AAE 450/490
TracSat Design Project

Critical Design Review

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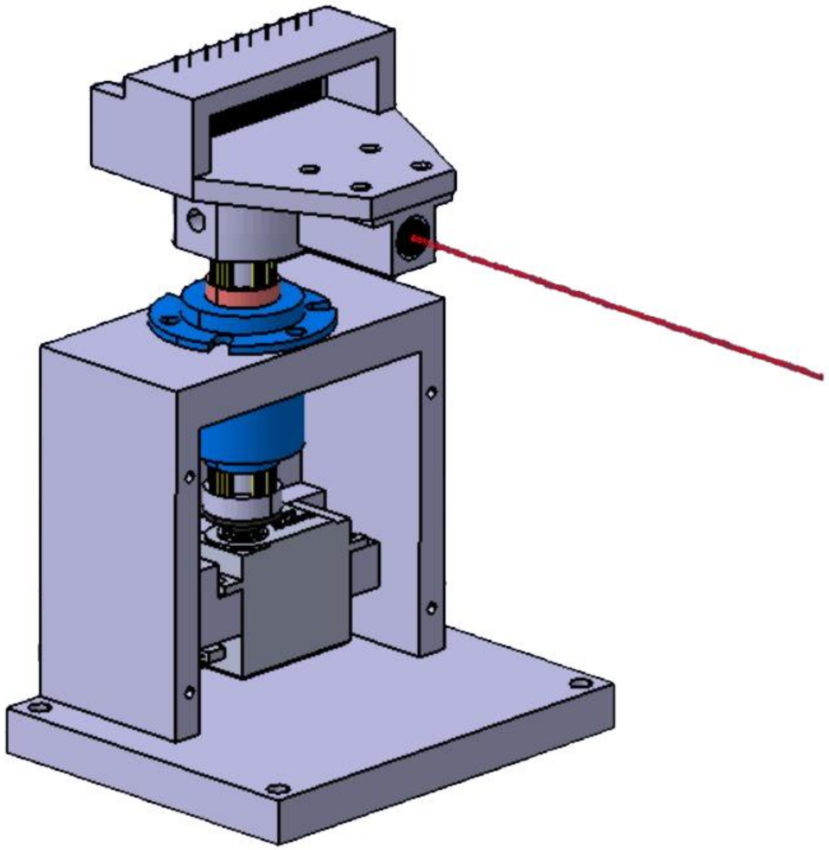

Funded by: General Atomics

Team Members:
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Agenda

- Project Overview
- Laser Link System
- Electronics
- Laser Tracking System
- Hardware and Propulsion
- Questions

Project Overview

- Mission Objectives and Requirements
- Mission Success Criteria
- Timeline

Mission Objectives and Requirements

Mission Objectives	
MO 1	Develop a “levitation base” for CubeSat testing and demonstration.
MO 2	Develop CubeSat capable of translational movement.
MO 3	Demonstrate transmission of video between a CubeSat and Ground Station via a 50 kHz tracking laser communication.
MO 4	Maintain communication between CubeSat and Ground Station during movement

System Requirements

System Requirements	
SR 1	LLS must track and maintain link with CubeSat at velocity up to 10cm/s
SR 2	LLS must be able to re-establish link if lost.
SR 3	LLS must be able to transmit data at rate of at least 50kHz
SR 4	PLS air bearings must be able to maintain levitation with less than: 5 degrees of rotational drift and 5cm of translational drift, after 30s of operation
SR 5	PLS thrusters must be able to produce purely translational movement with less than: 10 degrees of rotational drift and 10cm of translational drift, after 8ft.

Mission Success Criteria

Criteria	MIN	FULL
LTS Connection	System must maintain laser link in all directions	N/A
LLS Connection	System must be able to re-establish link if lost.	System must be able to re-establish link if lost within 5 seconds
Data Transfer	System must be able to transmit data at rate of at least 50kHz	System is capable of supporting 240p video at 10 frames/ second
Stationary Operation	5 degrees of rotational drift and 5cm of translational drift, after 30s of operation	5 degrees of rotational drift and 5cm of translational drift, after 45s of operation
Translational Operation	10 degrees of rotational drift and 10cm of translational drift, after 8ft.	5 degrees of rotational drift and 5cm of translational drift, after 8ft.

Timeline

- Major components ordered
- All systems mapped out

Jan '20

- All major components manufactured and assembled
- Initial integration of subsystems
- Begin full integrated testing

Feb '20

Mar '20

Apr '20

- Complete final designs of all systems
- Complete full integration of all systems
- Final testing

Laser Link System

- Background
- Hardware Options
- LLS Architecture
- Auxiliary Software

Purpose & Requirements

Purpose

The purpose of the Laser Link System is to provide a controller, user interface, and system architecture to transmit various telemetry between the CubeSat and Ground Station.

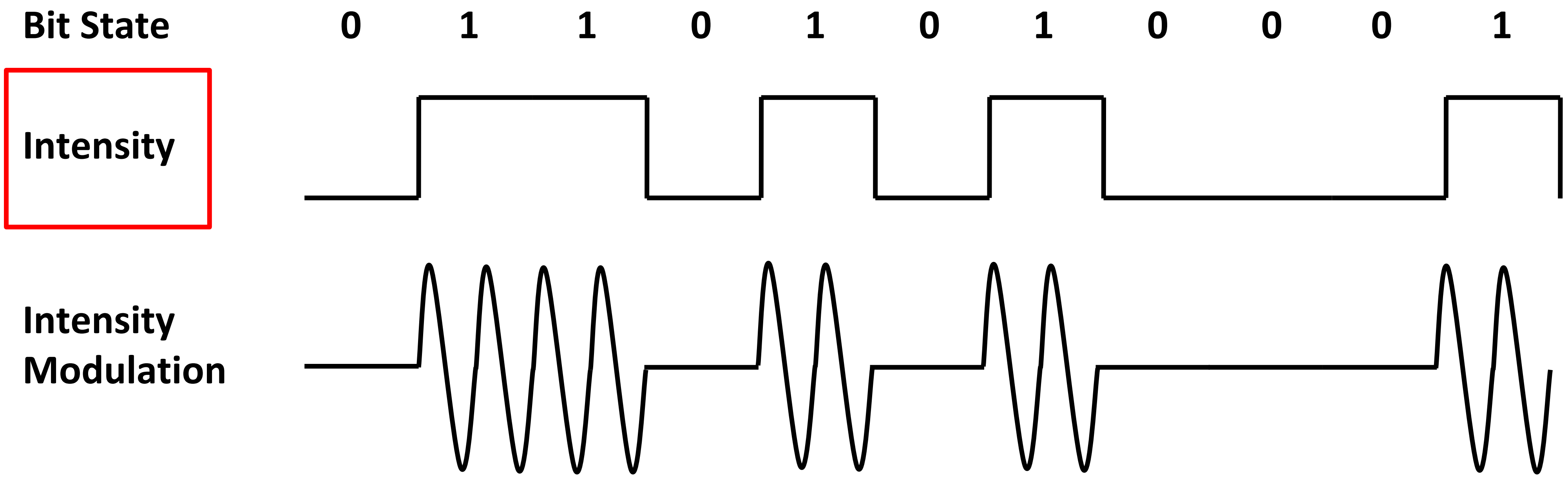
Requirements

- LLS shall provide uninterrupted uplink and downlink communication throughout the movement of the CubeSat
- LLS shall be transmit the data at the rate no less than 50 kHz
- LLS shall transmit live video during downlink

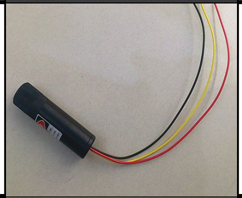
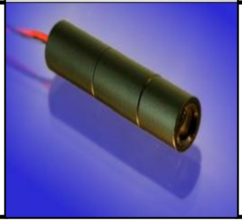
Laser Theoretical Background

Transistor-Transistor Logic (TTL)

- TTL is a particular kind of laser modulation that only allows for on/off laser states
- On/Off states allow us to encode 1/0 bits which represent information packets
    - If the system detects the laser in the "on state", it will read the value as a "1"



Laser Options

Company	Image	Max TTL Frequency	Supply Voltage	Power	Wavelength	Price	Notes
Adafruit *(US)*		50 kHz	5±0.2 V DC	5 mW	650 nm	$18.95	Meets temporary frequency requirement of 50 kHz
Civil Laser *(China)*		1 MHz	3-5 V DC	5-90 mW	650 nm	$49.00	Production and shipping is limited due to coronavirus outbreak
Roithner Lasertechnik *(Austria)*		1 MHz	3-5 V DC	5 mW	635 nm	$66.47	Currently out of stock (minimum 50 piece order)
Frankfurt Laser Company *(Germany)*		1 MHz	5±0.5 V DC	1-50 mW	630-960 nm	$655.00	Expensive, but has many technical specifications up to consumer choice

* All lasers have focusable lenses which is necessary for the LTS system

** Yellow wire seen in first three lasers is specifically used for modulation

Current Laser

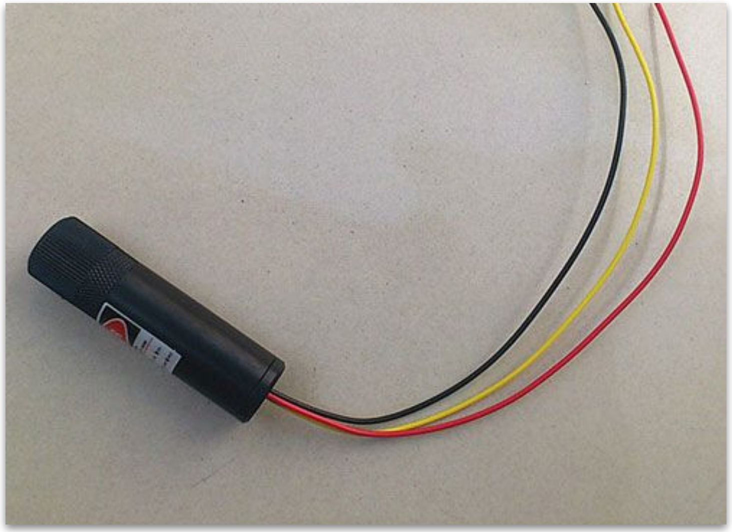
Adafruit TTL Laser Diode

- The laser has the following performance parameters:
  - Max TTL frequency: 50KHz
  - Price: $19
- Useful as a temporary laser to test preliminary data transfer with updated microcontroller.
- Similar dimensions to original laser, so previous structural mechanisms have not changed

Future Laser

Civil Laser TTL Laser Diode

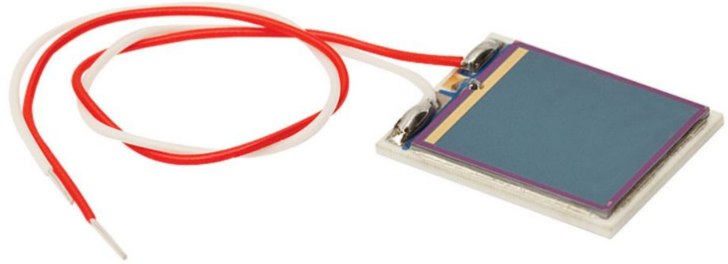
- For future semesters, to attain long-term goal of 1 MHz transmission frequency, we will look to purchase from Civil Laser
  - Max TTL frequency: 1 MHz
  - Price: $49
- Currently not available because of export regulations, but it will obtain an ideal transmission rate for a reasonable price
- Has similar physical and structural design to Adafruit laser, so it will be simple to update the LLS/LTS system



Detector

ThorLabs FDS1010 Photodiode

- Requirement: Rise Time must match or exceed frequency at which laser operates
- The photodiode has the following performance parameters:
  - Responsivity: 0.725 A/W
  - Active Area: 100mm^2
  - Rise/Fall Time: 65 ns
  - Wavelength: 350 - 1100 nm
- Five photodiodes will be included in detector array on Ground Station and CubeSat as a part of the LTS system



System Architecture

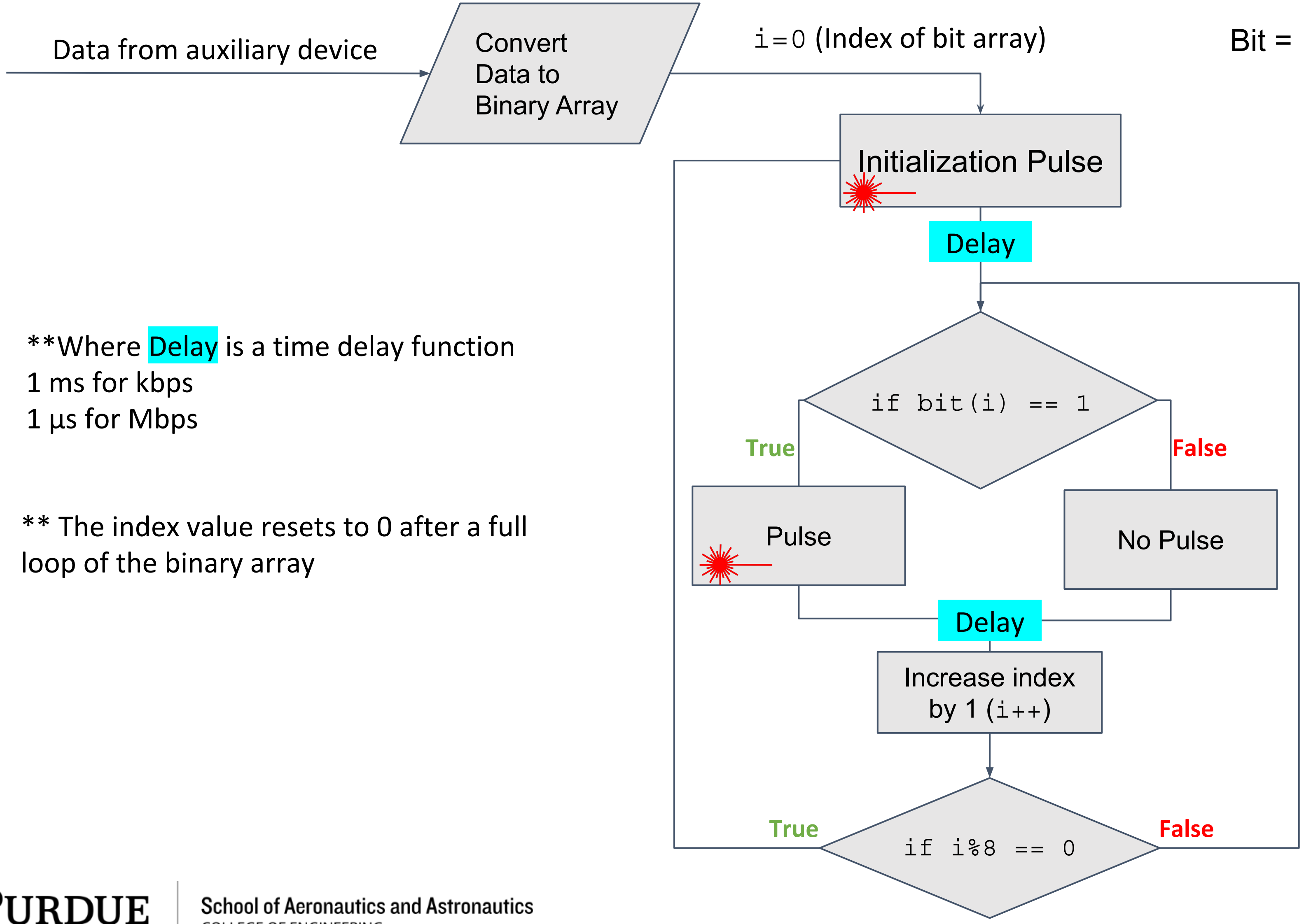
Important System Requirements:

- Convert data into binary and transmit as pulses through laser (using TTL).
    - Must be efficient and fast — data will often be streamed in real-time.
    - Conversion must occur in phases due to limited storage space for data/bit arrays
- Receive data with minimal loss and convert back to original data.
    - Similar metrics to previous conversion

Error Mitigation:

- Phase shift due to in-program delays:
    - Mitigated by newer algorithm deployed last semester. Required laser/receiver to remain in phase for only 8 bits. Then reset.
    - **Initialization Pulse** removed all phase shift issues.
- Inaccurate delay function from board. Will alter data irreparably.

System Architecture (Laser)

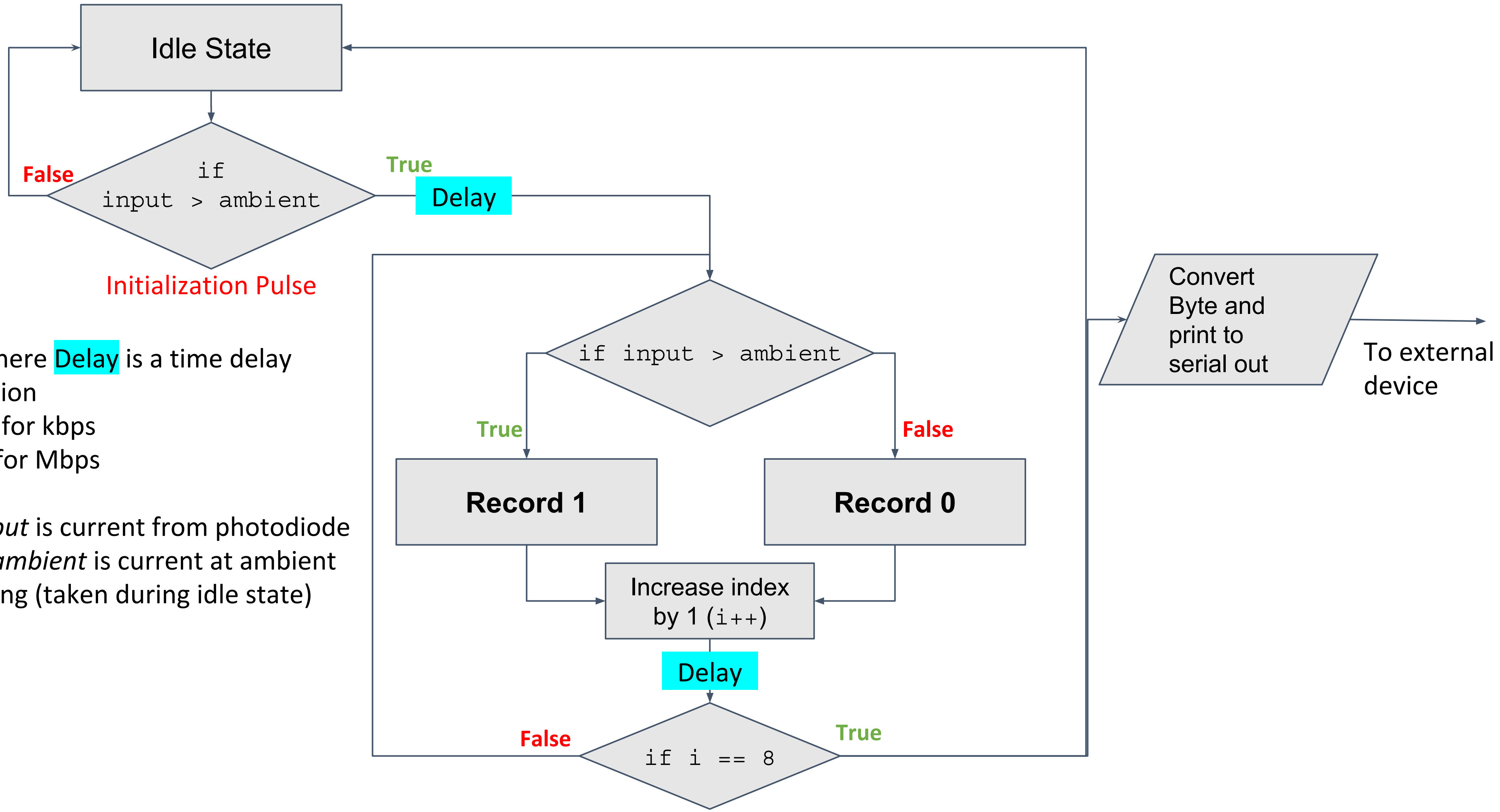


Bit = [01001010|11101010|10010101|00101010…]

**Where Delay is a time delay function
1 ms for kbps
1 µs for Mbps

** The index value resets to 0 after a full loop of the binary array

System Architecture (Receiver)



**Where Delay is a time delay function
1 ms for kbps
1 µs for Mbps

***input* is current from photodiode and *ambient* is current at ambient reading (taken during idle state)

Telemetry

Level of Complexity	Telemetry Contents	Data Rate Required	Additional Challenges
1	Basic test information (sentence, simple bit string)	< 1 kbps	N/A
2	Commands to CubeSat (translate, stop, send specific data)	~1 kbps	Requires developed Ground Station user interface
3	CubeSat state information (translation speed, rotation rate, power levels, etc.)	~100 kbps	CubeSat must be integrated with primary avionics sending information to LLS
4	Video from CubeSat at varying levels of quality (grayscale → compressed → 480p → 1080p)	> 1 Mbps	Requires little-to-no packet loss and very high data rates.

Ground Station & Auxiliary Software

LLS System Integration

- The laser system must obtain data from external sources (Camera, IMU, GUI)
- After transmission, the data must be processed and utilized. (Performing commands, plotting IMU data, displaying video…)
- Communication to/from PYNQ through serial connection.
- Python library from last semester will be repurposed to communicate with board.

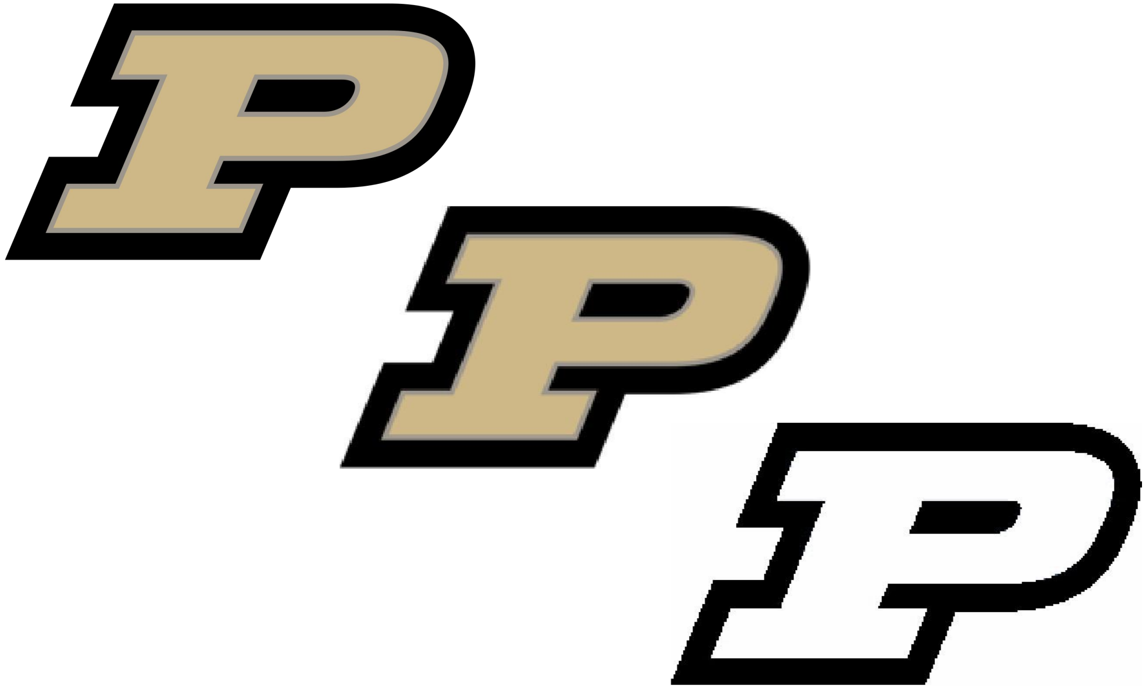
```
sendData(data)
data = receiveData()
reset()
```

Ground Station & Auxiliary Software (cont.)

Video Transmission

- Begin by picture transmission. Send array of bits, then rebuild when received.
- Improve system speed and efficiency to allow for 24 frames per second.
- "Ultra-compressed" black and white images have highest efficiency. Good for initial testing. (1 -> black, 0 -> white)

Type of Image	Size of Pixel Matrix (bits)	Transmission time at 1 Mbit/s rate	Data Rate Required for 15 fps
Uncompressed High Quality Image	18,864,000	18.86 seconds	282.9 MHz
Compressed Low Quality Image	754,560	0.75 seconds	11.25 MHz
Ultra- Compressed Black and White	94,320	0.094 seconds	1.41 MHz

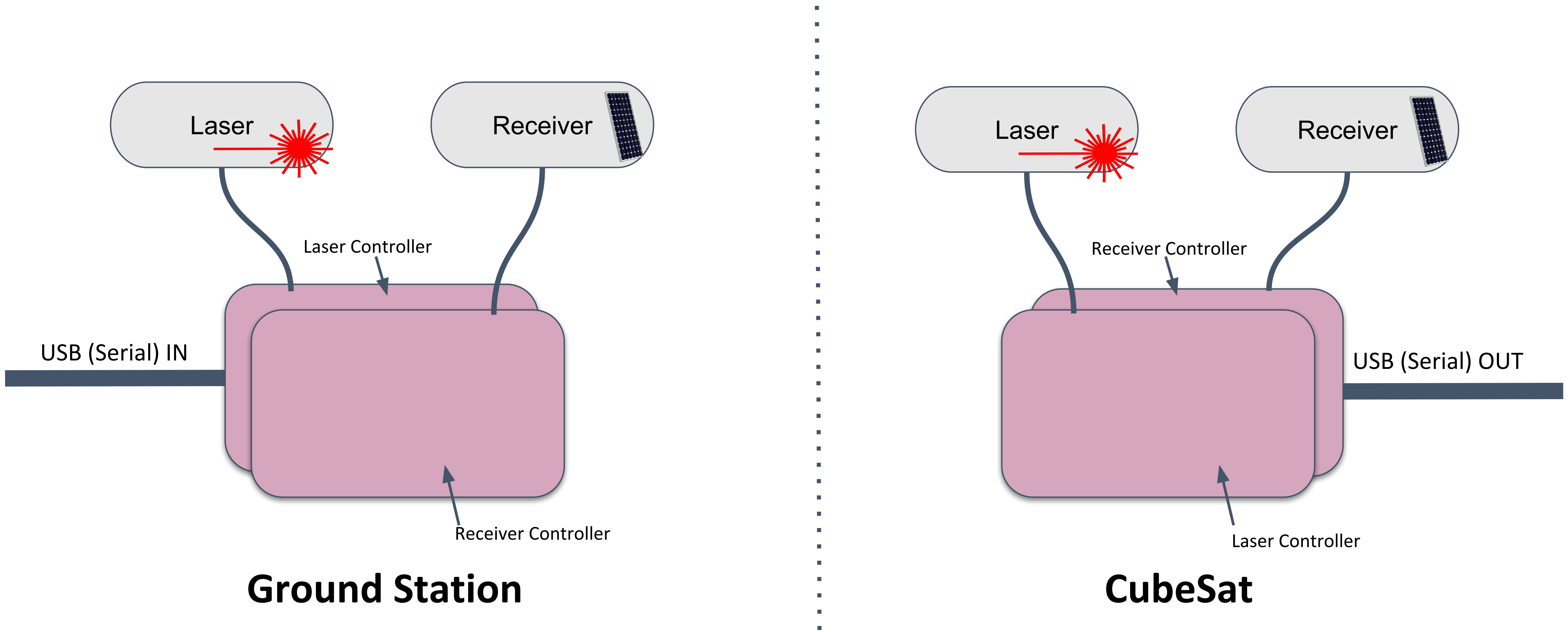


Black and White Compressed Image

Colored and Compressed Image

Colored and Full Quality Image

Full LLS System Diagram



Note: LLS system uses separate and unique boards not connected to the LTS system

Electronics

- Microcontroller
- PCB/Power
- Solenoids

Microcontroller

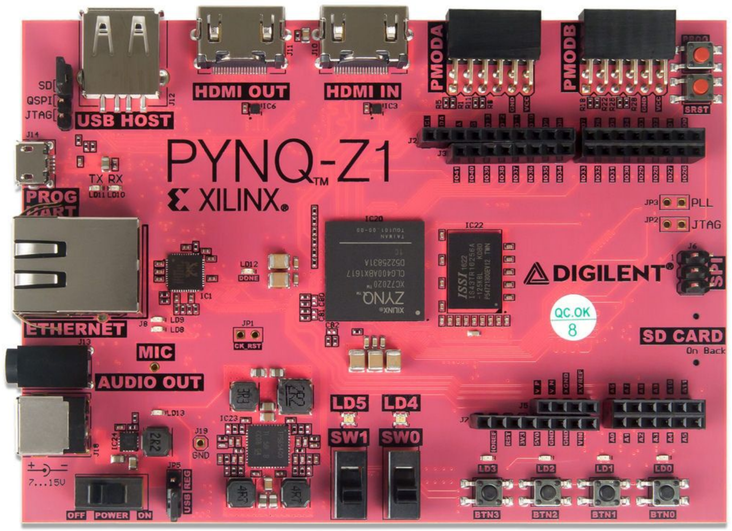
Digilent PYNQ-Z1

Requirements:

- 1 MHz digital input/output speed
- Fit the form factor of the CubeSat
- Programmable with either Python or C/C++
- As many I/O pins as Arduino/Raspberry Pi
- 12 V power to satisfy power budget

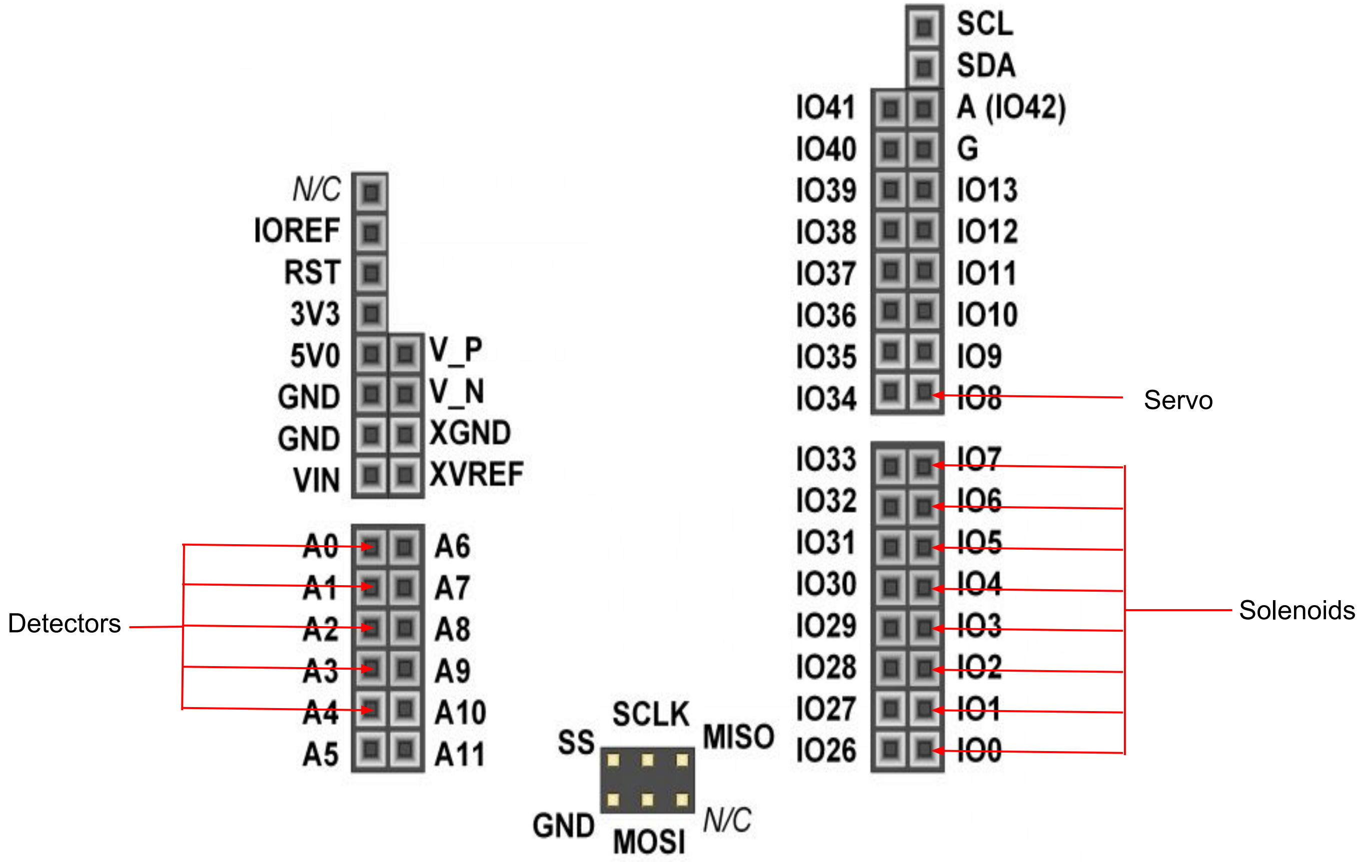
Capabilities/Features:

- 8 high-frequency IO PMOD ports
- High frequency Arduino Shield
- Variable power range (7-15 v)

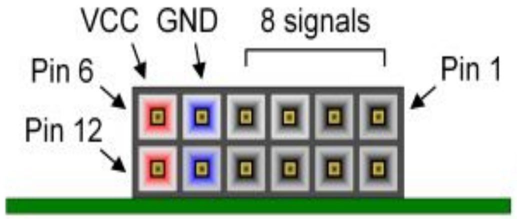


Pin Overview

Satellite I/O

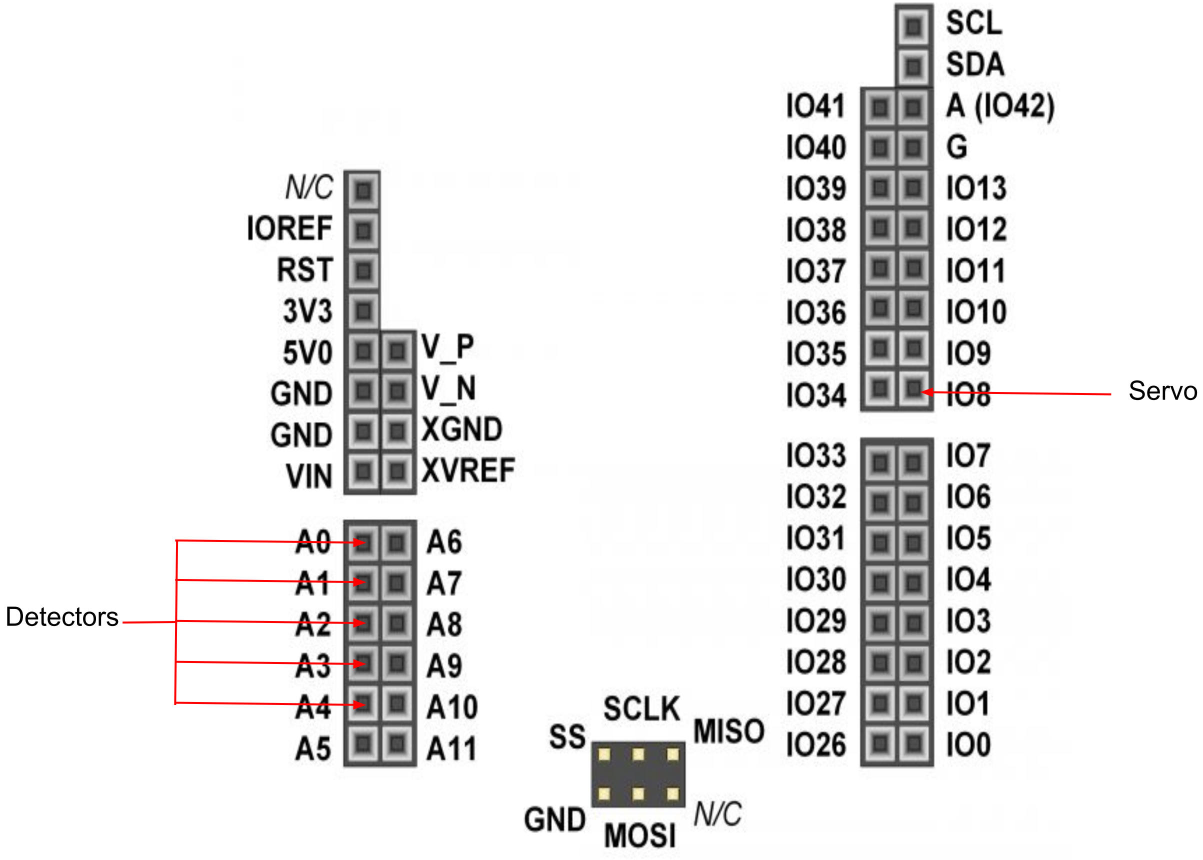


- PMOD will be dedicated to laser I/O with power being supplied from board through VCC/Ground connectors on PMOD
  - Laser is considered a peripheral in this system

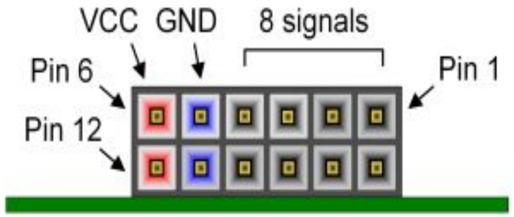


Pin Overview (cont.)

Ground Station I/O



- Capability for external microcontroller to interface with ground station to decode and display video



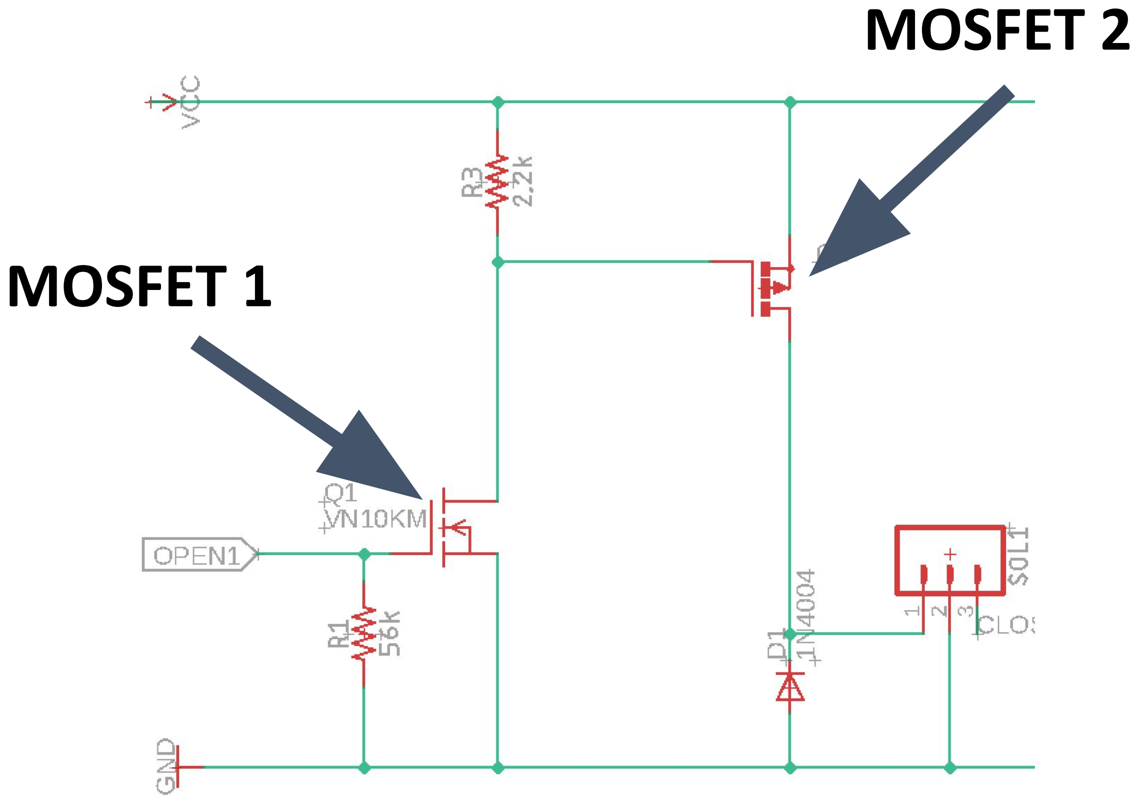
PCB

Requirements:
- Supply power to microcontroller, servo motor, and solenoids
- Allow microcontroller to interface with solenoids to open and close as needed
- Fit CubeSat form factor

MOSFET 1: On Characteristics	
Minimum	Maximum
0.8 V	3.0 V

MOSFET 2: On Characteristics	
Minimum	Maximum
-2.0 V	-4.0 V

Circuit Design Features:
- Uses 1 N-Channel and 1 P-Channel MOSFET
- Accommodates wide array of microcontrollers



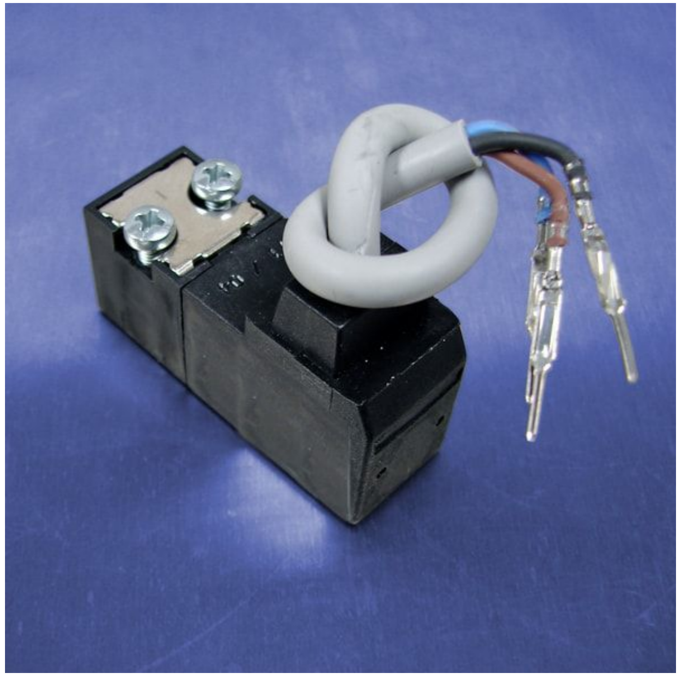
Solenoids

Requirements:

- Easily actuate between open and close
- Compact form factor
- Minimal impact on power budget
- Operate in range of voltages supplied by battery

Selected Component:

- Pneumadyne 2 Way Magnetically Latching Solenoid

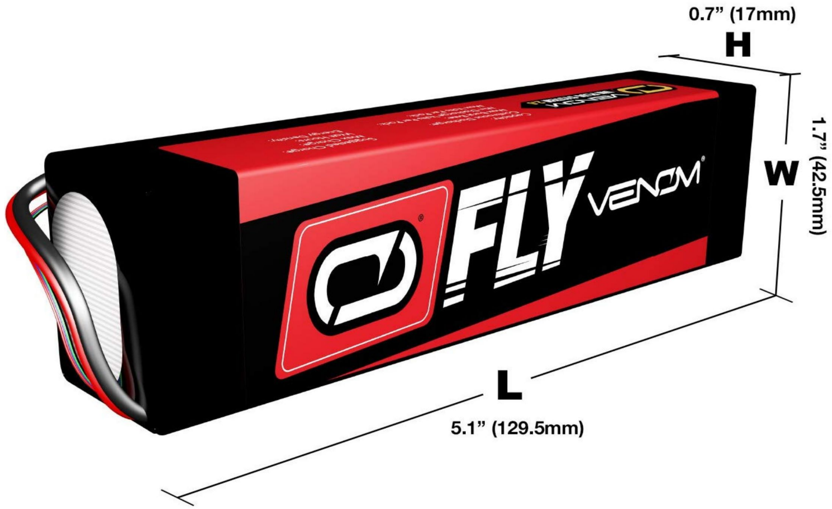


Power	Voltage	Voltage Tolerance	Response Time
4 W	12 V	-5% , +10%	10 - 12 ms

Power Budget and Battery

Requirements:
- Give preliminary estimate of power needs for our system

Selected Component:
- 11.1 V 3 Cell LiPo Drone Battery 3200 mAh
- When fully charged, operates at 12.6 V and steadily decreasing from there towards nominal voltage



Normal Power Use Case (40 Minute Operating Time)						
Item	Amps (Amp)	Voltage (V)	Power (W)	Duty Cycle	Watt-hours	mAh
Microcontroller	0.8	12	9.6	1.0	6.4	533.33
Solenoid (x4)	0.3333	12	4.0	0.022	0.00977	0.814
Servo Motor	0.25	5	1.3	1.0	0.13889	27.78
					Total:	**561.925**

Worst Power Use Case (40 Minute Operating Time)						
Item	Amps (Amp)	Voltage (V)	Power (W)	Duty Cycle	Watt-hours	mAh
Microcontroller	2.5	12	30.0	1.0	20	1666.66
Solenoid (x4)	0.3333	12	4.0	0.220	0.293	24.444
Servo Motor	0.8	5	4.0	1.0	0.444	88.89
					Total:	**1691.11**

Laser Tracking System

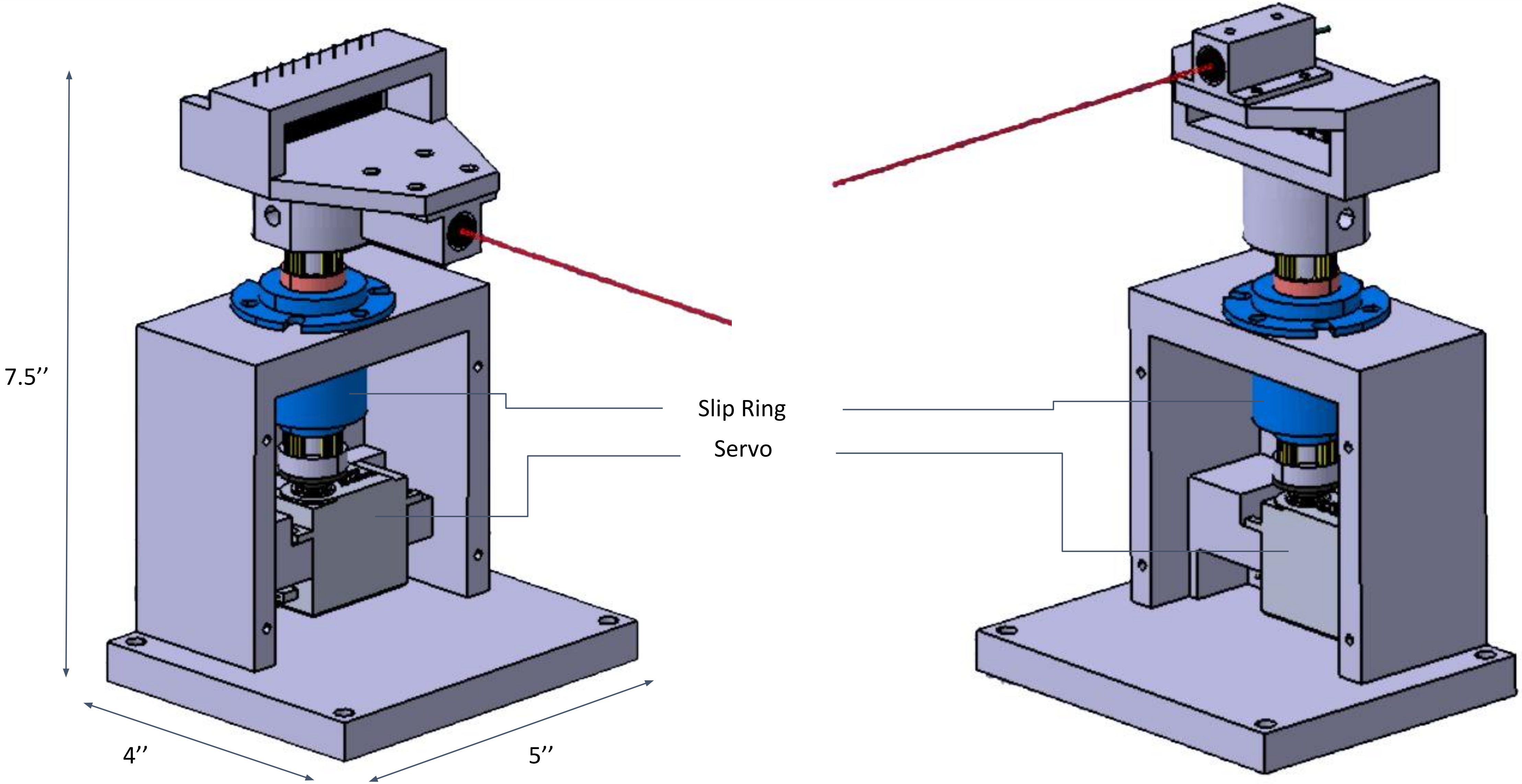
- Topic 1
- Topic 2
- Topic 3

Requirements

The Laser Tracking System has the following requirements

- The LTS must be able to establish, maintain, and re-establish laser contact between the ground station and CubeSat
- LTS must have motor capable of rotating the LLS at a acceptable speed
- LTS will use the microcontroller selected by the team
- The LTS will be tested before TRR using the testbed purchased last semester

Schematic

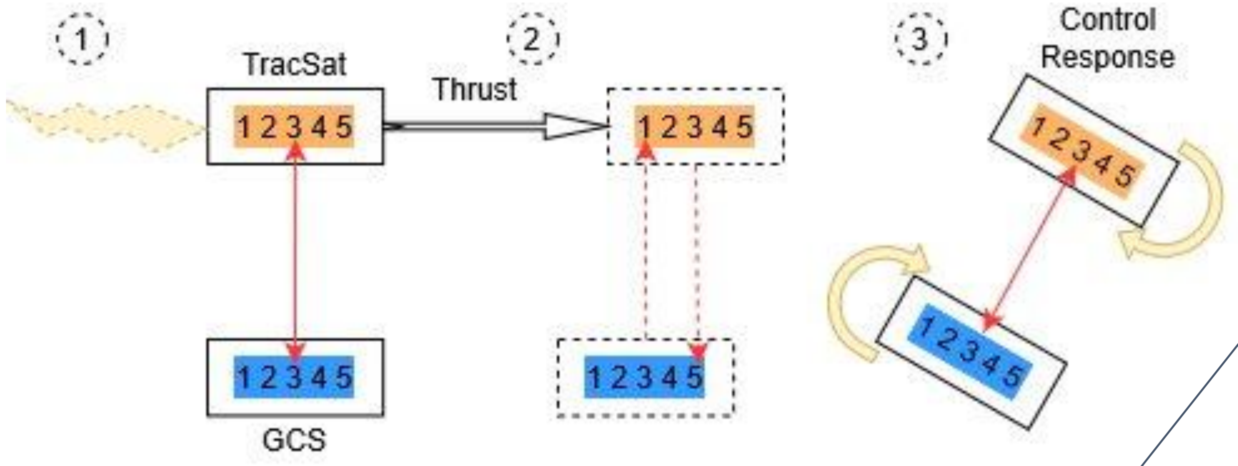


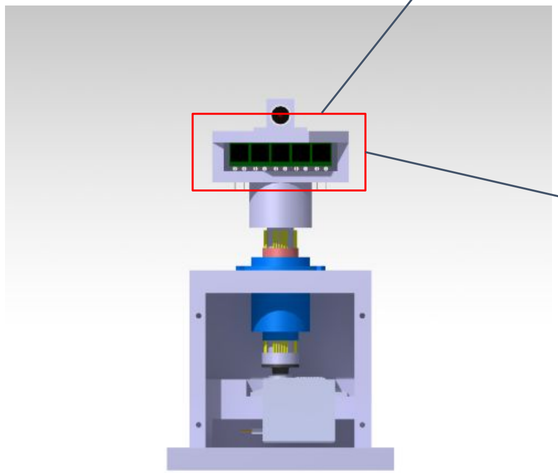
Motor

AR-3606HB Continuous Rotation Servo

- The motor has the following performance parameters:
  - 6.7 kg-cm of torque
  - 71 RPM with no load
  - 4.8V minimum voltage
- Specifications: 4.05 x 2 x 3.8 cm
- CR servo allows for precise speed control with 360 degrees of rotation

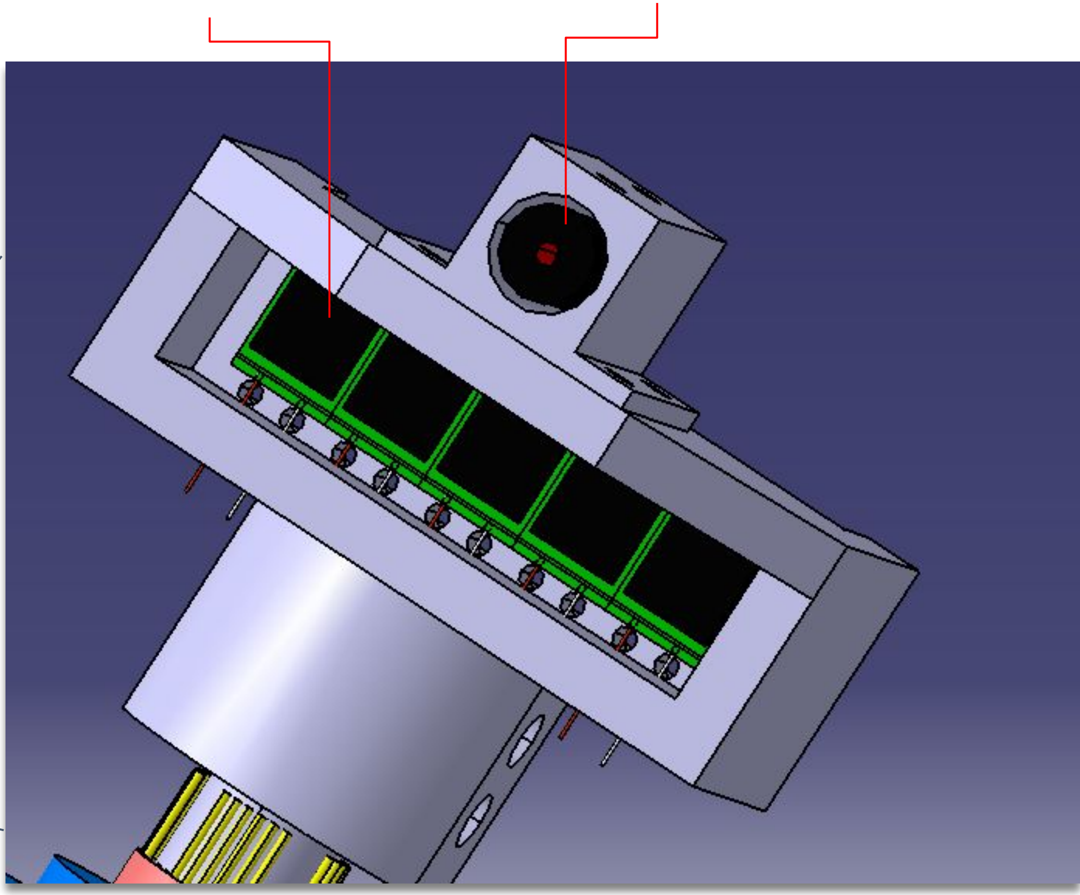
Detector Array Set-Up





Photodiode Sensors

Laser

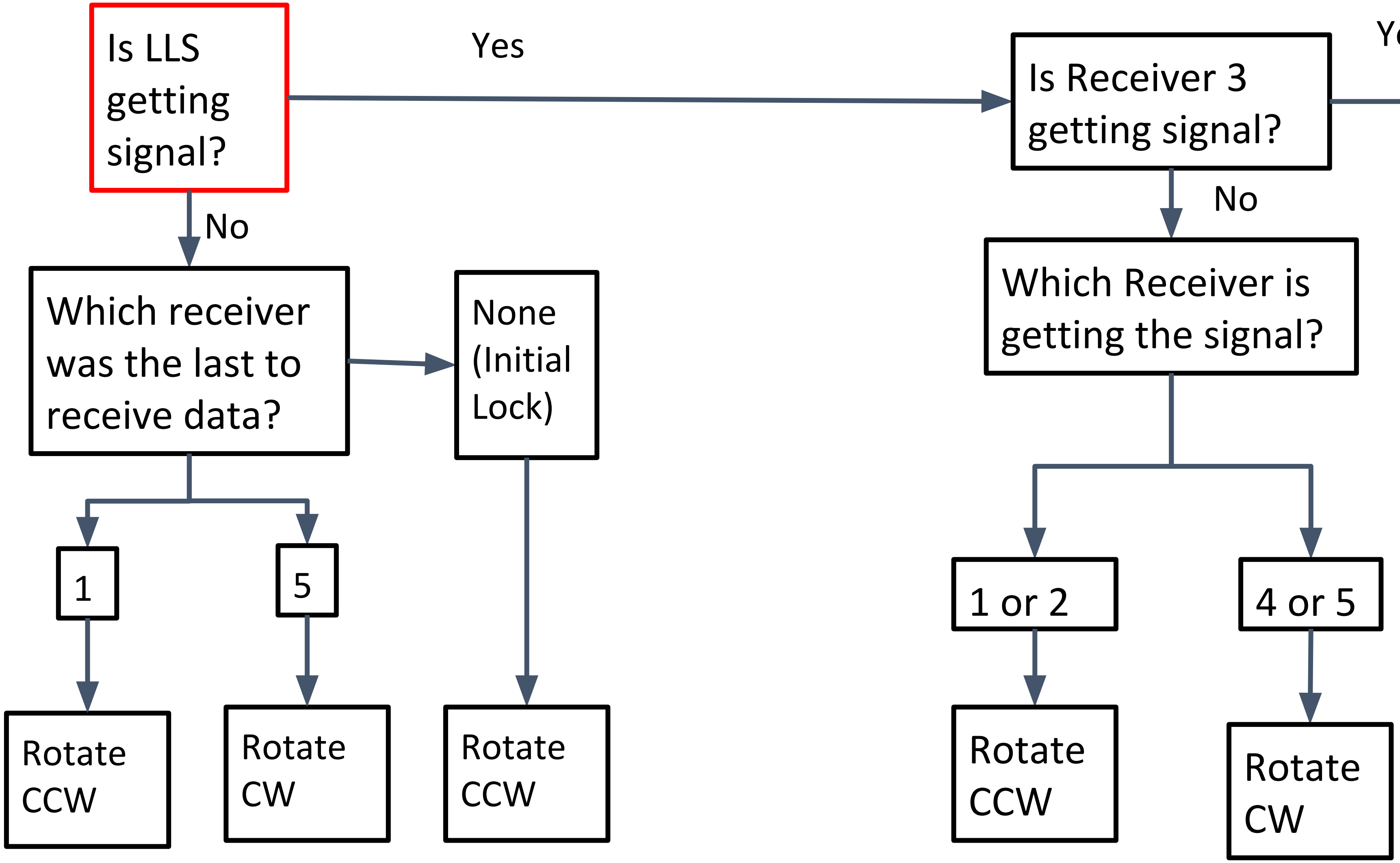


LTS Control Software

LTS Control System is designed to rotate the receivers and laser diode to keep it in constant contact with the Ground Station.

- Control System operates with on-off logic
  - ‘On’: Laser is hitting center laser receiver
    - No Movement
  - ‘Off’: Laser is not hitting center receiver
    - Either hitting an off-center receiver or no signal
    - LTS rotates to get back to center receiver

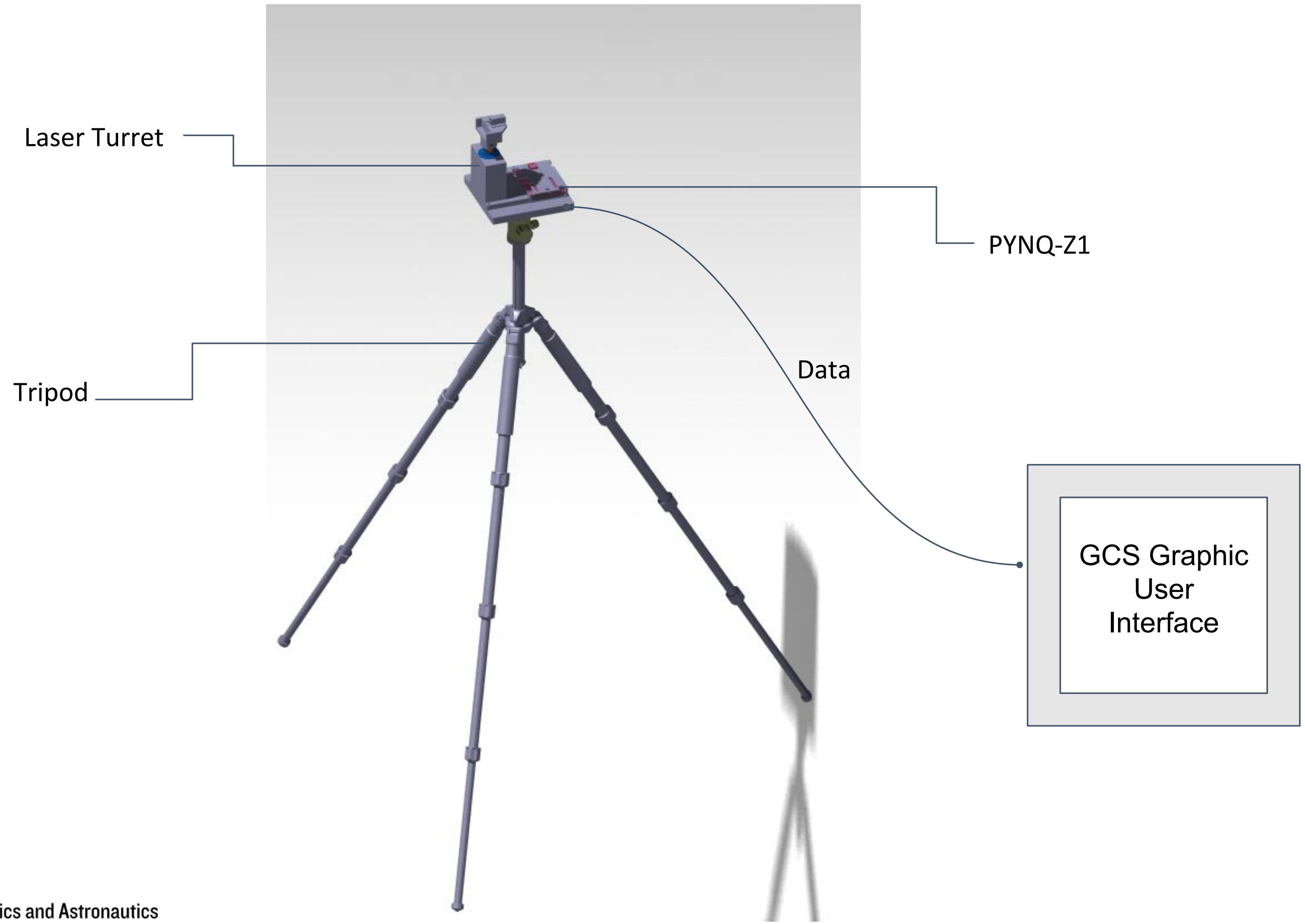
Control Schematic: CubeSat



Notes:

- Ground Station has same algorithm with reversed directions
- Logic needs odd number of receivers

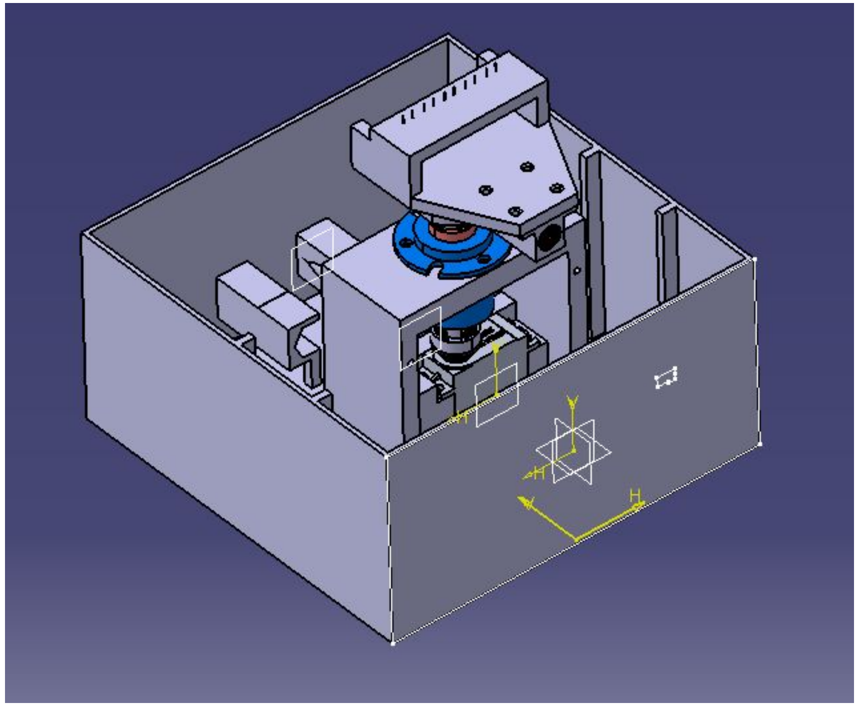
Ground Control Station

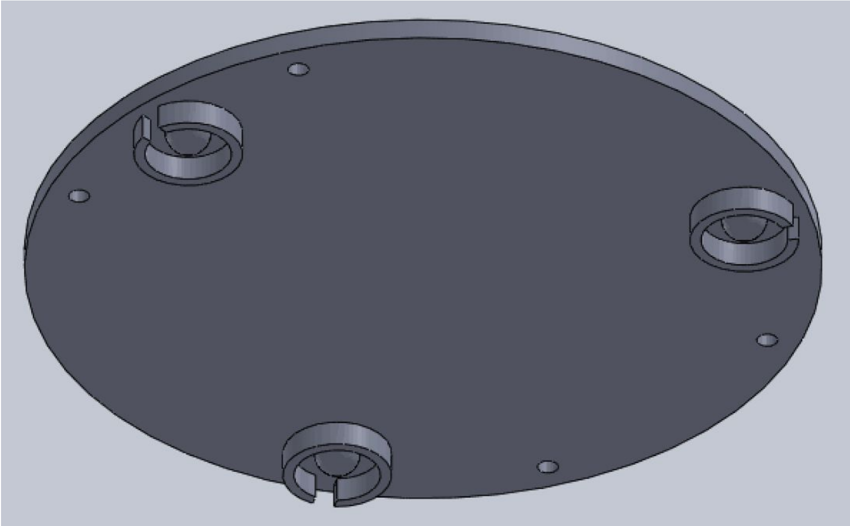


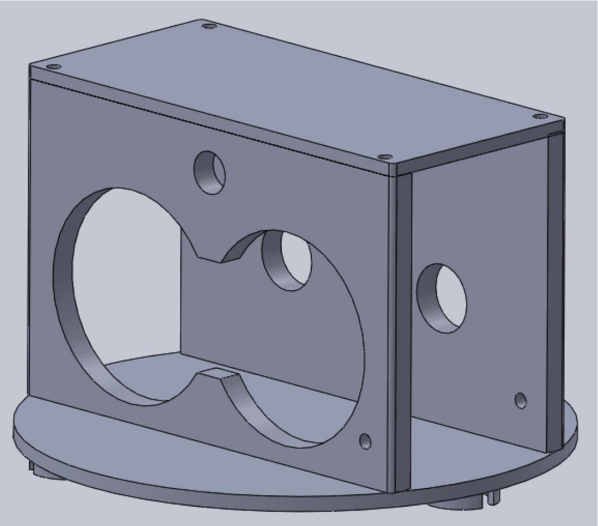
Hardware and Propulsion

- CubeSat and Base Models
- Final Components
- The Drift Problem
- Experimental Results

CubeSat and Base Models

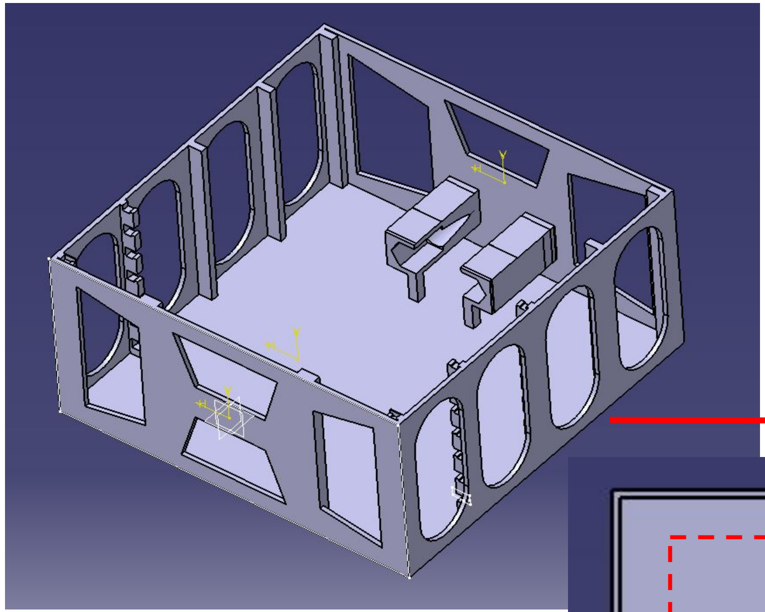


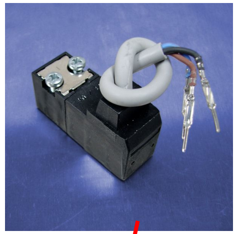


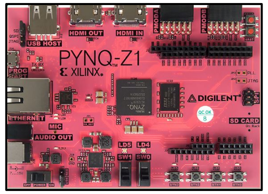


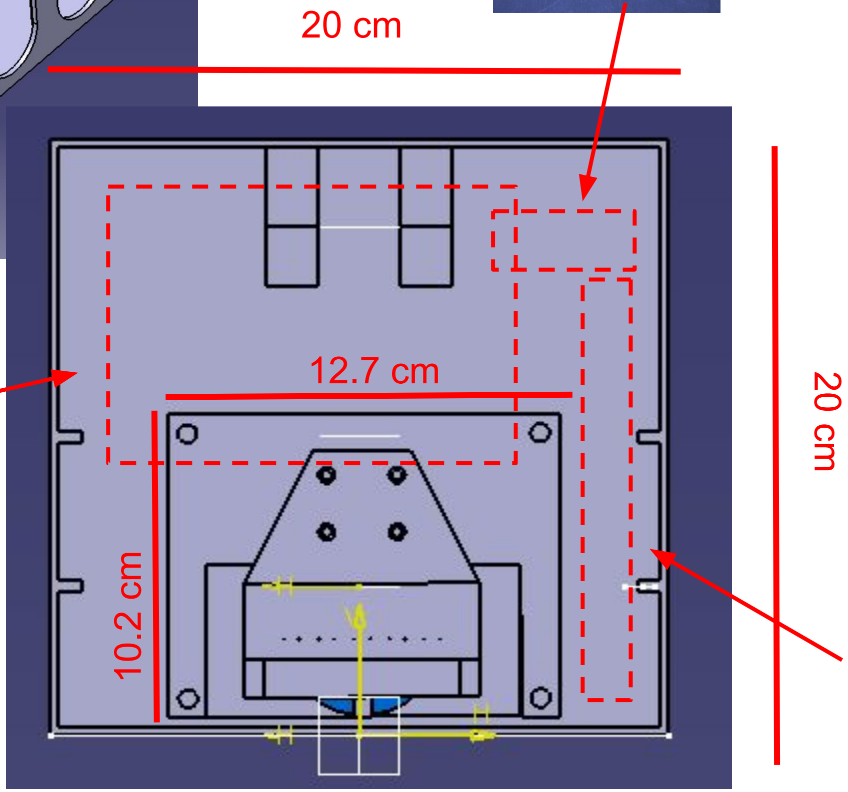
- CubeSat designed with space efficiency, ease of assembly/modification in mind
- Base features cup design with half-sphere “pegs” that precisely point the air bearings towards the surface, helping eliminate drift due to downward thrust deviation
- Base rigidly holds tanks and propulsion system in place, allowing for minimal variability in mass distribution

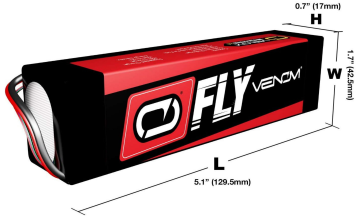
CubeSat Internal Layout





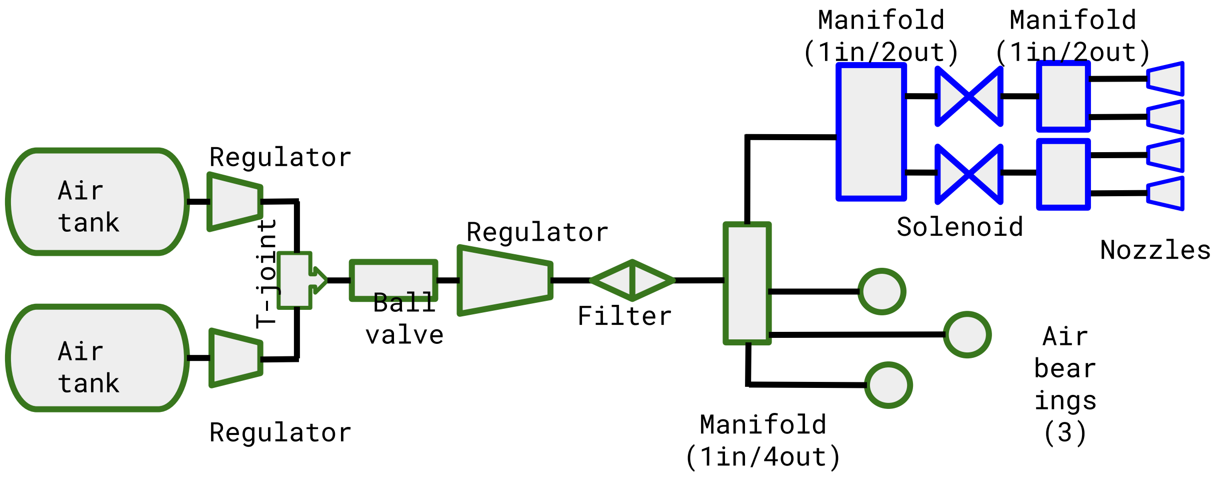


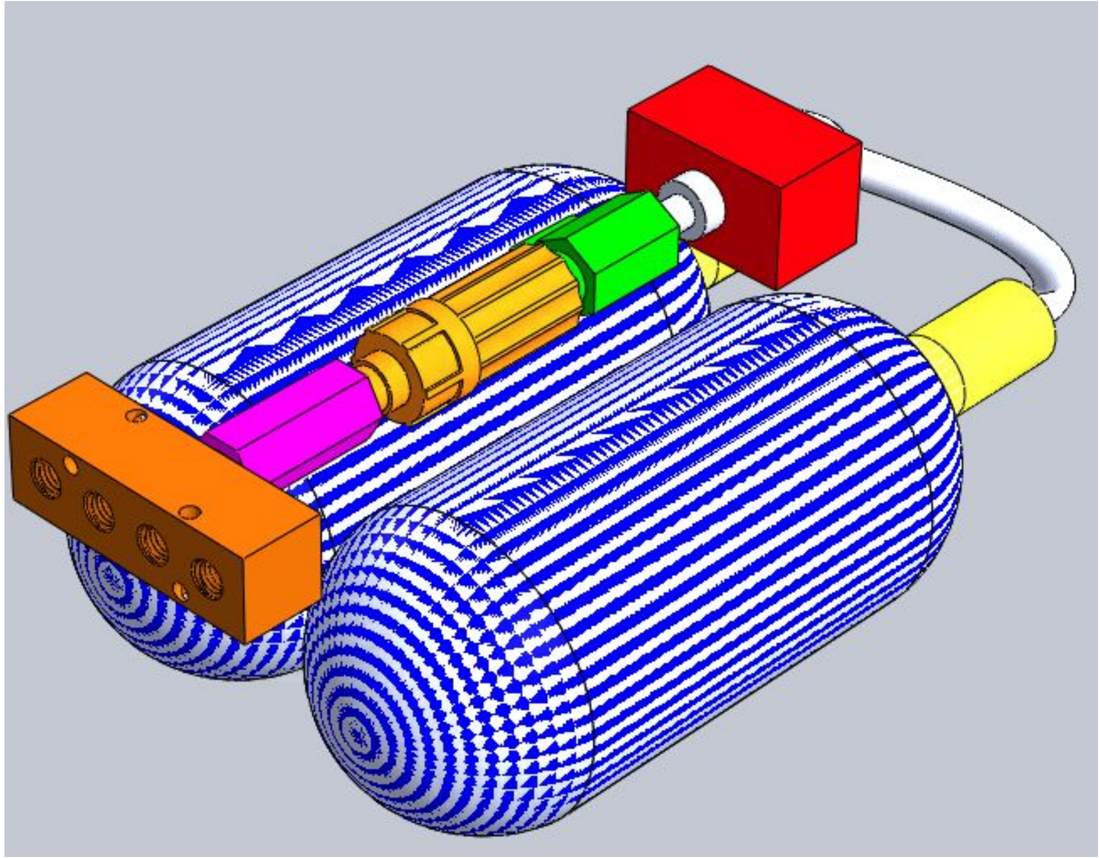




- Size: 4U (20 x 20 x 10 cm)
- “Shelf” system allows for ease of modification
- Secure mounts for nozzles
- Open design allows for ease of assembly
- Mount for laser/receiver on top of CubeSat
  - Future iteration will “Pop up” from inside

Propulsion System Model





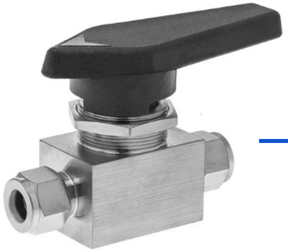
- Two air tanks provide >20 minutes of levitation time (at 2000 psi)
    - Provide ~10 minutes of run time if using nozzles (at 2000 psi)
- 1st stage regulators bring air to 300 psi, which other components can handle
- Ball valve functions as “on/off switch”
- 2nd stage regulator brings air to 80 psi for use in the air bearings and nozzles
- Straight flow manifold delivers air to three air bearings directly, and one manifold for the nozzles
- Once headed for the nozzles, the air passes through the manifold into one of two solenoids and out evenly through two nozzles

Final Components

Air Tanks (x2) (4500 psi)
1st Stage Regulator (300 psi)

T-Joint

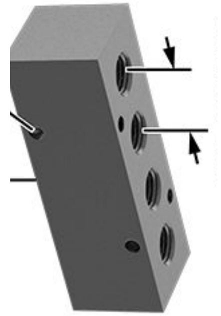
Ball Valve



2nd Stage
Regulator (80 psi)

Air Filter

Straight-Flow
Manifold



Air Bearings (x3)

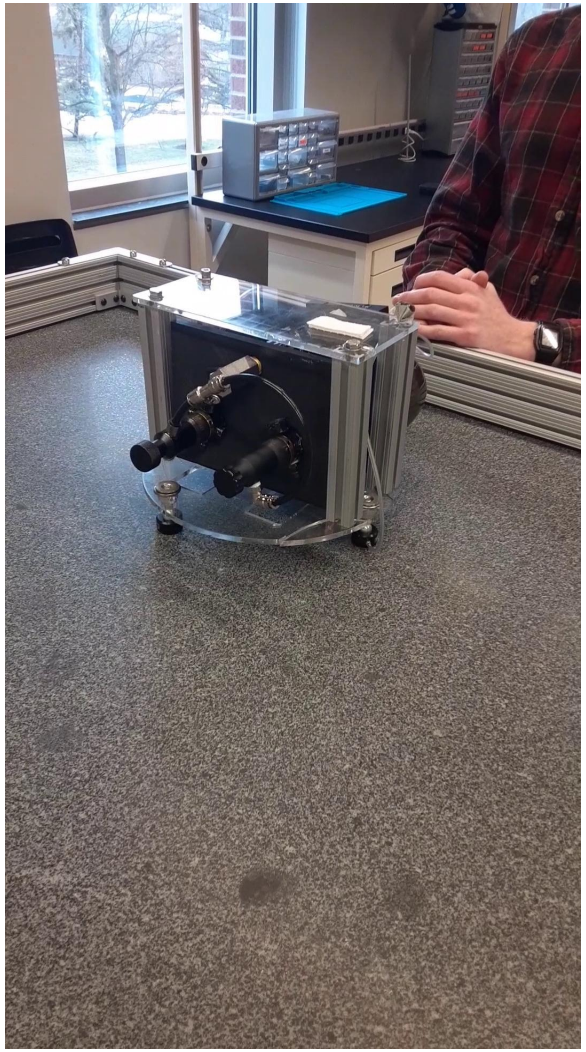
Adjustable Nozzles (x4)

- Air Consumption: 8-26 cfm @ 100 psi
- Airflow Rate: Adjustable
- Max. Inlet Pressure: 150 psi

The Drift Problem

- CubeSat drifts
  - Differing performance of air bearings, length of tubing, base flex, orientation of bearings, weight distribution, table (?), air currents (?), initial conditions
- Makes it hard for laser comms
- List of other problems
- Propulsion and Levitation System must be able to provide free, **one-dimensional** translational motion
- PLS must maintain **steady levitation** with drift less than 5 degrees (rotational) and 5 cm (translational) after 30 seconds of becoming “stationary”
- PLS must move translationally 8 ft with drift less than 10 degrees (rotational) and 10 cm (translational)
- PLS must be precise enough such that the final position must not be more than 5 cm in any direction from the desired final position

Experimental Results / Best Performance



Original Configuration

Improved Configuration

- Original Configuration
  - Drifted ~15-20 cm in 10 sec
  - Rotate ~10-15 deg counterclockwise in 10 sec
- Improved Configuration
  - Drifted ~2-3 cm in 10 sec
  - Rotated ~2-5 deg counterclockwise in 10 sec
- Differences
  - Length of tubing
  - Weight distribution
  - Orientation of bearings
  - Position of bearings
- Best Performance
  - 2 cm drift in 10 sec
  - 2 deg counterclockwise rotation in 10 sec

PURDUE UNIVERSITY

School of Aeronautics and Astronautics
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