Payload Subsystem

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Introduction, Mission and Requirements:

The following presents the refined payload subsystem for the 3U CubeSat - which is designed to perform the RPO - Rendezvous Proximity Operations in alignment with the competition objectives. It consists of the two camera systems optimized specifically for docking station identification, space debris identification and proximity operations according to the phases defined.

The payload design prioritizes modularity, sensor integration, and reliability in space environments while ensuring compliance with CubeSat standards.

The camera subsystem is optimized for mission objectives, emphasizing high-resolution imaging, real-time processing, and redundancy to support the CubeSat's ability to identify a docking station and space debris.

The distance sensors are integrated to facilitate depth estimation and proximity measurements, improving CubeSat navigation accuracy during docking operations.

The CubeSat must autonomously navigate towards a docking station, identify fiducial markers (AprilTags or QR codes), and execute a docking maneuver while tracking space debris in a simulated low-Earth orbit (LEO) environment. As per competition guidelines, the CubeSat's cameras are ideally used for Phase II and Phase III which have the following objectives:

- Docking Station Identification: Recognize the fiducial markers on the docking plate.
- Space Debris Detection: Identifying and track objects in the mystery room.
- Navigation Assistance: Supporting ADCS for orientation and stabilization.
- Redundancy and Fail-Safe Operations: Preventing mission failure due to single-camera failure.

and the Distance sensors will be required for:

- Proximity measurements: Determining CubeSat distance from docking station and debris.
- Collision avoidance: Enhancing autonomous maneuvering capabilities.
- Depth estimation: Supporting stereo imaging for docking operations.

Camera Payload Strategy - Cameras, Positions and Justification.

The CubeSat's camera payload strategy includes the following cameras:

1. RBPi AI Camera

- Frame Rate: 60 FPS (adjustable for power efficiency)
- Why this is a good camera: Facilitates both object detection and fiducial marker tracking, ensuring high-accuracy docking and debris identification.
- Field of View: 80°
- Resolution: 12 MP
- Power Consumption: ~2W

2. Secondary Camera - Raspberry Pi Camera Module V2 - [STATS] - [3]

- Purpose: Back camera for redundancy and movement stabilization.
- Resolution: 8 MP
- Field of View: 45°
- Frame Rate: 15 FPS at full resolution, 1080p @ 30 FPS, 720p @ 60 FPS, 480p @ 90 FPS.
- Key Feature: Fast shutter speed (1/10,000 sec) for precise capture.
- Power Consumption: ~1.5W
- Powered by: 3.3V/5V lines from PDU

Positioning Strategy and Justification:

To ensure mission success, the CubeSat integrates three cameras strategically placed at different positions: [1]

[Arducam IMX477 HQ] [to be replaced] [Raspberry Pi V2]

To ensure mission success, the CubeSat integrates two cameras strategically placed:

- Primary Camera (RBPi AI Camera): Positioned on the front side, center, tilted 10° ? downward to enhance fiducial marker recognition and docking plate visibility.
- Secondary Camera (RPi V2): Mounted on the back wall~~, tilted 20-30°,~~ providing a fixed perspective that reduces the need for continuous CubeSat reorientation and serves as a redundancy measure.

This strategy follows inspiration from **Sharjah-Sat-1** CubeSat and **MarCO**, which effectively utilized opposing camera placements for mission-critical imaging without excessive spacecraft rotation.

This design, drawing inspiration from the Sharjah-Sat-1 CubeSat's optical system [4], ensures that our CubeSat can autonomously navigate towards a docking station, detect fiducial markers, and execute docking maneuvers while maintaining redundancy and fail-safe imaging capabilities.

Additionally, the camera positioning strategy takes cues from the CubeSat MarCO, which effectively utilized two cameras placed on opposite sides to monitor antenna deployment and spacecraft orientation without requiring excessive rotation. Following a similar approach, the tertiary camera in our design was introduced to passively track docking maneuvers, inspired by MarCO's strategy of placing cameras in opposing positions to verify critical spacecraft functions. This configuration allows the CubeSat to monitor its approach and docking operations in real-time, reducing dependence on constant attitude adjustments, thereby minimizing power consumption while ensuring optimal imaging from multiple angles [1].

[The ideation for position takes inspiration from the CubeSat MarCo]

Camera Utilization across the phases:

Phase II:

- ADCS Pointing & Stabilization Test: The Primary Camera- Tilted ~10° Downward will verify CubeSat orientation and track fiducial markers for initial positioning. The downward tilt ensures fiducial markers are visible earlier, reducing reliance on ADCS corrections.

Phase III:

- Mid-Range Rendezvous: Both the Primary & Secondary Cameras will be used to detect the docking station and confirm CubeSat alignment using fiducial markers. The combination of wide-area and close-up imaging provides redundancy and improved depth perception.
- Proximity Operations: Secondary Camera (RPi V2), due to its high frame rate capabilities, will track the docking plate in real-time, ensuring precise maneuvering. This phase requires rapid data capture for accurate docking adjustments.
- Final Approach & Docking: All three cameras will be utilized:
- Primary Camera: Wide tracking of the docking plate to provide situational awareness.
- Secondary Camera: Close-up verification of alignment, ensuring precise placement.
- Tertiary Camera: Fixed perspective to ensure CubeSat remains stable, reducing the need for unnecessary attitude adjustments.
- Post-Docking Validation: Tertiary Camera will provide a final verification of docking success, capturing a stable, unaltered perspective of the docking interface to confirm secure attachment without the need for CubeSat movement.

Risks:

Risks:

The CubeSat payload subsystem presents several key risks that require mitigation to ensure mission success:

- Radiation Exposure: Camera sensors may degrade over time due to prolonged exposure to space radiation. Mitigation: Use radiation-tolerant shielding and implement periodic sensor recalibration to maintain performance.
- Thermal Variability: Extreme temperature swings in space could impact camera performance. Mitigation: Apply thermal insulation, active temperature regulation, and space-rated materials to ensure consistent operation.
- Data Processing Delays: Large image files could slow down the On-Board Computer (OBC), affecting real-time decision-making. Mitigation: Implement onboard image compression, prioritize essential data processing, and filter non-critical images.
- Mechanical Vibrations: Vibrations during launch may misalign camera components, affecting imaging accuracy. Mitigation: Use vibration-resistant mounting materials and conduct pre-flight vibration tests to ensure stability.
- Power Constraints: Continuous operation of multiple cameras may strain the CubeSat's power budget. Mitigation: Optimize camera usage schedules, implement low-power standby modes, and ensure power-efficient data handling.
- Field of View Obstructions: Components or unexpected space debris may obstruct camera views. Mitigation: Utilize multi-camera redundancy and strategic positioning to maintain visibility from different angles.
- Communication Latency: Delays in relaying captured images to the ground station could affect decision-making. Mitigation: Prioritize onboard autonomous image processing and store critical image data for transmission during optimal communication windows.

Changes from previous submission- Preliminary Design Review:

- Camera Selection Updated: Initially considered lower-resolution sensors -> upgraded to IMX477 HQ and RPi V2 for superior imaging.
- Improved Camera Placement: Adjusted angles (Primary at 10° down, Secondary at 20-30°) for optimal fiducial tracking.
- Stereo Imaging Integration: Using Secondary camera's angle to assist in depth estimation for docking.
- Processing Optimization: Prioritized image filtering and data handling improvements to avoid excessive bandwidth usage.

These changes ensure that the payload subsystem is better suited for RPO tasks while minimizing risks and improving CubeSat efficiency.

Connections to other systems and external systems:

The camera subsystem in the 3U CubeSat for Rendezvous Proximity Operations (RPO) must be integrated with various onboard systems to ensure real-time imaging, data processing, and autonomous navigation.

- On-Board Computer (OBC): Processes image data and runs detection algorithms.
  - Primary Camera - Interface: MIPI CSI-2 (2-Lane/4-Lane)
  - Secondary Camera - MIPI CSI-2 (2-Lane)
  - Tertiary Camera -MIPI CSI-2 (2-Lane) otherwise USB-to-MIPI CSI-2 Bridge
  - MIPI CSI-2 Multiplexer : Can be used to connect all three at once; only two would be active at a time - Ideally Secondary + Tertiary
  - FPGA-based CSI-2 bridge: FPGA acts as a camera controller -> merges data streams -> OBC reads from a single CSI-2 input - Requires more power and data
- Attitude Determination & Control System (ADCS):
  - Uses camera data for orientation and stabilization.
  - Cameras send position data to OBC → OBC processes fiducial location → ADCS receives correction inputs.
- Communication System: [redacted]
  - Transmits images and processed data to the ground station.
  - Critical docking images are compressed and transmitted
- Power Distribution Unit (PDU):
  - Provides power to cameras efficiently
  - Primary Camera ~ 2W and Secondary Cameras ~1.5W each

Coordinate Systems and Positions: [IGNORE for now, part of research]

To ensure accurate camera positioning and depth estimation, the CubeSat system follows well-defined coordinate systems:

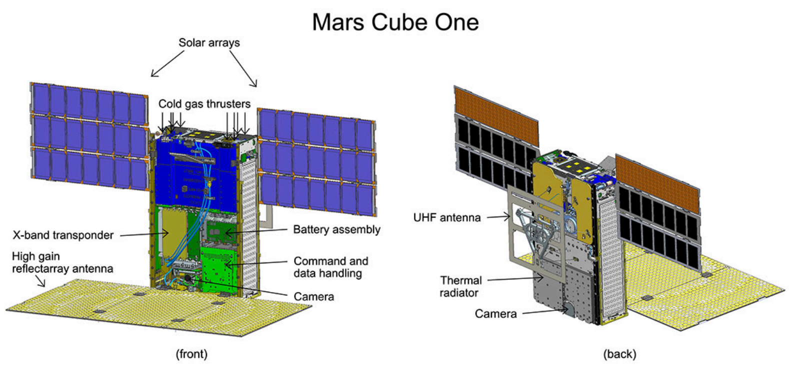
1. Body-Fixed Coordinate System (FCS): Aligned with the CubeSat's structure, where the X-axis aligns with the CubeSat's forward-facing direction.
2. Instrumental Coordinate System (ICS): Defined for each camera, where the X-axis follows the optical axis of the camera.
3. Photo Coordinate System (PCS): Defines the image reference frame with u (horizontal) and v (vertical) axes.

Each camera is positioned based on these coordinate systems to optimize tracking efficiency:

- Primary Camera (HQ Clone, Tilted 10° Downward): Positioned along the CubeSat's FCS X-axis to track the docking station.
- Secondary Camera (RPi V2, 20-30° Tilt): Placed at an angle to allow stereo-based depth estimation.
- Tertiary Camera (RPi V2, Fixed Perspective): Mounted perpendicular to the primary camera to provide a stable, passive tracking reference.

These defined coordinate systems enhance depth estimation, improve fiducial marker tracking, and minimize CubeSat rotation, aligning with stereo imaging best practices for space applications.

<u>References:</u>



[1] : “Significant development work occurred that identified the major contributions in the project including selection of the right cameras for wide angle and narrow angle observation, the right computer interface to perform timely autonomous detection of the meteor events, inaddition to development of meteor detection algorithms: https://arxiv.org/pdf/1809.02042:

- https://www.arducam.com/product/b0242-arducam-imx477-hq-camera/ [2]
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