Autonomous Robotics and Control Lab (ARCL)

Bayesian Active Sensing and Planning Applied to Attitude Dynamics and Spacecraft Control

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Motivation

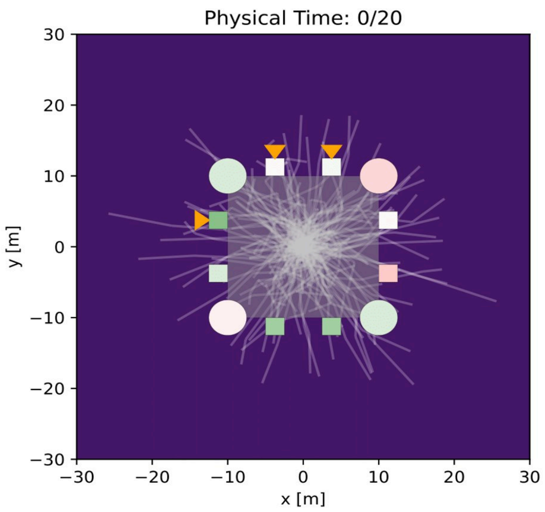
- Satellites are critical for global communication and security
  - Enable scientists to study the Earth
  - Provides information for those in unsafe conditions
- To continue providing these services, satellites must be robust to failures
- Engineers currently combat failure using redundancy
  - Allows multiple failures to occur without compromising objectives

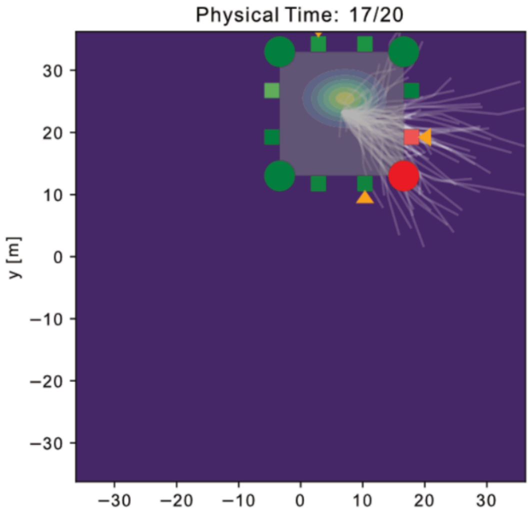
Planes are able to maintain altitude with only one engine over water.

The Issue With Redundancy

- Decision to incorporate redundancy is not without penalty
  - Increases the weight, complexity, and cost of system
  - Requires significant time to test and redesign

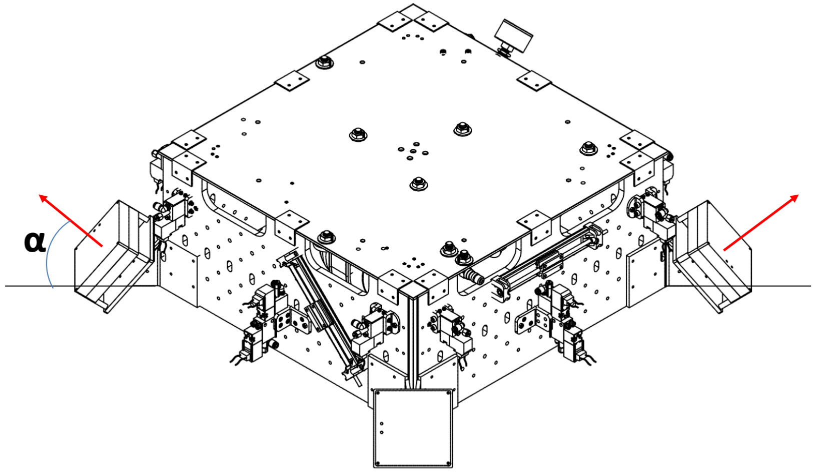
- Biggest issue:
  - If a redundant system fails, source of failure is not easily identifiable
- Scientists at ARCL lab have a developed novel FDIR algorithm
  - Identifies faulty sensors and actuators in redundant system





Fault Detection for Attitude Dynamics

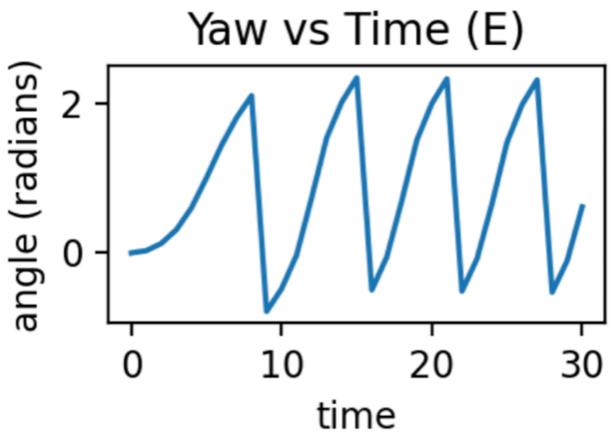
- We seek to extend this novel algorithm into 3D space
  - Identify faulty actuators and sensors affecting spacecraft's attitude (orientation)
- Began by developing physics simulation determining how actuators affect attitude
  - Contemporary spacecrafts utilize reaction wheels to add torque to spacecraft system.
  - Adds torque by storing angular momentum
- Orientation of reaction wheels match the M-STAR satellite prototype

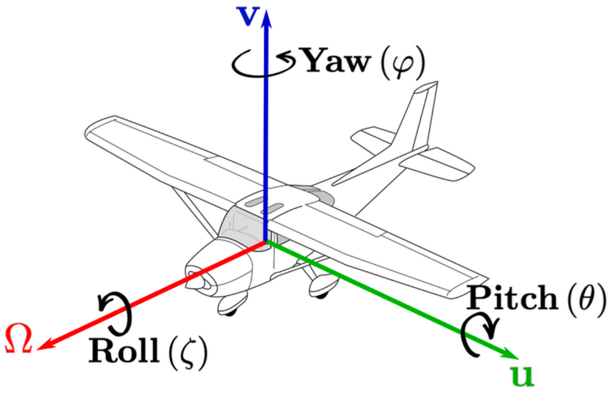


M-STAR satellite prototype with reaction wheels fixed on the corners

Adapted from Y. K. Nakka

Reaction Wheel Simulation

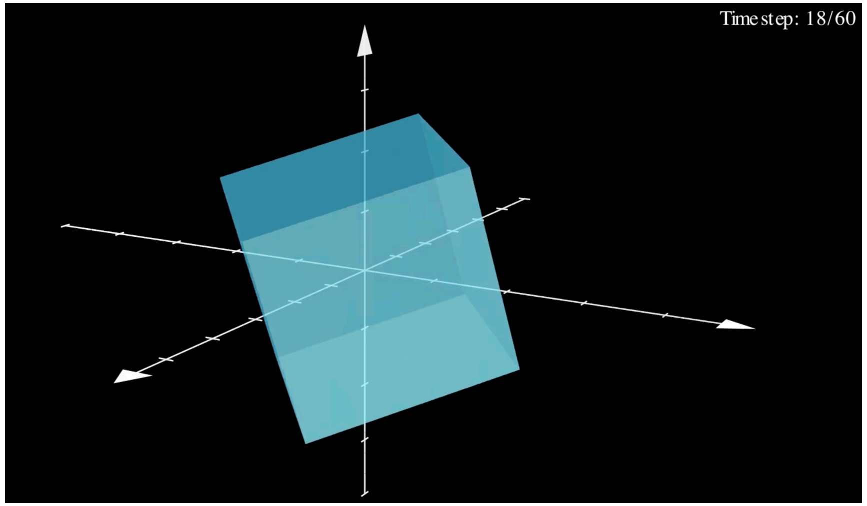




- Derived the kinematics governing how torque affects the spacecraft's yaw, pitch, and roll angle.
  - Utilized Euler angles
- Kinematics can propagate system forward one time step
- Critical issue with Euler Angles:
  - Singularity point when pitch approaches 90 degrees
  - Can be used to model aircraft, but not spacecraft

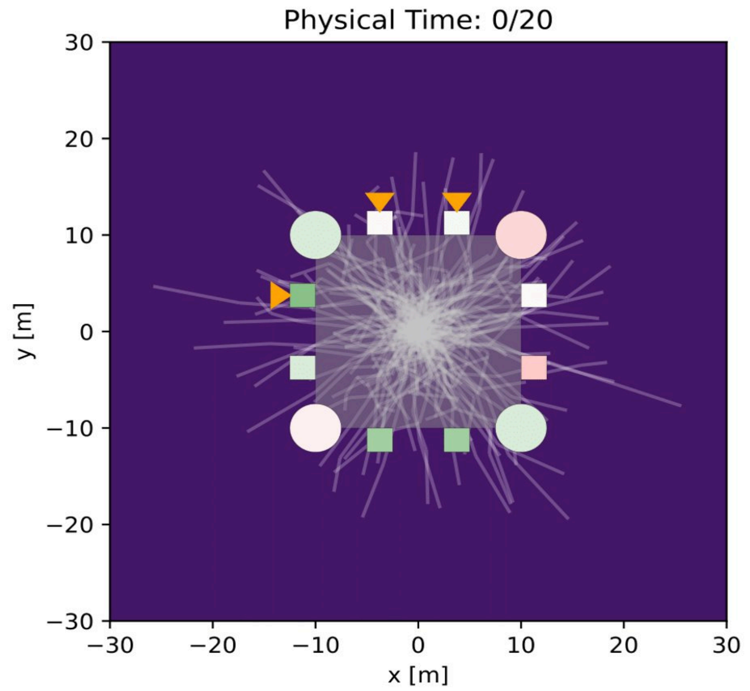
Euler Angles vs. Quaternions

- Quaternions
  - Set of hyper-complex numbers that extends $\mathbb{R}$
  - Better represents orientation in 3D space
  - No singularity point
- Re-derived attitude kinematics using quaternions
- Integrated into simulation
- Created a visualizer to rotate spacecraft object
  - Spacecraft is modeled as a cube, but any shape can be used



Snapshot of cubeSAT in visualizer

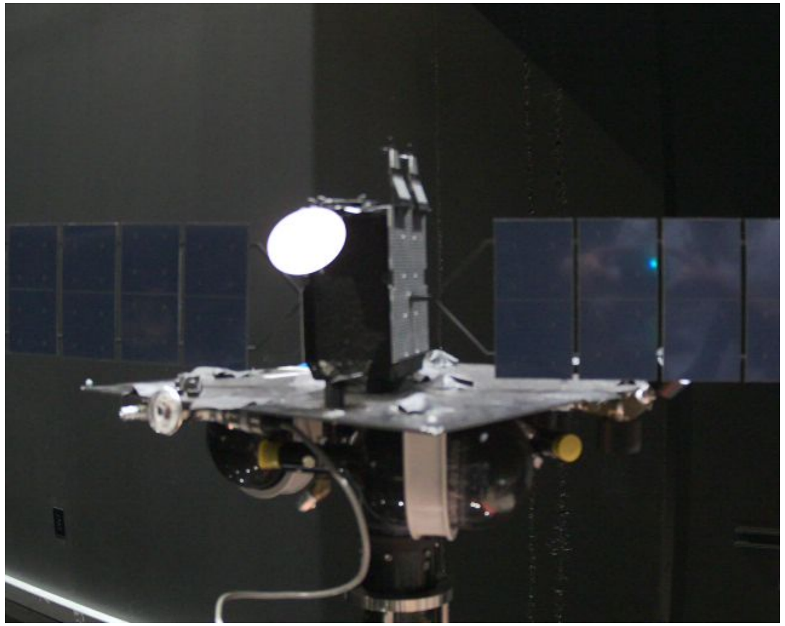
Integrating Physics Simulation



- Began integrating physics engine into my mentor's FDIR codebase
  - Modified pipeline to differentiate attitude simulation from planar
  - New model keeps track of 11 states
    - Angular velocity (3)
    - Quaternion (4)
    - Reaction wheels (4)
- Created sensing matrix
  - Extremely simple model
  - Pivot point for research
    - New goal: raise the level of realism in the sensing matrix

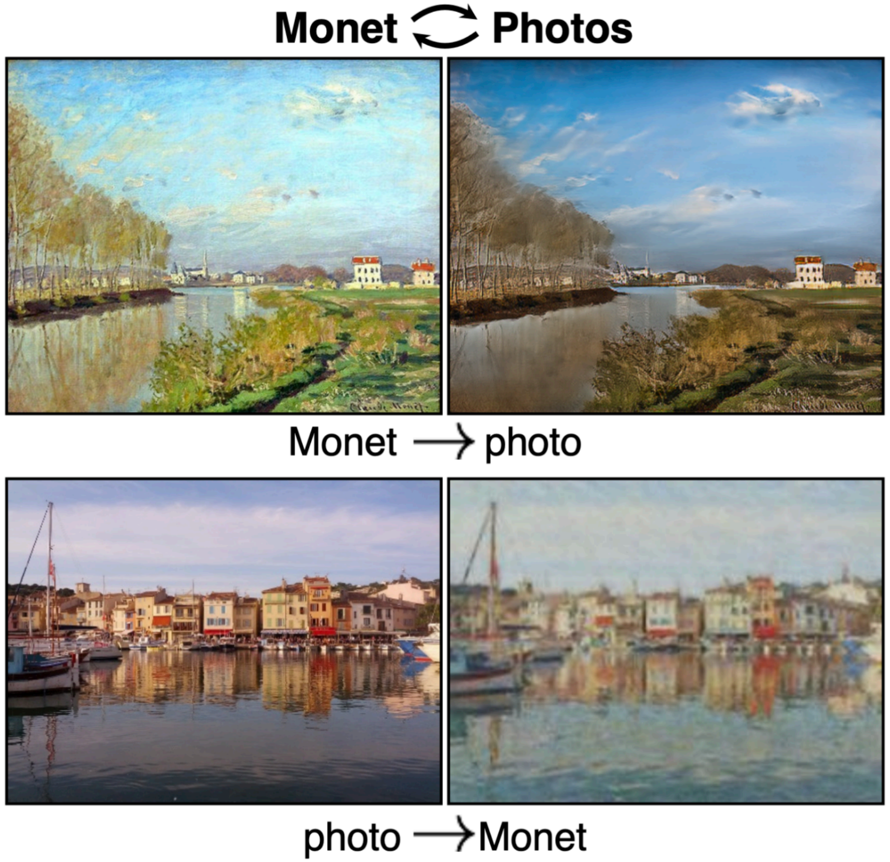
RGB to Infrared Images

- We seek to develop an algorithm that can:
  - Detect the presence of a failure mode
  - Recover from failure
- Lab is working on a novel star tracking algorithm to determine orientation w.r.t other spacecraft
  - Utilizes Infrared Cameras
- No large dataset for faulty/nominal IR images exist
  - **However**, large datasets for RGB images exist
- Develop a framework to convert RGB spacecraft images to IR images
  - cycleGAN



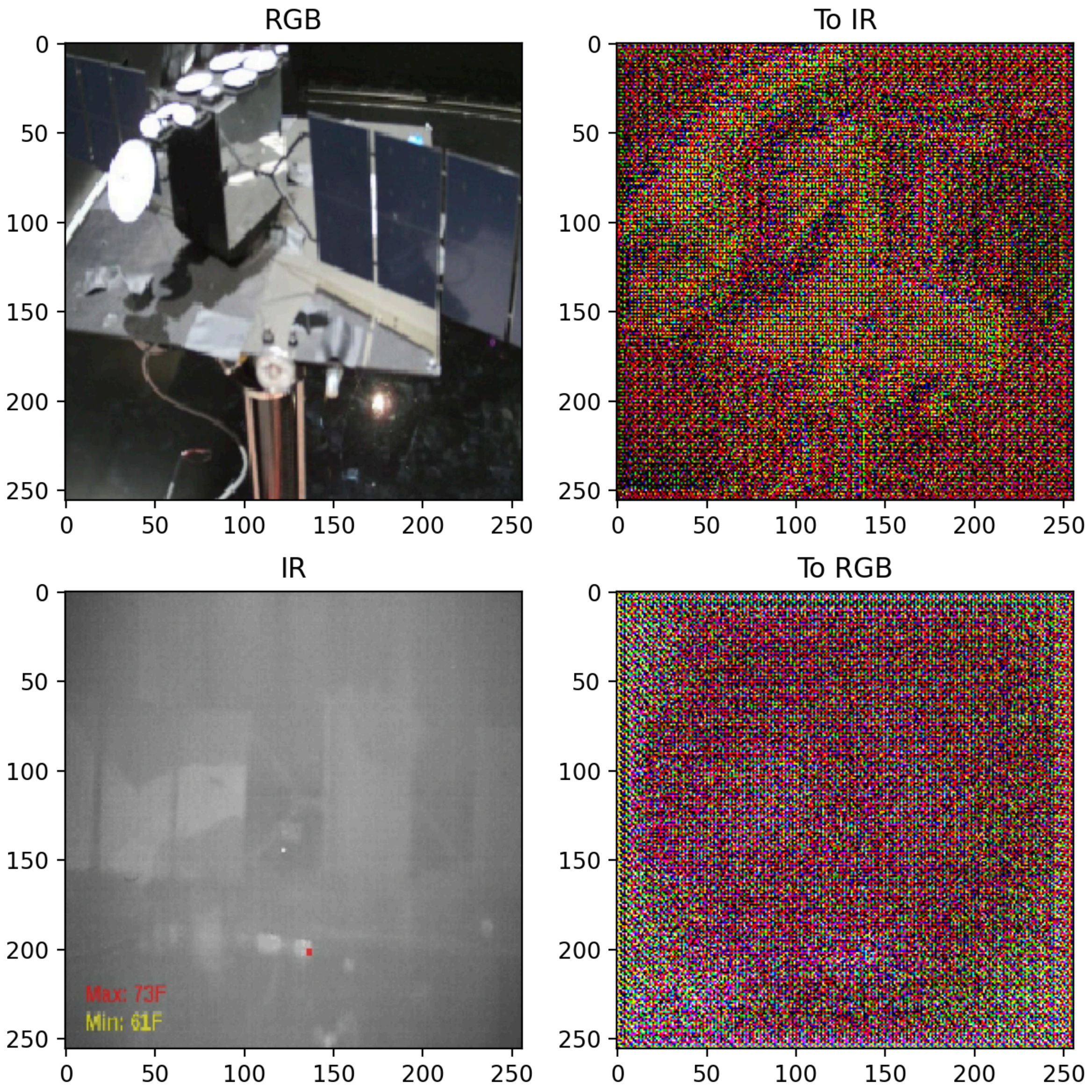
Example RGB image of spacecraft prototype. Image taken in ARCL Lab, but thousands more exist online

cycleGAN



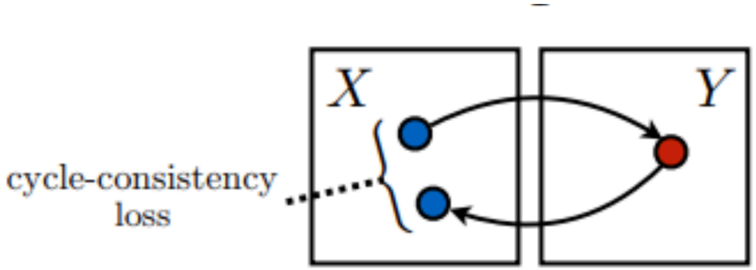
Adapted from J. Y. Zhu et. al

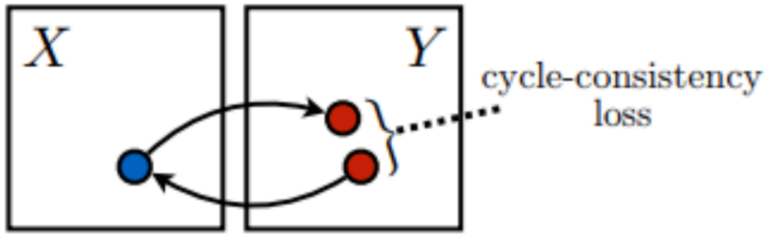
- CycleGAN – neural network that transforms images between domains
  - Horses to zebras
  - Monet to photograph
- Best for our purposes because images are unpaired.
- Began by constructing two objects:
  - Generator G that transforms RGB images to IR images
  - Generator F that transforms IR images to RGB images
- With no restrictions, neither generator can accurately transform images


RGB
To IR
IR
To RGB
Max: 73F
Min: 61F
0
50
100
150
200
250

Tuning cycleGAN

- Impose restraints on generators to accurately transform images between RGB and Infrared
  - Challenge: Data is unpaired, so we cannot compare generated data to a target
- Define two loss functions:
  - **Cycle Consistency Loss**
    - Difference between an image and the image passed through both generators
  - **Identity Loss**
    - Difference between an image and the image passed through opposite generator





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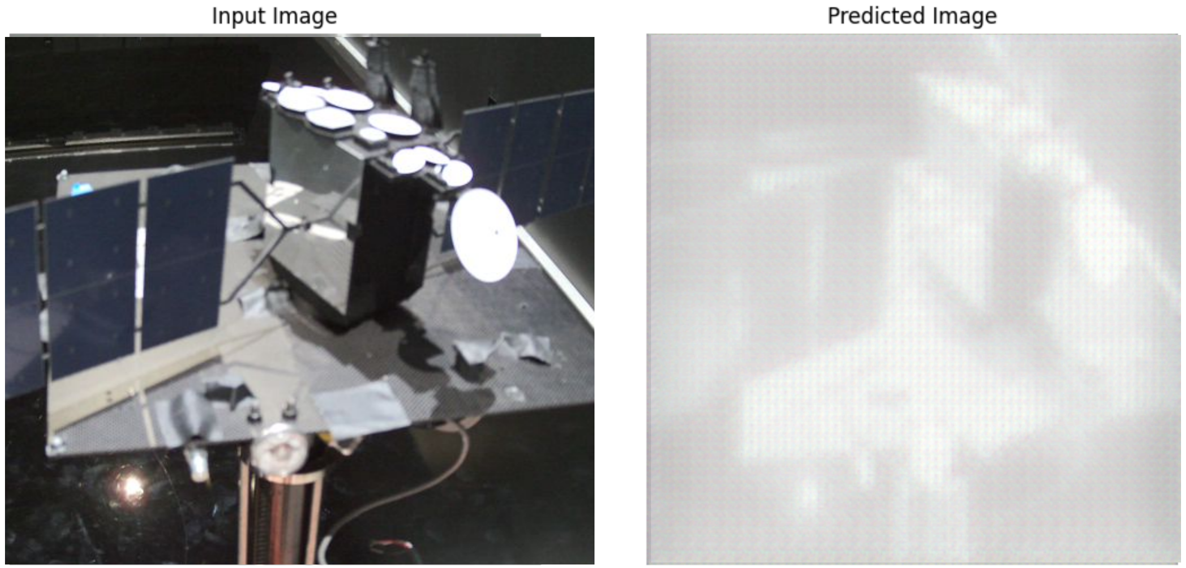
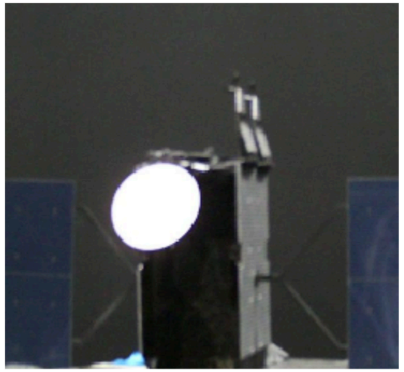
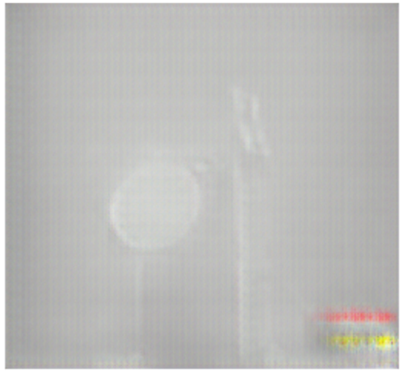
cycleGAN Results:

- Successfully converts RGB Images of satellites to Infrared images
  - Does not merely convert to greyscale
- Began developing a procedure to artificially overlay hot pixels and remove them
  - Hot pixels are removed by replacing the physical photoreceptor
  - We seek a software approach to remove damaged pixels.



Adding Hot Pixels


Original RGB image


Generated IR image


IR image with hotpixels

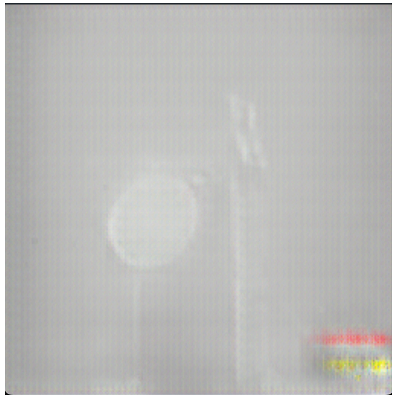
- Pseudo-randomly chose ten sites for each generated infrared image
  - Maximized the pixel intensity at each site
- Artificially added hot pixels.
- Utilized openCV (computer vision) to remove hot pixels.
  - Existing research recommends using median blur
    - Removes critical infrared data
    - Post processing to sharpen image would require too much time and computational energy

Removing Hot Pixels

- Compared median blur to original image
  - Pixels with a greyscale intensity greater than a threshold are flagged as hot pixels
    - Classifies hot pixels with extremely high accuracy
  - Replaces flagged pixel in original image with the grey pixel in the blurred image
    - Only the intensity of hot pixels are changed
  - Original image remains sharp and free from hot pixels

Generated IR image + hot pixels

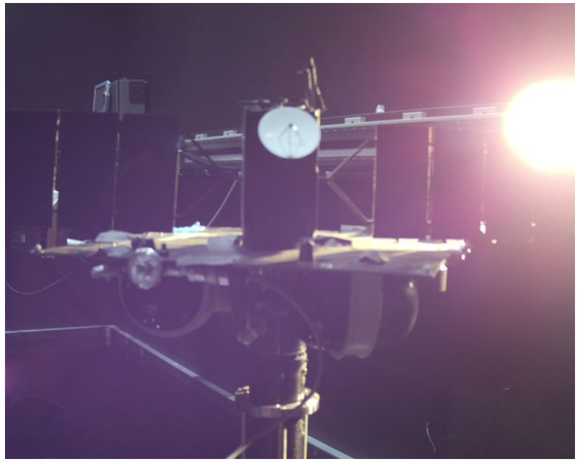
IR image with median blur



IR image using direct comparison

Future Work

1. Expand the algorithm to create a belief state for the detected image
    - Return a probability from [0, 1] that image contains hot pixels
    - Determine the next action that the spacecraft must take to verify the sensor has hot pixels
        - i.e. a different angle with the same camera
    - Resulting 3-tuple: (observation, belief, action) is a POMDP
        - Can be easily integrated into the lab’s existing FDIR algorithm
    - POMDP can be easily integrated into the lab's FDIR framework
2. Experiment with other types of failure modes
    - Solar glare



Example RGB image of spacecraft prototype with artificial solar glare

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Citations

- Zhu, J. Y., Park, T., Isola, P., & Efros, A. A. (2017, March 30). *Unpaired Image-to-Image Translation using Cycle-Consistent Adversarial Networks*. arXiv.org. https://arxiv.org/abs/1703.10593v7
- *A Six Degree-of-Freedom Spacecraft Dynamics Simulator for Formation Control Research - CaltechAUTHORS*. (n.d.). A Six Degree-of-Freedom Spacecraft Dynamics Simulator for Formation Control Research - CaltechAUTHORS. https://authors.library.caltech.edu/88874/