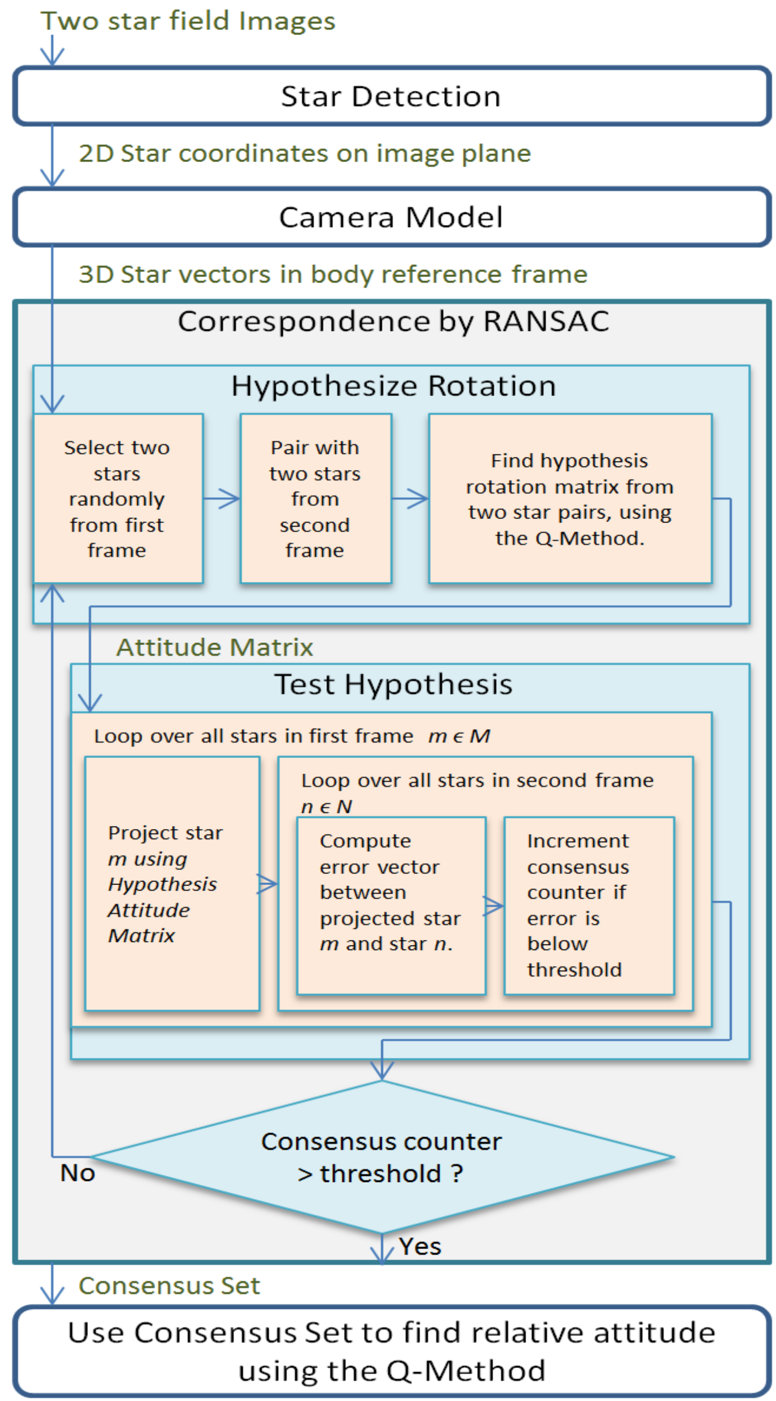

Detected Stars in first frame
Detected Stars in second frame


Detected Stars in first frame
Detected Stars in second frame
Paired stars using RANSAC

Random Sample Consensus (RANSAC)

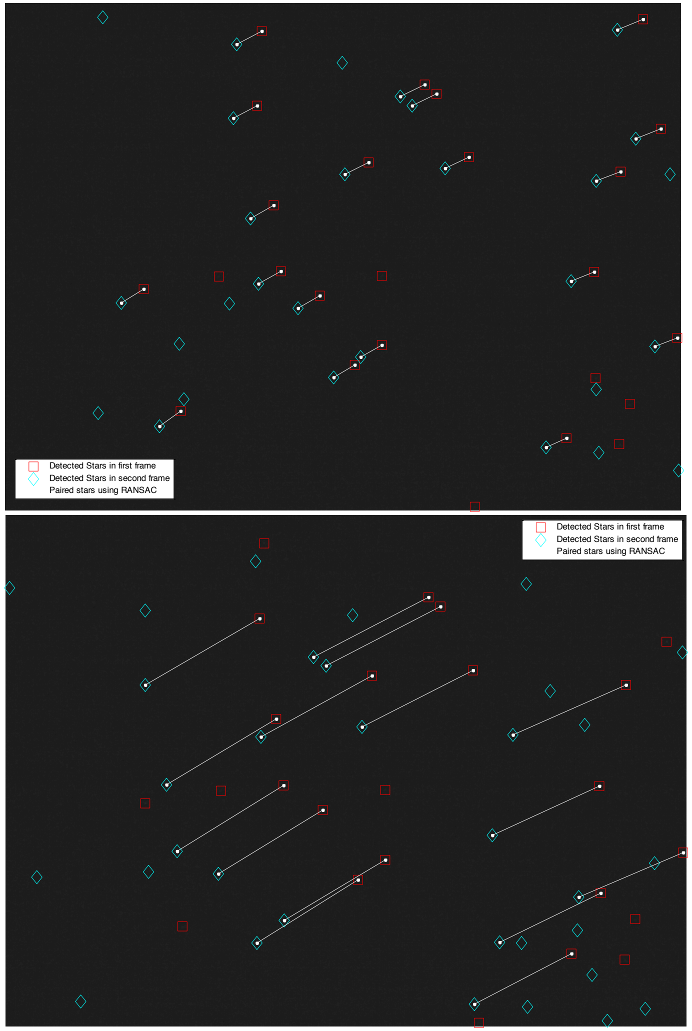
- RANSAC: iterative method to estimate parameters of a mathematical model from a set of observed data which is contaminated a large number of outliers that do not fit the model.
- The steps of RANSAC can be summarized as
  - **Hypothesize:** A hypothesis rotation is calculated using randomly selected star pairs across frames.
  - **Test:** The estimated rotation matrix is tested against all the stars in the two frames. Stars that show consensus are counted towards the Consensus Set (CS).
  - **Iterate:** RANSAC iterates between the above two steps until a random hypothesis finds "enough" consensus to some selected threshold.

S. A. Rawashdeh, J. E. Lumpp, "Image-Based Attitude Propagation for Small Satellites using RANSAC", IEEE Transactions on Aerospace and Electronic Systems, vol. 50, no. 3 pp 1864-1875, 2014.



False Star Rejection using RANSAC

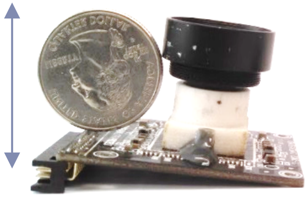
- Random Sample Consensus (RANSAC) approach is **effective at rejecting stars that do not show agreement with underlying motion.**
- RANSAC can **tolerate up to 50% un-pairable "stars"** (noise, stars leaving or entering, shot noise, etc).
- Hypothesis: RANSAC as a filtering step before star database search

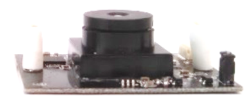


Imager Design

2014, XIMEA corp.

24.3 mm



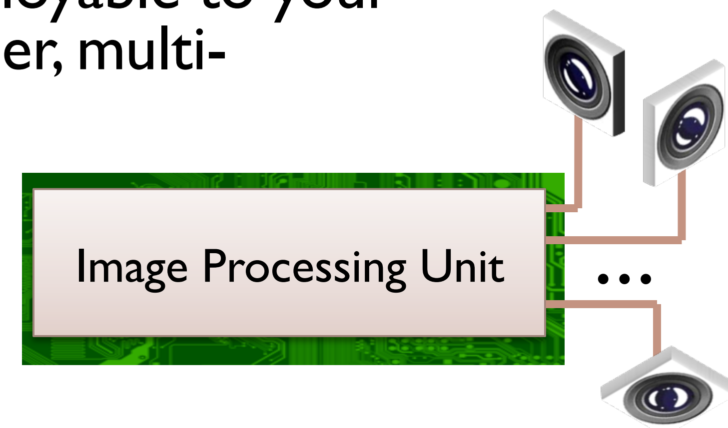


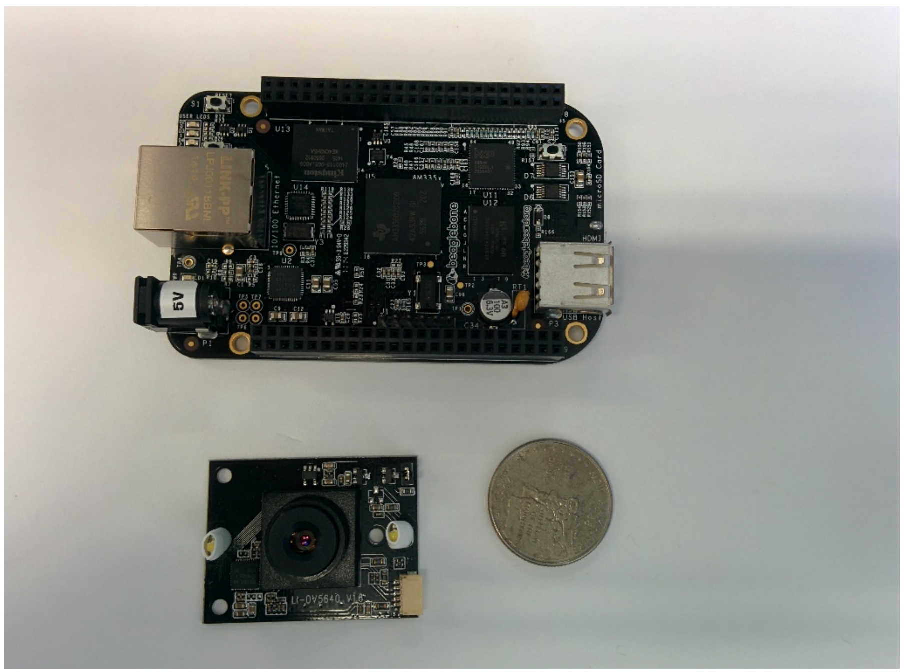
11 mm

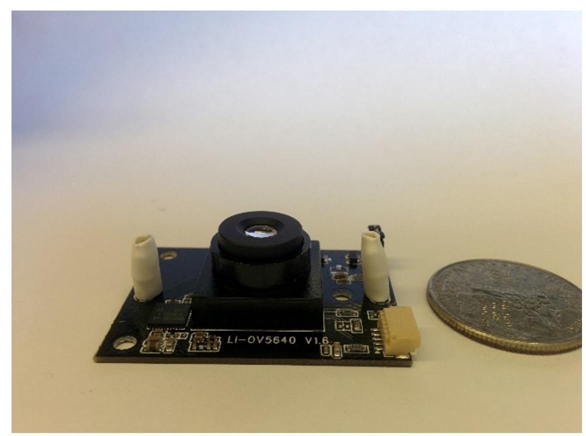
	Current Design	*Proposed Design*
Sensor	Aptina MT9P031 (5MP, 1/2.5”)	OmniVision OV5640 (5MP, 1/4”)
Lens	Hi Res 16mm, F/1.2, 1/3”	Hi Res 6.3mm, F/2.0, 1/2.5"
Lens Height	Image plane to lens top: 24.3 mm	Image plane to lens top: **11mm**
Field of View	15.2° x 20.2 °	24.5° x 32.5 °
Dimmest Star Visible	Magnitude 5.7	**To be tested.**
Number of stars in view	Avg 22.9, Min 8 stars (threshold at magnitude 5.7, as found in tests)	Avg 15.3, Min 5 (with conservative threshold at magnitude 4.5)
Connectivity	Parallel data bus (1 camera, 1 processor board)	USB, smaller centralized processor, **multiple camera nodes**

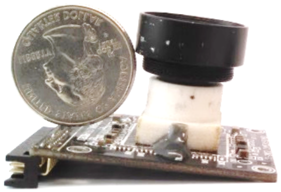
New Topology

- A centralized image processing system, and multiple miniature cameras (facing various directions)
- Software developed under Linux; deployable to your favorite Linux system (rad-hard, smaller, multi-purpose, etc)







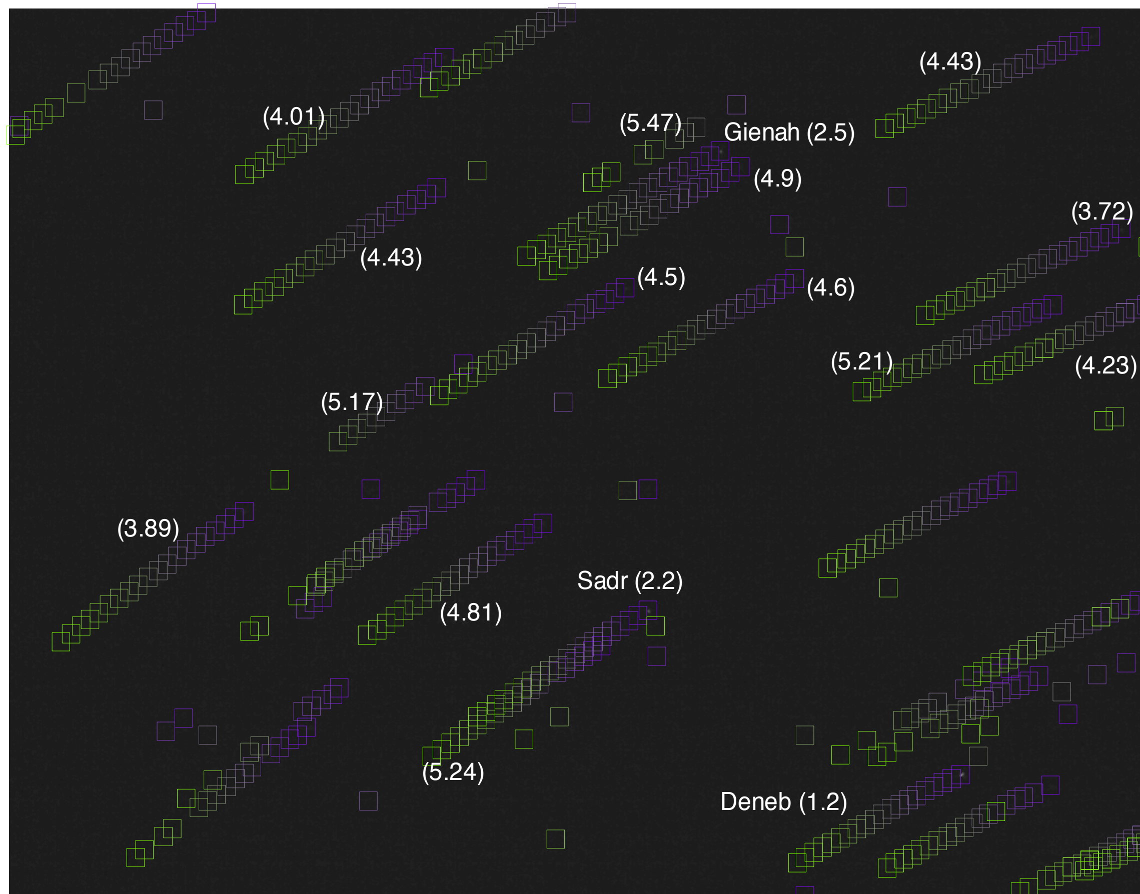


Night-Sky Tests - Sensitivity

Illustration of detected stars in first photo set of the Cygnus constellation. A photo was taken every minute as Earth rotated in inertial space, every color represents star detections in a single photo and star apparent magnitudes are marked.

Reliably detected stars of magnitude ~5.2

Expected on orbit: magnitude ~5.7



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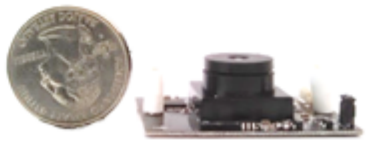


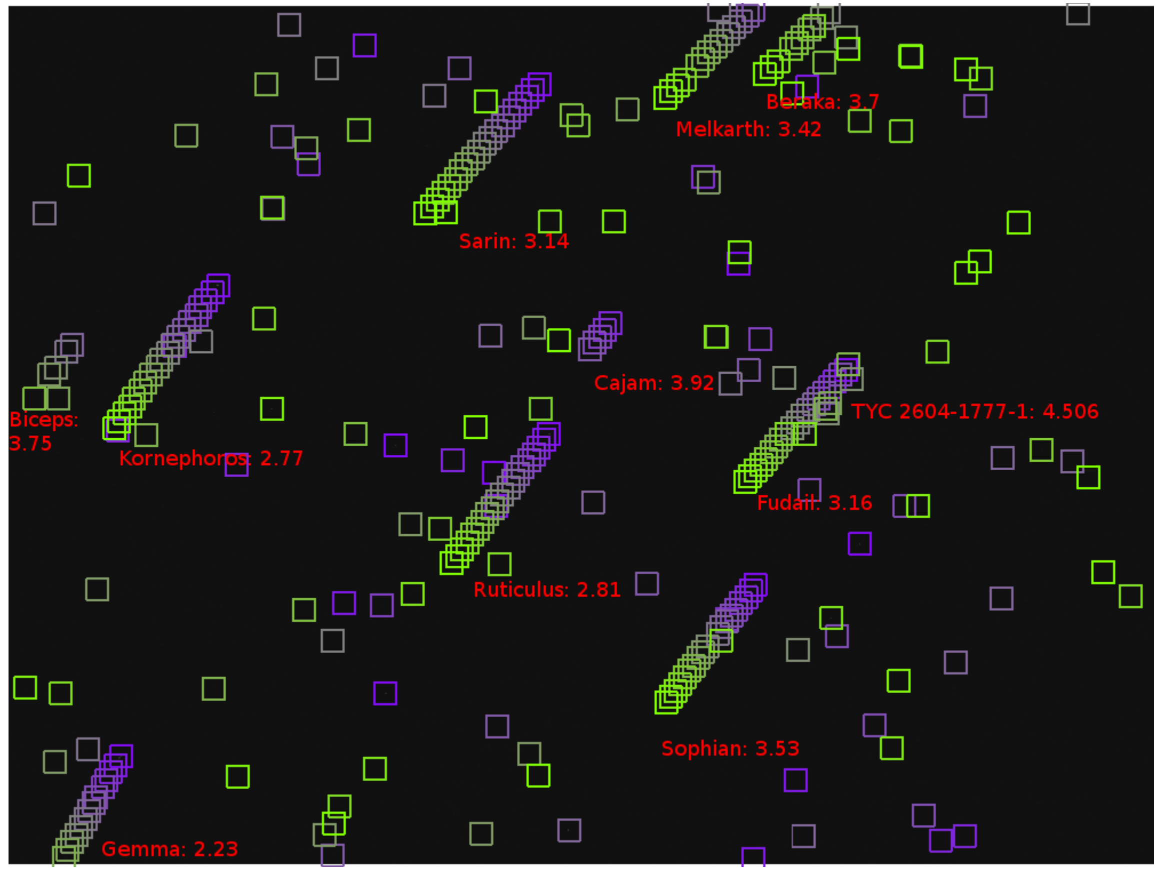
New Sensor Preliminary Results: Night-Sky Tests - Sensitivity

Illustration of detected stars in first photo set of the Hercules constellation. A photo was taken every minute as Earth rotated in inertial space, every color represents star detections in a single photo and star apparent magnitudes are marked.

Reliably detected stars of magnitude ~3.5

Expected on orbit: magnitude ~4.5

Weather Conditions in test:
- Moon Phase: Waxing Gibbous
- Humidity: 55% to 60%



Star Database Simulations

- For star detection threshold of magnitude 4.5 and FOV of 24.5° x 32.5°
- Sweeping the sky using SKY2000 Star Catalog:
  - On average 15.3 stars are in view
  - At least 5 stars in view in the darkest parts of the sky

Camera Array

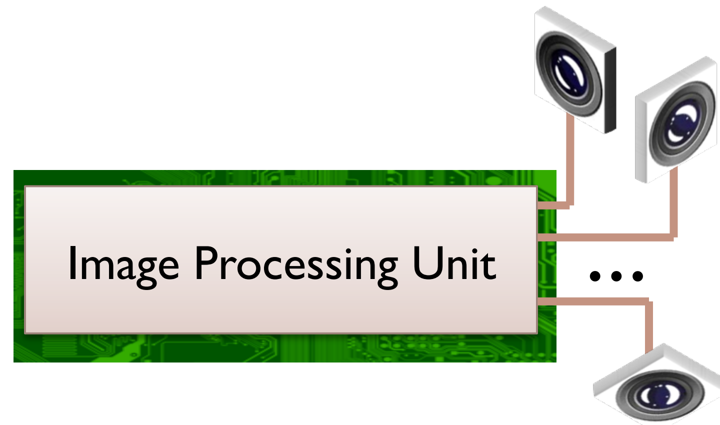
- Star Tracker FOV typically 8 ~ 15°
- Miniature Camera FOV = 24.5° x 23.5°

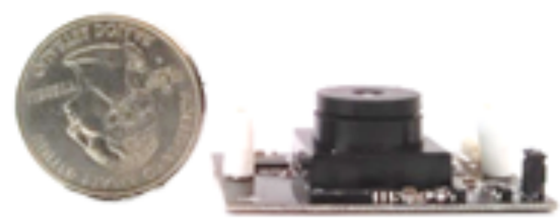
Advantages:

Wide view increases chances of bright stars in view; i.e. camera does not have to be as sensitive to dim stars as narrower cameras.

Disadvantages:

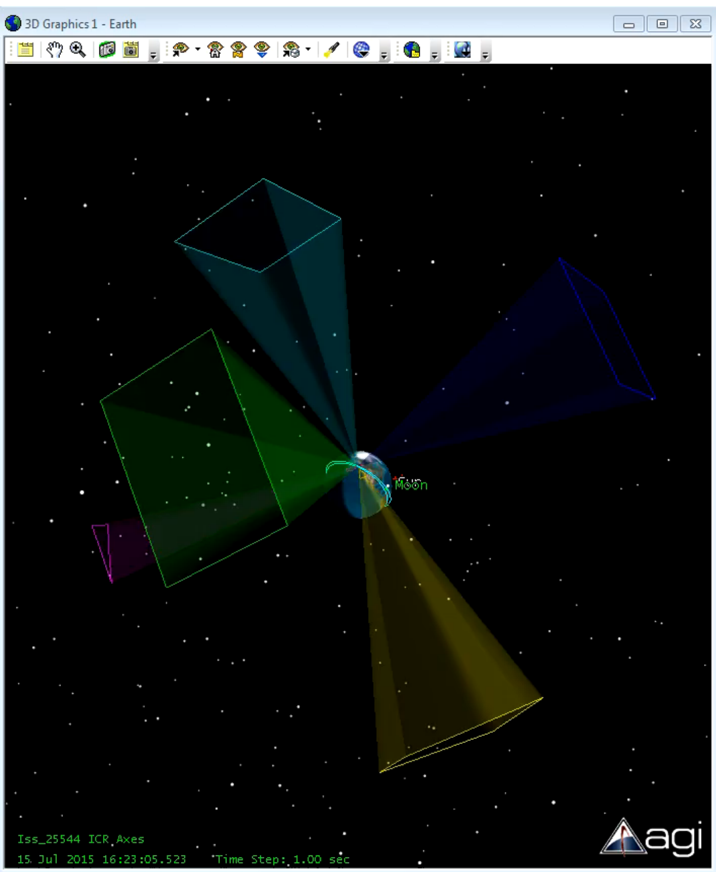
Wide view increases chances of obstruction in view (Earth, Moon, etc.)

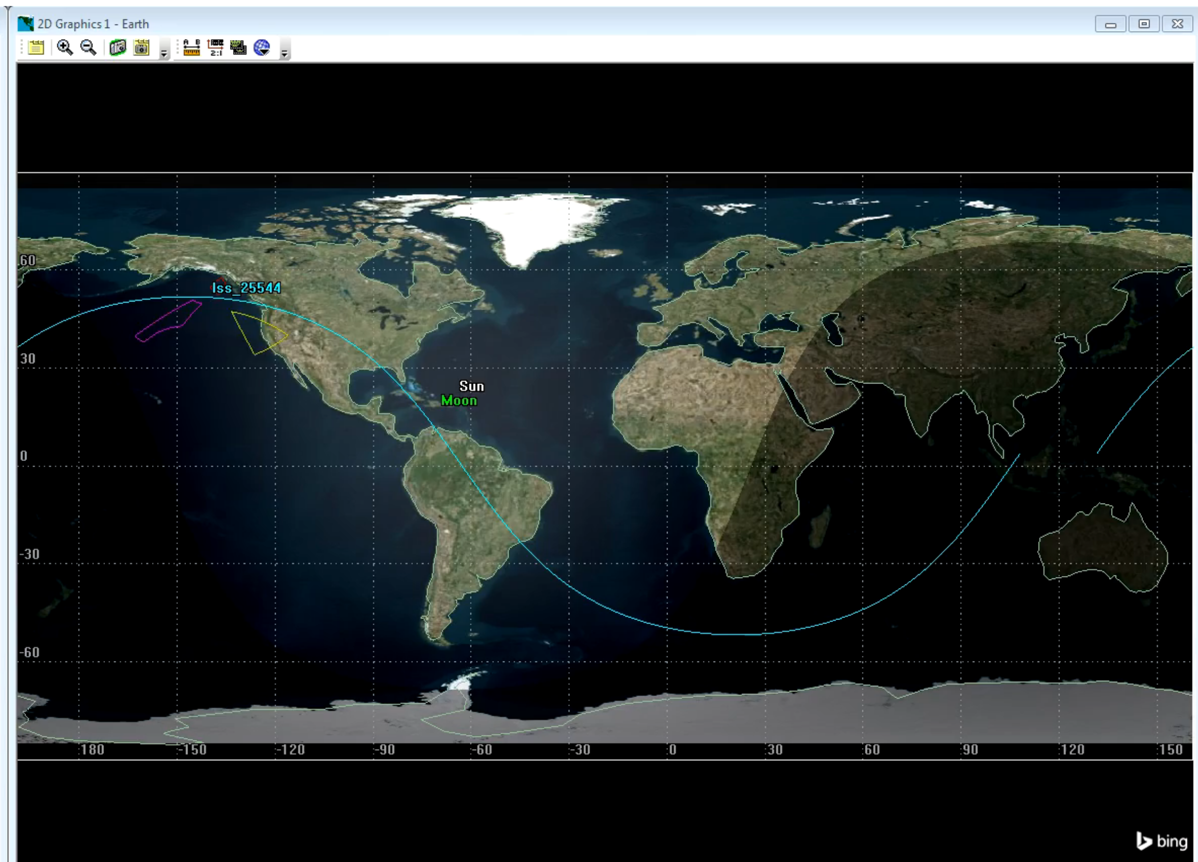




Camera Array View of Sky

- When one camera is obscured, another camera may provide a view of the stars.
- A level of fault tolerance comes with multiple imagers in the system.





Conclusion

- Modern Linux single-board computers and USB camera modules enable a camera array topology with centralized processing
- Miniature cameras produce noisy images, primarily because of the small lens aperture.
- Using "Random Sample Consensus" (RANSAC) by taking two photos and detecting the underlying rotation produces a "Consensus Set" in the presence of up to 50% noise (unpairable stars).
- This form of RANSAC could be used as a filtering step or as a search approach to identify stars (star tracker).
- Where the field of view using a small lens may be considered too wide (obstructed too often), a camera array can be used, enabled by the small size and the USB bus advantage.

Thank You

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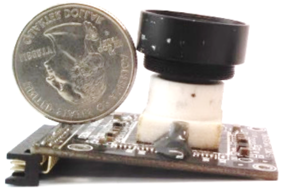

Stellar Gyroscope – Simulated Image Set

Essentially: For two images of a star field, produce rotation estimates

(three degree-of-freedom / quaternion).