Democratization of Self-Landing Rocketry

Raise the Ratio!

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Initial Problem Identification and Ideation

Phase I

Background Context

- Rockets can land themselves now!
- SpaceX, BlueOrigin, etc. pioneered this technology
- Makes rockets more reusable
- Involves advanced controls

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Problem

- In order for researchers to test novel control theory algorithms they need a test bed to do so
- Most test beds have been built with commercial purpose in mind; either to contract out to companies or companies building their own subscale test beds
- A cheap, open source test bed would allow researchers an easy way to advance their research

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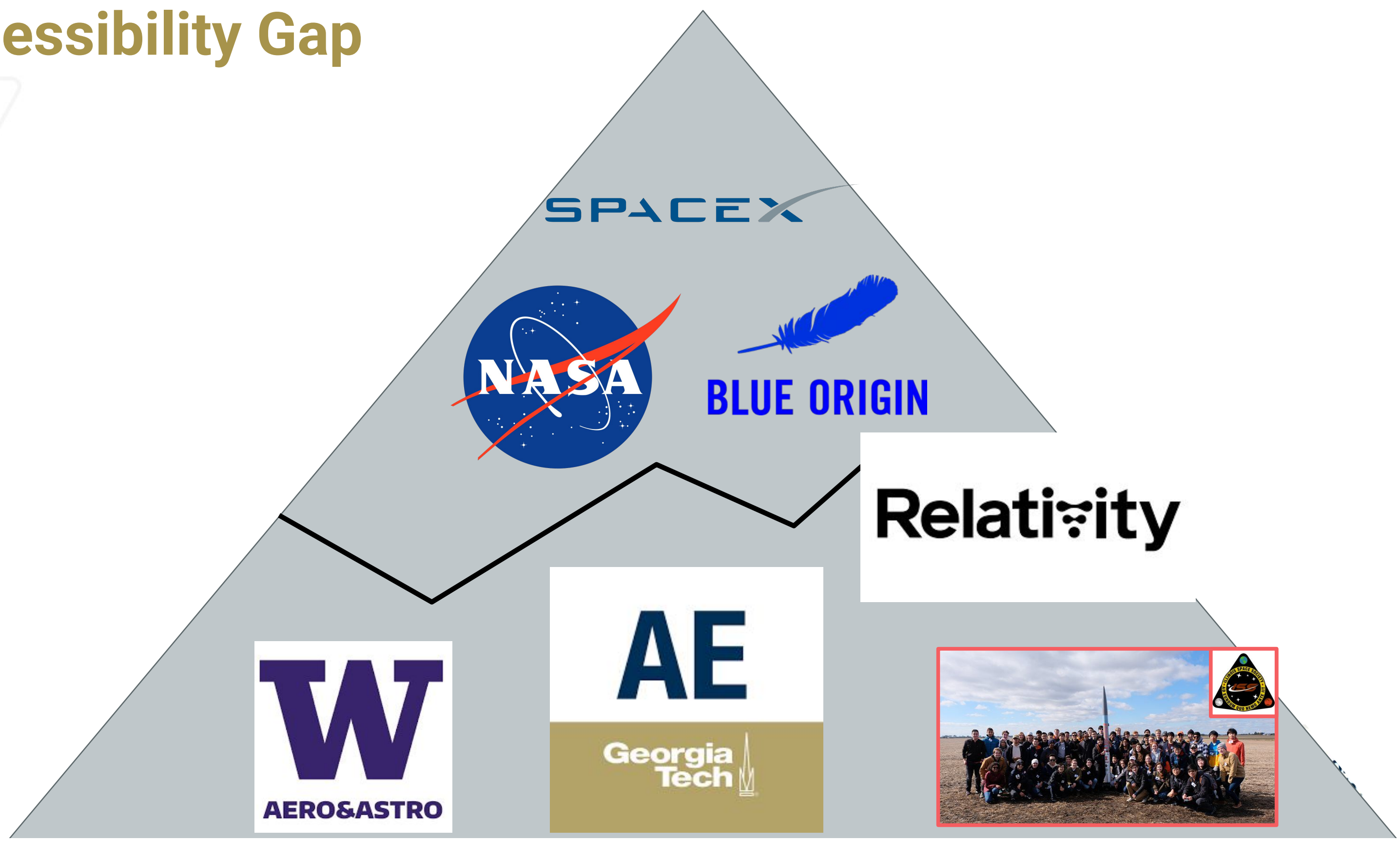
Other similar products

Electric Small Scale Rocket

SpaceX ‘Grasshopper’

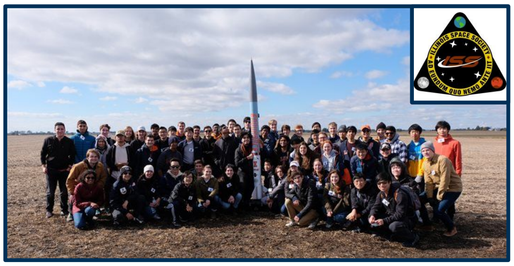
Masten Space Systems ‘Xombie’

Accessibility Gap



Market research

- High impact potential among research labs, startups
- No cheap GN&C test bed exists (budget of most labs to be feasible is <$5000)
- NASA sees this as an issue and has proposed controls test beds



Proposal

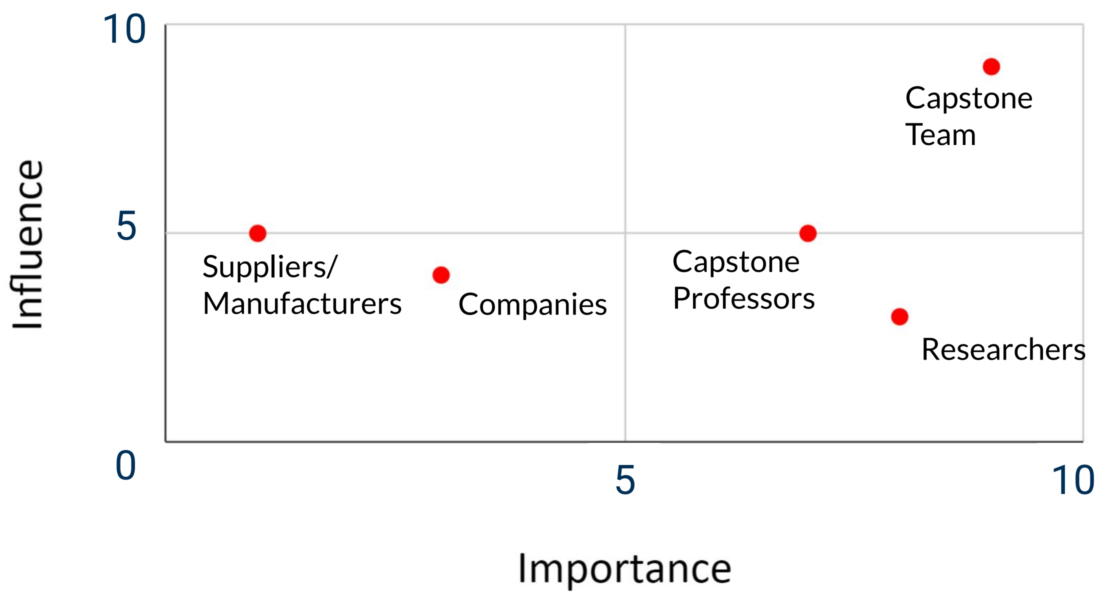
Create high-fidelity test bed that is:

- Highly accessible to small-budget groups
- Can implement self-landing and self-stabilizing flight control algorithms
- Represent actual rocket characteristics

Proposal

- Self-landing rockets are the future, but require a lot of engineering iterations to succeed.
- And, outside of giant companies with infinite resources, testing is impossible for smaller budget labs and startups
- Our team plans to develop a cheap, high-fidelity test bed to validate landing controls of rockets, modeled like an inverted pendulum.
- This opens the door for more researchers and hobbyists to experiment with self-stabilization at a democratized scale.
- This will result in faster testing and more successful touchdowns of self-landing rockets!

Stakeholder Matrix



Specifications

			For: Low Cost, Low Risk Test Bed			Page:
			Specification			
No.	Date	D/W	Requirements	Responsible	Source	How Validated
General						
No.1	9/15/23	D	System shall cost < $1000	Team	Capstone Website	Examination
No.2	9/15/23	W	System components should be off the shelf.	Team	Team	Examination
No.3	9/15/23	D	System shall have sufficient documentation for rapid use	Lily	Team	Examination
No.4	9/15/23	D	Bill of Materials shall be available for free on an open source online platform.	Charlie	Team	Examination
No.5	9/15/23	D	Installation instructions shall be available for free on an open source online platform.	Josh	Team	Examination
Functional						
No.31	9/19/23	D	The vehicle shall deploy landing gear when approaching ground vertically.	Team	Team	Demonstration
No.32	9/19/23	D	The vehicle shall actuate yaw.	Team	Team	Demonstration
No.36	9/19/23	D	The vehicle shall actuate pitch.	Team	Team	Demonstration
No.37	9/19/23	D	The vehicle shall activate roll.	Team	Team	Demonstration

*Not all specifications are listed for conciseness

Specification

Physical Characteristics						
req.9	9/15/23	W	Volume shall be </= 2ftx2ftx4ft	Team	Team	Demonstration
req.10	9/15/23	W	Thrust to weight ratio is at least 4:1	Team	Team	Analysis
req.11	9/15/23	D	System shall withstand up to TBD lbf.	Team	Team	Test
Electrical						
req.12	9/15/23	D	The system shall allow for implementation of control algorithms	Robbie	Team	Analysis/Test
Mechanical						
req.17	9/15/23	D	The vehicle shall be mechanically capable of flight stability	Team	Team	Analysis
Performance						
req.20	9/15/23	D	The system shall be powered for at least TBD time.	Josh	Team	Analysis
req.21	9/15/23	D	The vehicle shall be capable of flight for TBD time.	Sam	Team	Analysis
Safety						
req.22	9/15/23	D	The power source shall have preventative overheating measures.	Lily	FAA	Test

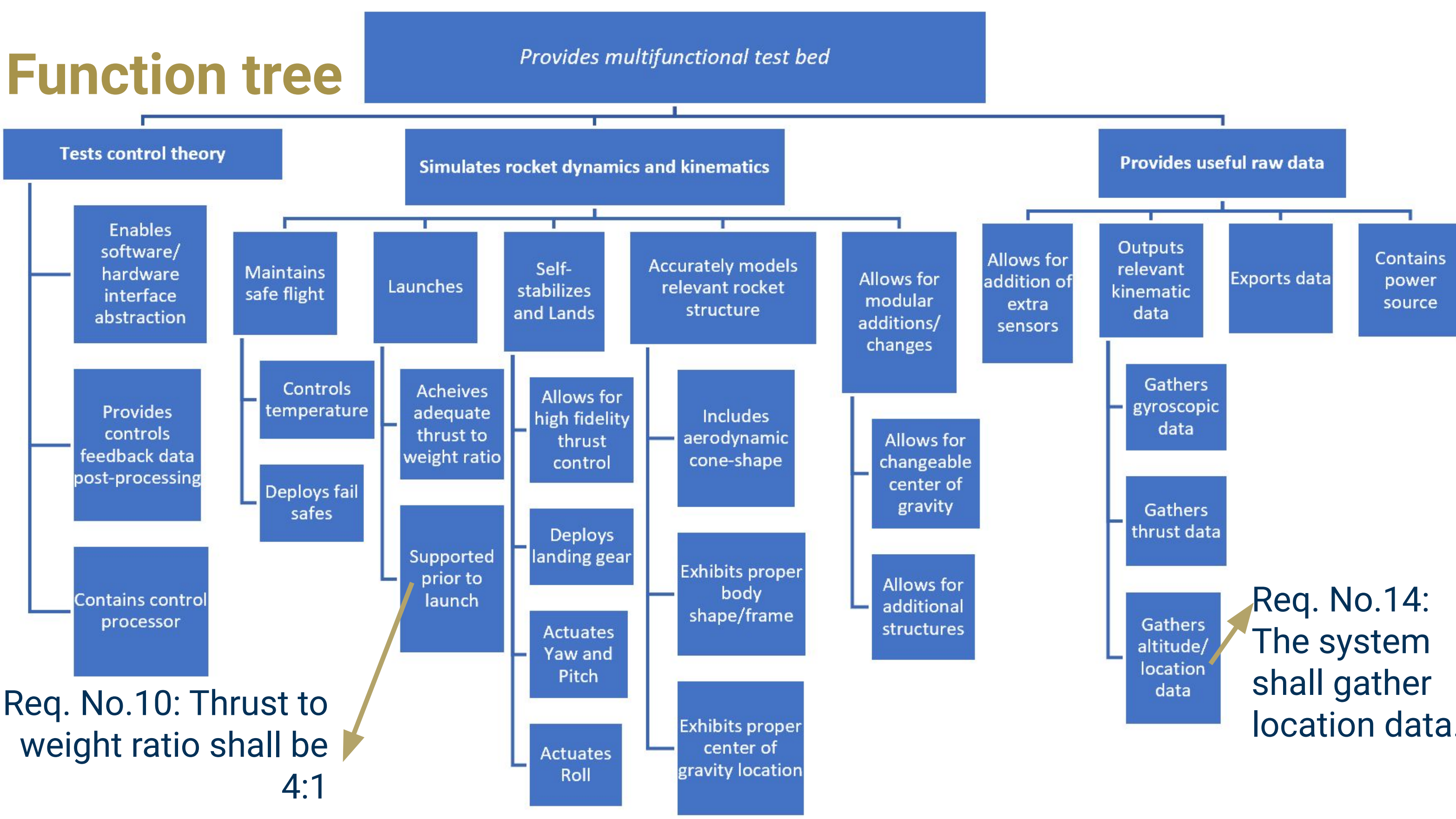
Regulations/Codes

FAA Regulations for hobby rockets:

- Does not cross into territory of foreign countries
- Is unmanned
- Does not pose a hazard to persons, property, or other aircraft

Sub-scale nature of our design encourages compliance to many regulations

Function tree



Morph Chart

Color-Coded Design Concepts:				
Design 1 (Cheap)	Design 2 (Quadcopt)	Design 3 (Coaxial)	Design 4 (Solid Fuel)	Design 5 (Costly)
Function	Mechanism #1	Mechanism #2	Mechanism #3	Mechanism #4
Enables software/Hardware interface abstraction	Hardware wrapper classes	Off the shelf libraries (I2C library)		
Provides controls feedback data post-processing	Exports to MAT file	Exports data in csv file	Exports to spreadsheet	MATLAB analysis tool
Contains controls processor	Microcontroller (Arduino, ESP32, etc.)	Raspberry pi	PLC	Quadcopter flight controller
Control of Temp	Increased time between tests / limit run time	Fans	Open airflow	Unneeded
Deploys fail-safes	Cushion pad	Parachute	Foolproof hardware design	
Includes aerodynamic cone shape	Parabola	Ogive	Cone	Blunt
Exhibits proper body shape	Skeleton frame	Cylindrical shape	Square shape	Triangular shape

Color Coded Design Concepts:				
Design 1 (Cheap)	Design 2 (Quadcopt)	Design 3 (Coaxial)	Design 4 (Solid Fuel)	Design 5 (Costly)
Function	Mechanism #1	Mechanism #2	Mechanism #3	Mechanism #4
Allows for roll actuation	Opposite coupled reaction fins	Coaxial rotors	Multi-rotor orientation	Reaction wheel
Deploys landing gear	Rocket legs	Airbag	Ground catch structure	Ground netting
Achieves adequate thrust to weight ratio	Drone motors	Compressed gas thruster	Liquid Fuel	Solid Fuel
Supported prior to launch	Simple pad	Pad and tower	Rocket legs	
Exhibits proper CG location	Forward CG	Balanced CG	Aft CG	
Allows for high fidelity thrust control	Drone motors	Compressed gas thruster	Liquid Fuel	Solid Fuel
Allows for yaw and pitch actuation	Drag fins (deployable or stable)	Thrust vectoring fins	Thrust gimbal	Multi-rotor orientation

Morph Chart (Cont.)

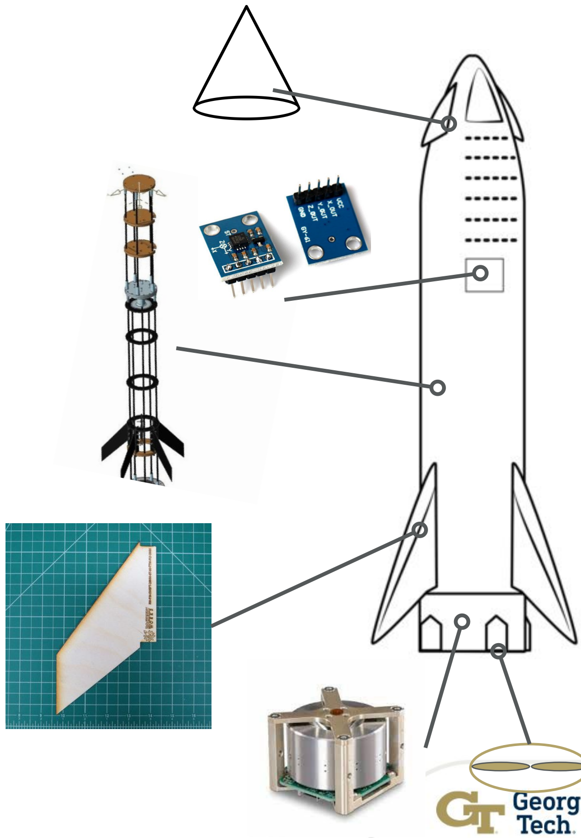
Color Coded Design Concepts:				
Design 1 (Cheap)	Design 2 (Quadcopt)	Design 3 (Coaxial)	Design 4 (Solid Fuel)	Design 5 (Costly)
Function	Mechanism #1	Mechanism #2	Mechanism #3	Mechanism #4
Allows for changeable center of gravity	Moveable battery/internal mechanisms	Addable weight	Payload bay	
Allows for additional structures	Bolt holes	Rail system	Velcro	
Allows for additional sensors	Payload GPIO	Accessible power rails	N/A	
Gathers gyroscopic data	MEMs IMU/gyro	Rotary gyroscope	Vibrating structure gyroscope	Optical gyroscope
Gathers acceleration data	MEMs IMU/accel	Analog accelerometer	Hall effect accelerometer	

Color Coded Design Concepts:				
Design 1 (Cheap)	Design 2 (Quadcopt)	Design 3 (Coaxial)	Design 4 (Solid Fuel)	Design 5 (Costly)
Function	Mechanism #1	Mechanism #2	Mechanism #3	Mechanism #4
Gathers altitude/location data	MEMs IMU/barometer	GPS	Time of flight sensor	Machine vision
Exports Data	Wifi (2.4GHz or 5.8GHz)	Bluetooth	Store locally then USB cable	SD card
Contains power source	Disposable battery	Rechargeable Battery	Solar Power	Compressed substances

DESIGN 1 (Cheap)

Highlights

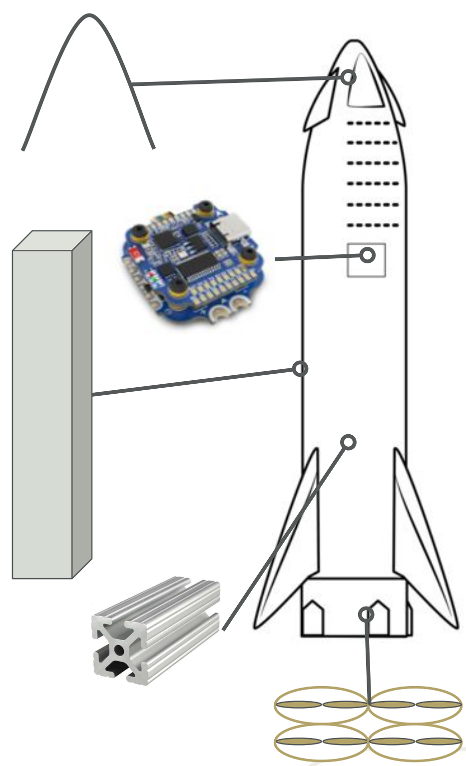
- Skeleton frame with cone head shape → open airflow
- Single drone motor
- Microcontroller + off-shelf libraries
- Drag fins → yaw/pitch actuation
- Reaction wheel → roll actuation
- Analog sensors (No combined IMU)
- Modularity: velcro and addable weight



DESIGN 2 (Quadcopter)

Highlights

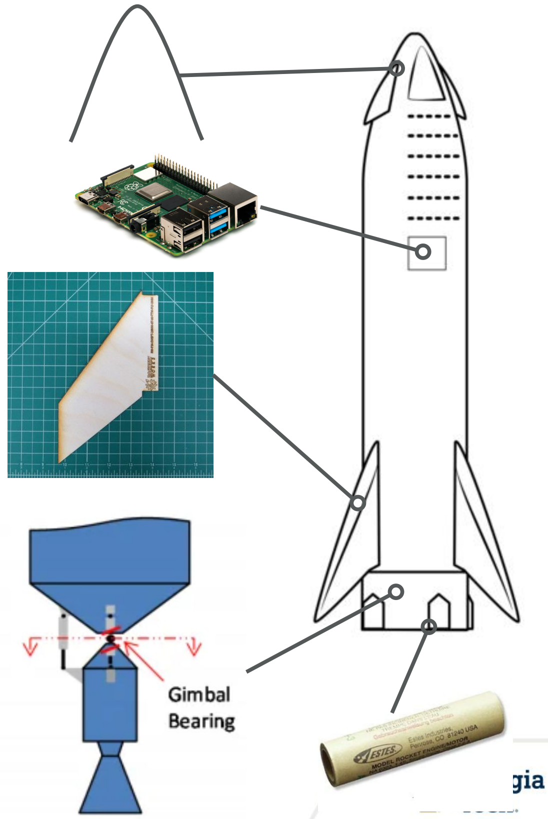
- Square body with parabolic head shape
- 4 drone motors on each corner → roll, yaw, and pitch actuation
- Quadcopter flight controller
- Modularity: bolt holes, additional sensors, moveable internals



DESIGN 4 (Solid Fuel)

Highlights

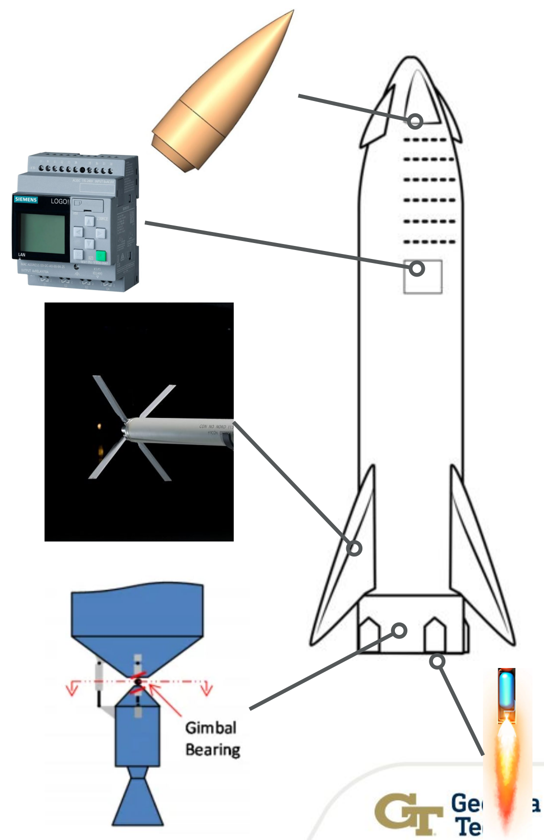
- Cylindrical body with parabolic head shape
- Solid fuel
- Coupled reaction fins → roll actuation
- Thrust vectoring fins →yaw/pitch actuation
- Raspberry pi
- Modularity: bolt holes, additional sensors, payload bay



DESIGN 5 (Costly)

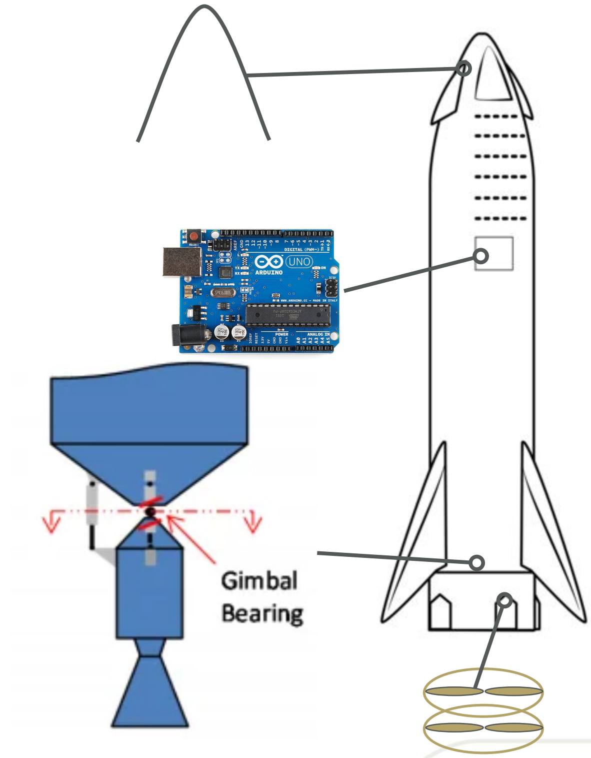
Highlights

- Cylindrical body with ogive head shape
- Liquid fuel used
- Coupled reaction fins for roll actuation
- Thrust vectoring fins for yaw/pitch actuation
- PLC
- Modularity: rail system, additional sensors, moveable internals



FINAL DESIGN:

- Cylindrical body with rounded head shape
- 2 coaxial rotors → roll actuation, thrust
- Thrust gimbal →yaw/pitch actuation
- Microcontroller
- Modularity: rail system, additional sensors, moveable internals



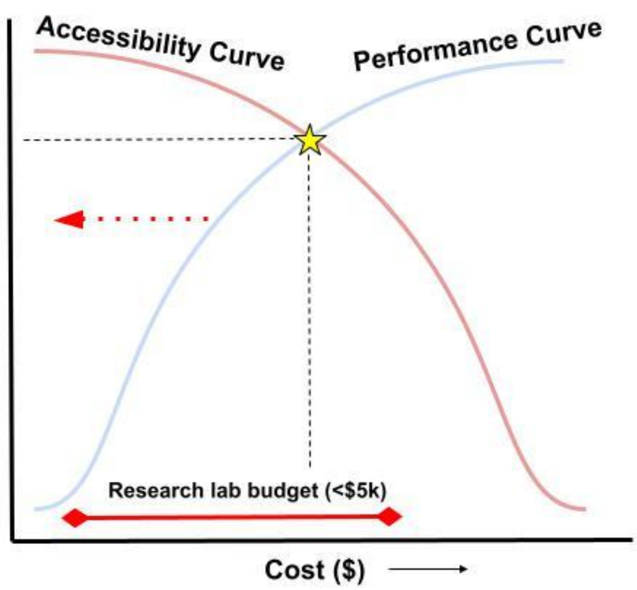
Meets all the functional requirements!

Preliminary Design Selection Process

- Highly complex design space
- Identified clear tradeoff between **vehicle performance** and **user accessibility**

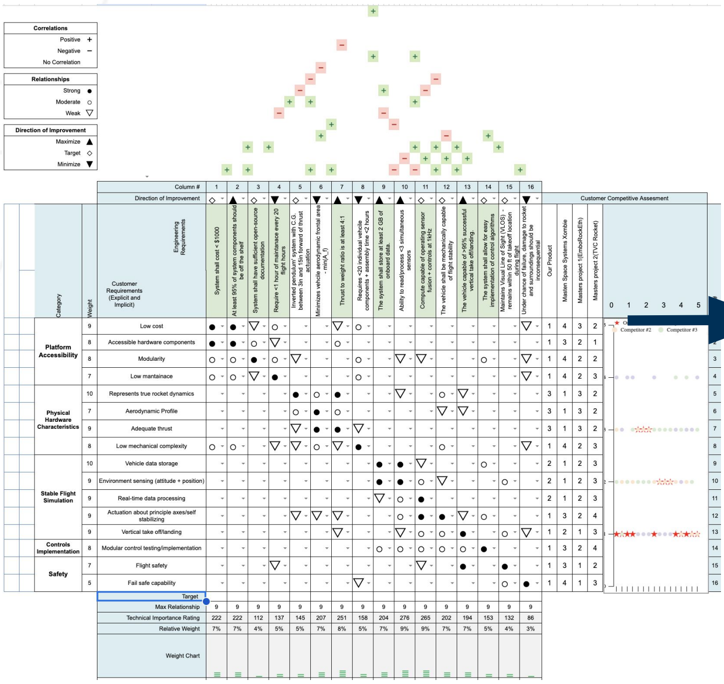
Design selection strategy:

- Utilize methods/tools to help **quantitatively** evaluate each design alternative based on:
  - Customer needs
  - Design constraints
  - Engineering/Functional Reqs
- Analytical tools used:
  - HOQ
  - Weighted decision matrix



House of Quality

Primary method for determining ranking/weighting requirements + criteria to evaluate proposed designs



Customer requirements derived from interviewing *customers*: **research labs, PhD's, professors, 'NewSpace' companies (Relativity, SpaceX).**

Category	Weight	Customer Requirements (Explicit and Implicit)
Platform Accessibility	9	Low cost
	8	Accessible hardware components
	8	Modularity
	7	Low mantainace
Physical Hardware Characteristics	10	Represents true rocket dynamics
	7	Aerodynamic Profile
	9	Adequate thrust
	8	Low mechanical complexity
Stable Flight Simulation	10	Vehicle data storage
	9	Environment sensing (attitude + position)
	9	Real-time data processing
	9	Actuation about principle axes/self stabilizing
	9	Vertical take off/landing
Controls Implementation	8	Modular control testing/implementation
Safety	7	Flight safety
	5	Fail safe capability

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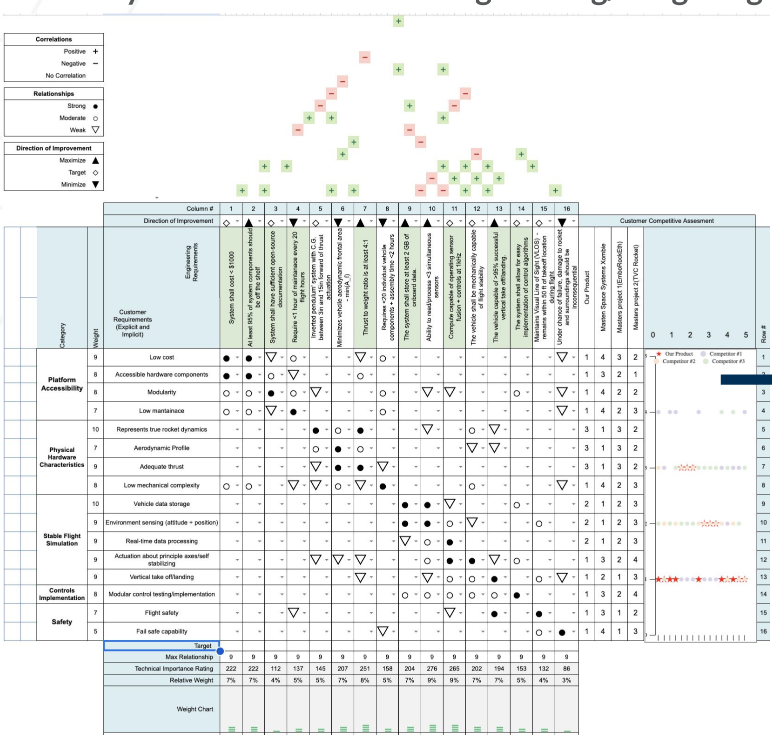
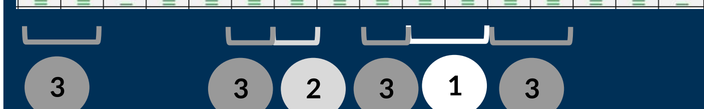
Primary method for determining ranking/weighting requirements + criteria to evaluate proposed designs



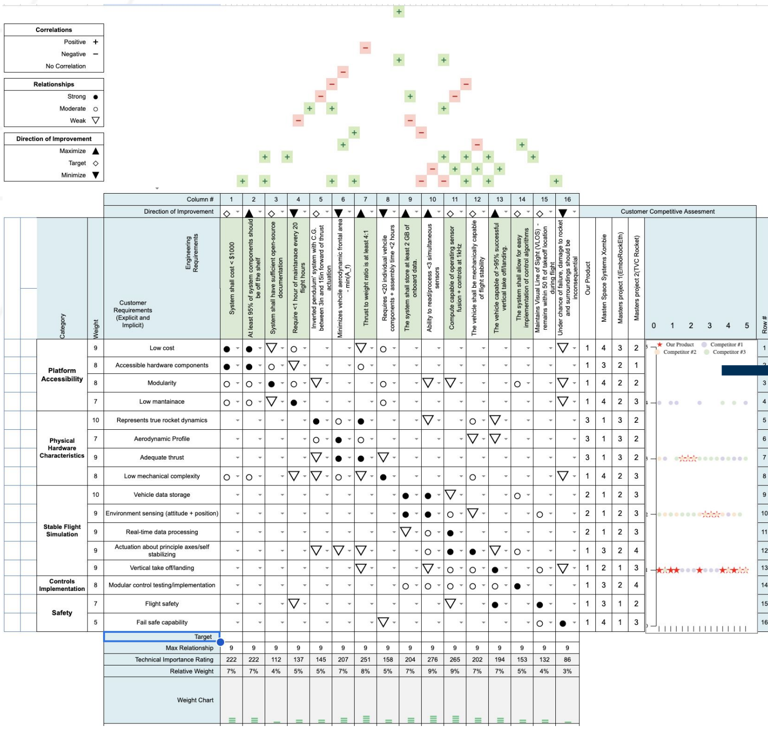
#	Direction of Improvement	Engineering Requirement	Technical Importance Rating	Relative Weight
1	◇	System shall cost < $1000	222	7%
2	▲	At least 95% of system components should be off the shelf	222	7%
3	◇	System shall have sufficient open-source documentation	112	4%
4	▼	Require <1 hour of maintanace every 20 flight hours	137	5%
5	◇	Inverted pendulum' system with C.G. between 3in and 15in forward of thrust actuation	145	5%
6	▼	Minimizes vehicle aerodynamic frontal area - min(A_f)	207	7%
7	▲	Thrust to weight ratio is at least 4:1	251	8%
8	▼	Requires <20 individual vehicle components + assembly time <2 hours	158	5%
9	▲	The system shall store at least 2 GB of onboard data.	204	7%
10	▲	Ability to read/process <3 simultaneous sensors	276	9%
11	◇	Compute capable of operating sensor fusion + controls at 1kHz	265	9%
12	◇	The vehicle shall be mechanically capable of flight stability	202	7%
13	▲	The vehicle capable of >95% successful vertical take off/landing.	194	7%
14	◇	The system shall allow for easy implementation of control algorithms	153	5%
15	◇	Maintains Visual Line of Sight (VLOS) - remains within 50 ft of takeoff location during flight	132	4%
16	▼	Under chance of failure, damage to rocket and surroundings should be inconsequential	86	3%



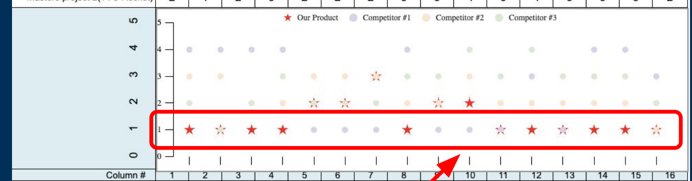
Detailed, actionable engineering requirements derived and ranked based on alignment with customer needs/requirements!

House of Quality

Primary method for determining ranking/weighting requirements + criteria to evaluate proposed designs



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Technical Importance Rating	222	222	112	137	145	207	251	158	204	276	265	202	194	153	132	86
Relative Weight	7%	7%	4%	5%	5%	7%	8%	5%	7%	9%	9%	7%	7%	5%	4%	3%
Weight Chart																
Our Product	1	1	1	1	2	2	3	1	2	2	1	1	1	1	1	1
Masten Space Systems Xombie	4	4	4	4	1	1	1	4	1	1	1	3	1	4	4	3
Masters project 1(EmboRockEth)	3	3	2	2	3	3	3	2	2	3	2	2	2	2	2	1
Masters project 2(TVC Rocket)	2	1	2	3	2	2	2	3	3	4	3	4	3	3	3	2



Based on the customer needs established through talking to/understanding customers:

- **Dominate competition in 11 of 16 reqt's**
- **Top 2 in 15 of 16 reqt's**

Decision Matrix

		5		3		1		2		4	
		Design 1 (Cheap)		**Design 2 (Quadcopt)**		**Design 3 (Coaxial)**		**Design 4 (Solid Fuel)**		**Design 5 (Costly)**	
Criteria	**Importance (0-10)**	**Rating (1-5)**	**Weighted Total**	**Rating (1-5)**	**Weighted Total**	**Rating (1-5)**	**Weighted Total**	**Rating (1-5)**	**Weighted Total**	**Rating (1-5)**	**Weighted Total**
Low cost	9	5	45	4	36	4	36	3	27	1	9
Accessible hardware components	8	5	40	4	32	4	32	2	16	1	8
Modularity	8	2	16	4	32	4	32	4	32	4	32
Low mantainace	7	2	14	4	28	4	28	2	14	1	7
Represents true rocket dynamics	10	1	10	2	20	3	30	4	40	5	50
Aerodynamic Profile	7	1	7	2	14	5	35	5	35	5	35
Adequate thrust	9	2	18	5	45	5	45	5	45	5	45
Low mechanical complexity	8	5	40	4	32	4	32	3	24	1	8
Vehicle data storage	10	2	20	4	40	4	40	5	50	5	50
Environment sensing (attitude + position)	9	3	27	5	45	5	45	5	45	5	45
Real-time data processing	9	3	27	4	36	4	36	5	45	5	45
Actuation about principle axes/self stabilizing	9	2	18	4	36	5	45	5	45	5	45
Vertical take off/landing	9	3	27	4	36	4	36	4	36	5	45
Modular control testing/implementation	8	3	24	5	40	5	40	5	40	5	40
Flight safety	7	3	21	4	28	4	28	2	14	2	14
Fail safe capability	5	2	10	2	10	2	10	4	20	4	20
Total		364		510		550		528		498	
Relative Total		0.55		0.77		0.83		0.80		0.75	
Rank		5		3		1		2		4	

Detailed Design

Phase II

First Principles Rocket Simulation

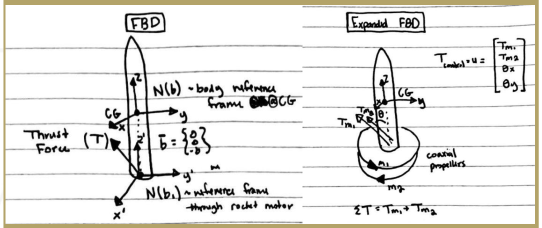
In such a complicated design space, where do we begin? How do we rapidly iterate and build an intuition around the mechanics of the rocket?

High Fidelity Rocket Simulation

Operating in a **highly complex multi-dimensional design space!**

Need a method to quickly and iteratively build intuition/test high level designs…

Kinematic Model



Foundational Equations

$$\vec{F} = m\frac{d\vec{V}}{dt}|_B + m(\vec{\omega} \times \vec{V})$$

$$\frac{d\vec{a}}{dt}|_I = \frac{d\vec{a}}{dt}|_B + \vec{\omega} \times \vec{a}$$

$$\vec{M} = \frac{d\vec{H}}{dt}|_B + \vec{\omega} \times \vec{H}$$

$$\Delta\tau_{M1-M2} = -\frac{D}{4\pi}(T_{M1} - T_{M2})$$

Equations of motion and analysis guided by the "Spacecraft and Aircraft Dynamics" Lecture by Matthew M. Peet at I.I.T

Python Model

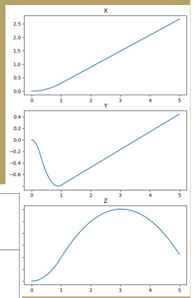
NumPy

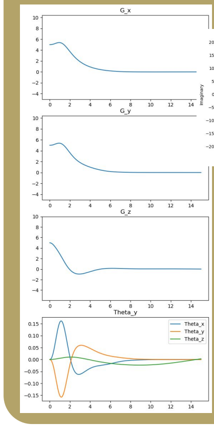
jupyter

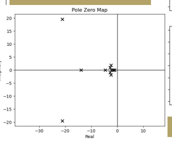
Simulation Outputs

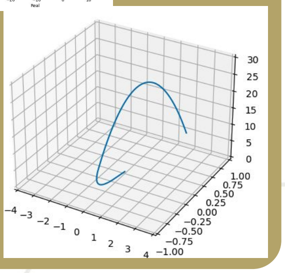
High Level Analysis Results:

- No more than ***15 deg*** TVC actuation required for control
- Naturally highly ***unstable*** system
- Valuable resource to ***prototype future flight controller regimes***

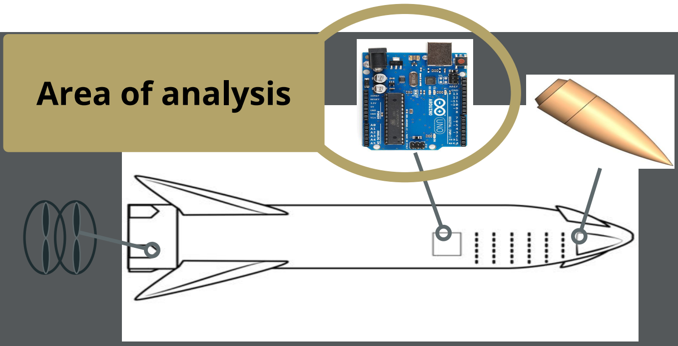








Electronics/Sensors



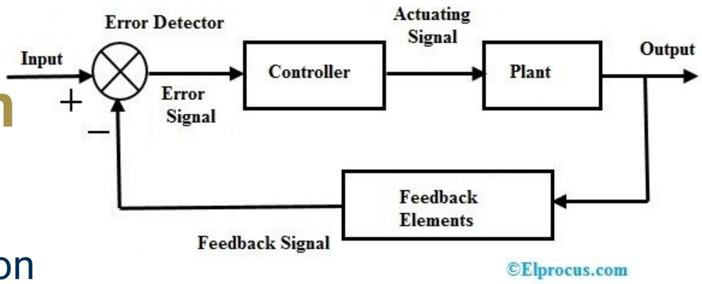
Sensors

- Needs:
  - Flight computer
  - Altitude
  - Absolute orientation
  - XY-position
  - Data storage
  - Thrust-vector actuators
  - Power connections
- Criteria:
  - Lightweight
  - Accurate
  - Communication compatibility
  - Voltage/Amperage compatibility
  - Minimal signal processing

Servo selection

- Needed for thrust-vector control
- Requirements:
  - Lightweight
  - High torque capability
  - Fast
- First selection was readily-available MG90S
- Opted for new (more expensive) Corona DS-843MG

Control-based sensor selection



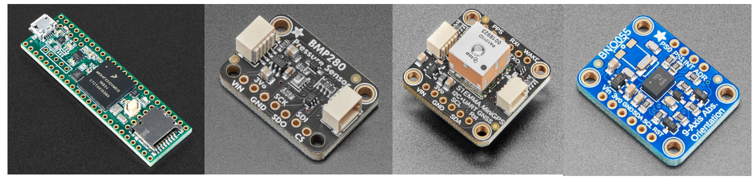
- Control loop must run faster than actuation
- From calculations we need 15° TVC actuation
  0.12 sec/60° * 1/15° (spec from servo)
  → .03 sec/15° → 1/.03 = 33.33 Hz
  (max frequency of servo, with safety factor controller will be at least 3x faster than this)
- Desired control loop frequency = 100Hz
  - **All sensors should be >= 100Hz to support control loop**

Sensor Selection v1

Function	Component Name	Comm Type(s)	Voltages	Frequency
Microcontroller/ Flight Computer	ESP 32	I2C, SPI, UART	3.3V, 5V (Out)	240 MHz
IMU	MPU 6050	I2C, SPI	2.4-3.6V	1 kHz
Altimeter	BMP 280	I2C, SPI	3.3-5V	200Hz
X-Y GPS	SAM-M8Q	I2C, UART	3.3	18Hz
Servos	MG90S	JR Connector	4.8-6V	~.12 sec/60°

NOTE: Table does not contain all selection criteria

Proposed Sensor Selection

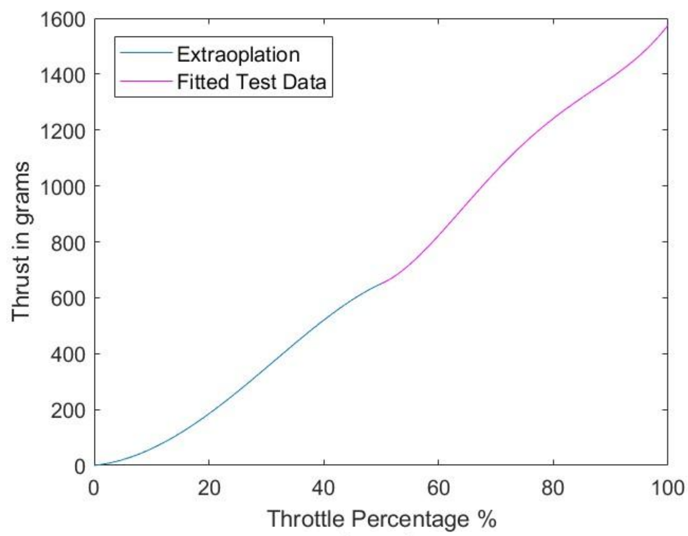


Function	Component Name	Comm Type(s)	Voltages	Frequency
Microcontroller/ Flight Computer	**Teensy 4.0**	I2C, SPI, CAN, UART	3.3V (Out)	600 MHz
IMU	**BNO055**	I2C	2.4-3.6V	100 Hz
Altimeter	**BMP 390**	I2C, SPI	1.3-3.6V	200 Hz
X-Y GPS	**PA 1010D**	I2C, UART	3.3-5V	10 Hz*
Servos	**Corona DS-843MG**	JR Connector	4.8-6V	~.12 sec/60°

*GPS will be upsampled so to not hinder control loop. Will be least important variable to monitor since objective is simply to levitate/land.

Propulsion

- Achieve 4:1 thrust to weight ratio
  - Extremely important! Modeled w/ throttle %
- Takes in battery power
- Uses off-the-shelf drone components
- >5 min flight time
- Controls roll (bonus)



$$Flight\ Time = \frac{Battery\ Ah\ Rating}{Load\ Currency\ \times number\ of\ motors}$$

$$@\ 100\%\ Throttle\ = \frac{1.05\ Ah}{40.35\ A\ \times 2}\frac{60\ mins}{1\ h} = 0.78\ mins$$

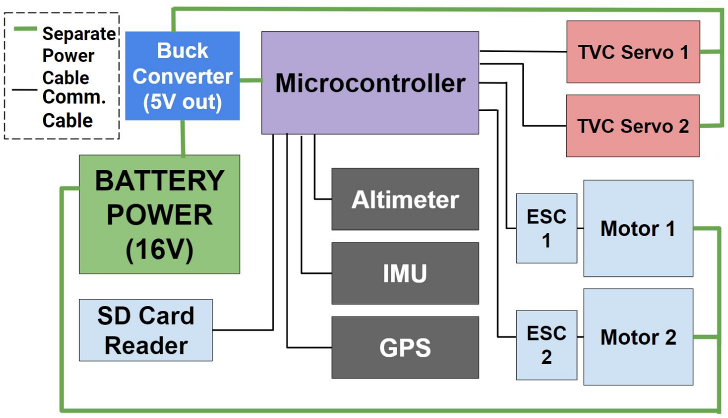
$$@\ 50\%\ Throttle = \frac{1.05\ Ah}{11.02\ A\ \times 2}\frac{60\ mins}{1\ h} = 2.86\ mins$$

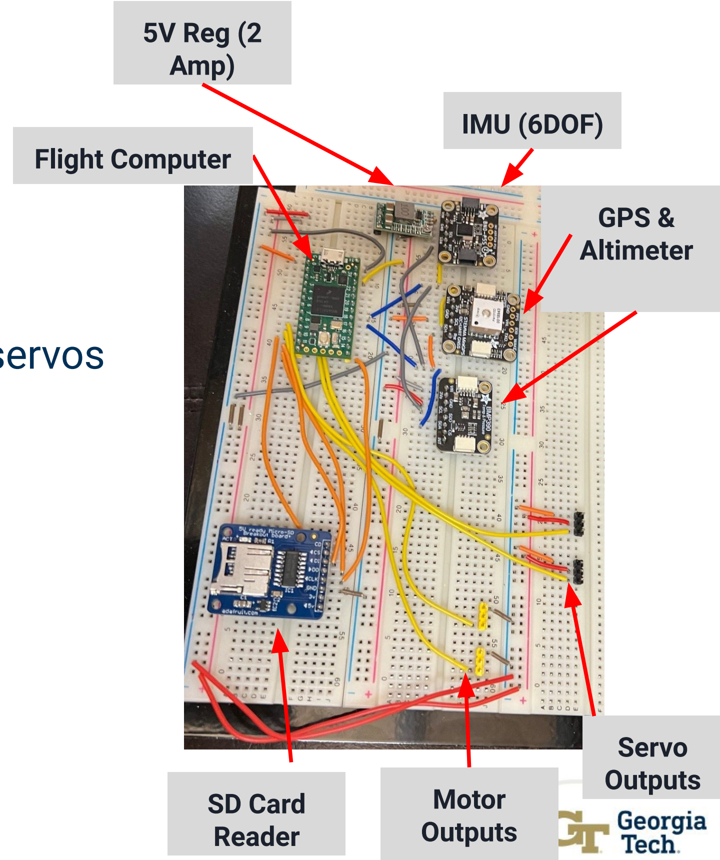
$$@\ 33\%\ Throttle(Hover) = \frac{1.05\ Ah}{8\ A\ \times 2}\frac{60\ mins}{1\ h} = 7.875\ mins$$

$$Linearized\ deceleration\ (0 - 33\%\ Throttle): \frac{1.05\ Ah}{5.5\ A\ \times 2}\frac{60\ mins}{1\ h} = 11.455\ mins$$

Electronics/Sensors

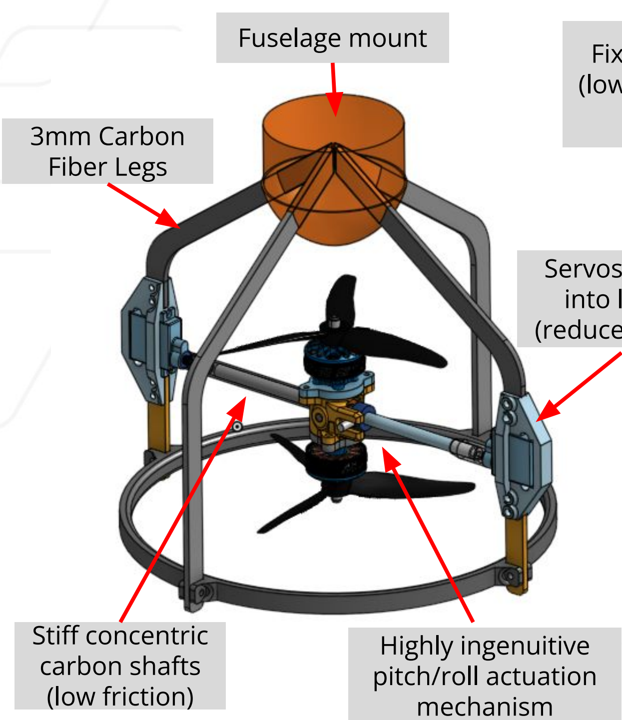
- Collect GPS, altitude, orientation
- Save data
- Communicate, provide power to sensors/servos



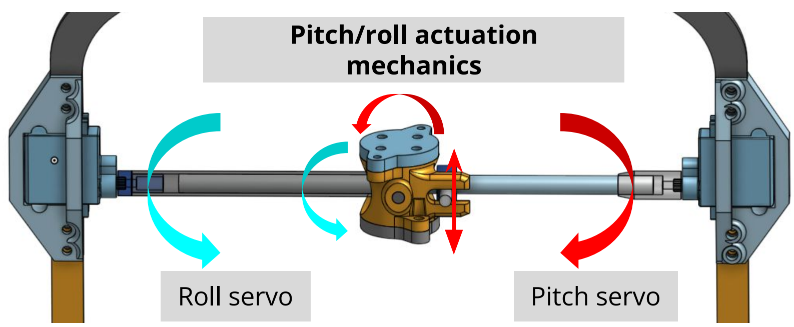


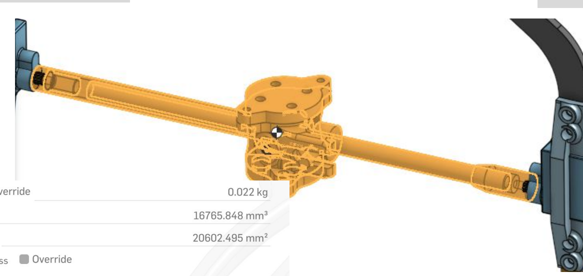
Georgia Tech

Thrust-Vector Control



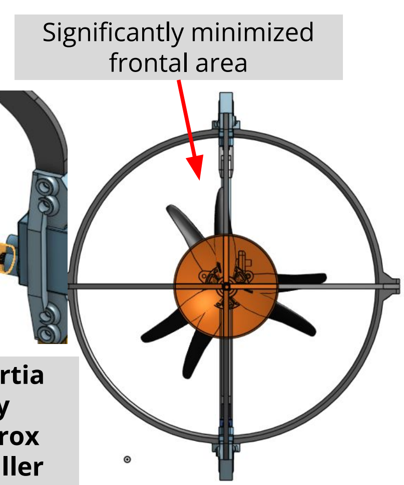
Clearance for up to 6” propellers





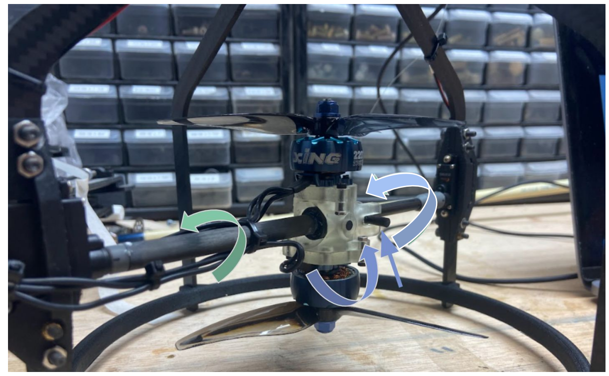
Mass	Override				0.022 kg
Volume					16765.848 mm³
Surface area					20602.495 mm²
Center of mass	Override				
X					6.022 mm
Y					-5.001 mm
Z					107.675 mm
Mass moments of inertia (kg mm²)	Override				
Lxx	23.243	Lxy	-0.001	Lxz	-4.157e-4
Lyx	-0.001	Lyy	23.391	Lyz	0.151
Lzx	-4.157e-4	Lzy	0.151	Lzz	2.104

Rotational inertia significantly reduced - approx 123 times smaller than V1 TVC!



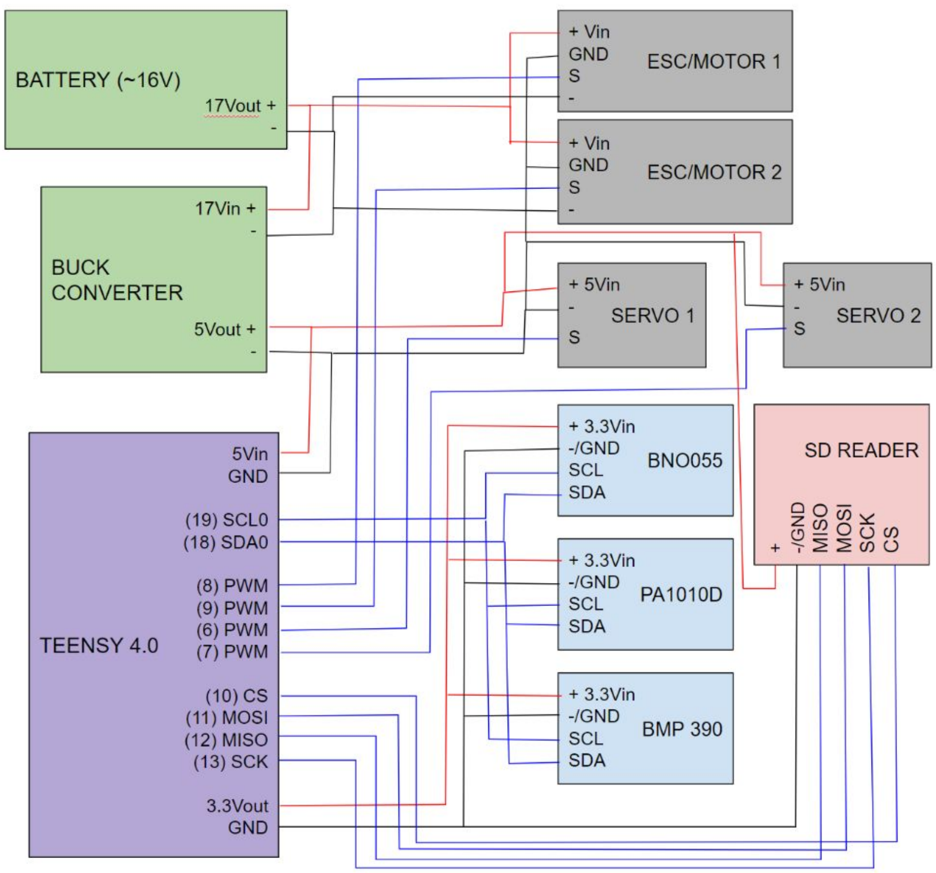
Thrust Vector Control

- Able to deflect 7.5 degrees in any direction
- Achieve max deflection at a fast rate
- Takes in inputs from microcontrollers



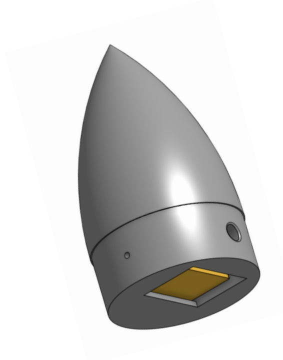
TVC Axis	Bandwidth (Hz)
Pitch Axis	~9 Hz
Roll Axis (Mech. coupler)	~8 Hz

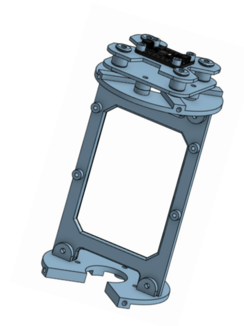
TVC Axis	Rise Time (To +/- 7.5 Deg)
Pitch Axis	0.10 sec
Roll Axis (Mech. coupler)	0.09 sec

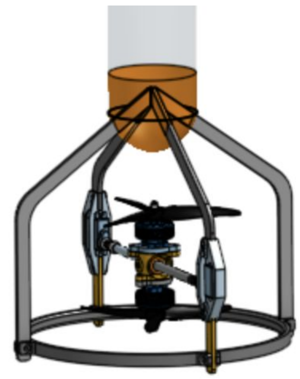


Rocket Body and Structure

- Mainly 3D printed or cut from easily-sourced materials
- Nose cone holding battery
- Sensor mounts with vibration dampening
- Landing gear protects motors

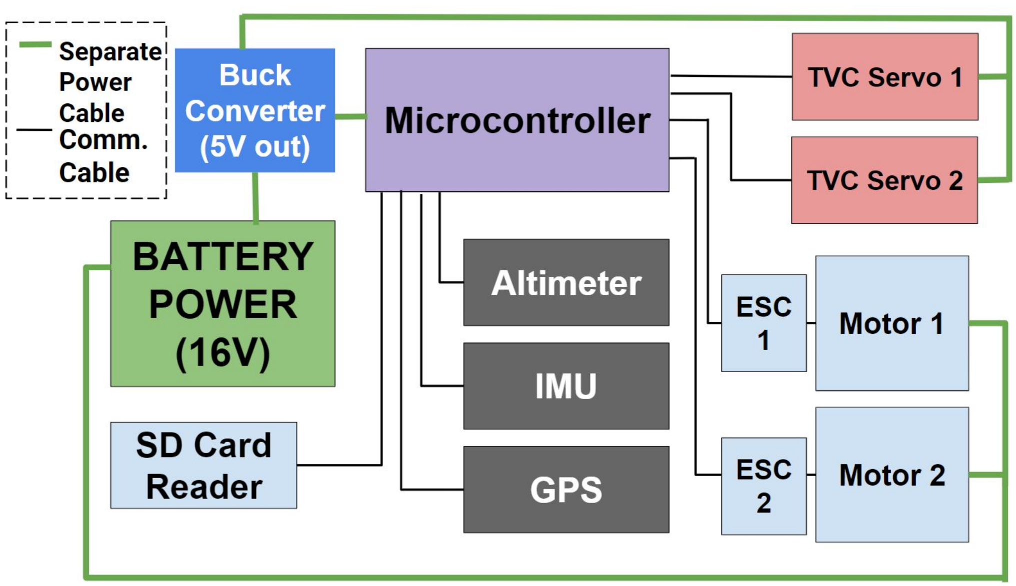






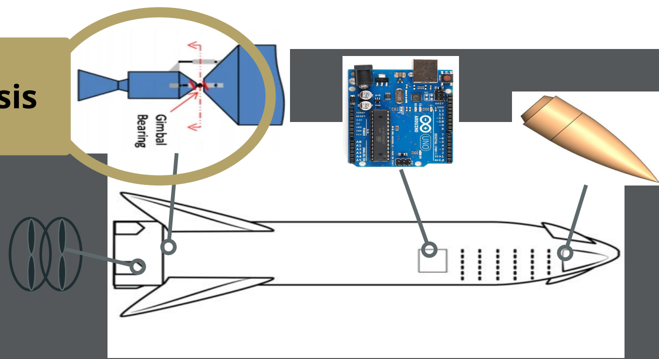
High-level wiring schematic

- Motors/Actuators need separate power input
- I2C communications preferred for sensors
- Modeled in CAD with connections in mind
- Will bench-test before mounting on rocket



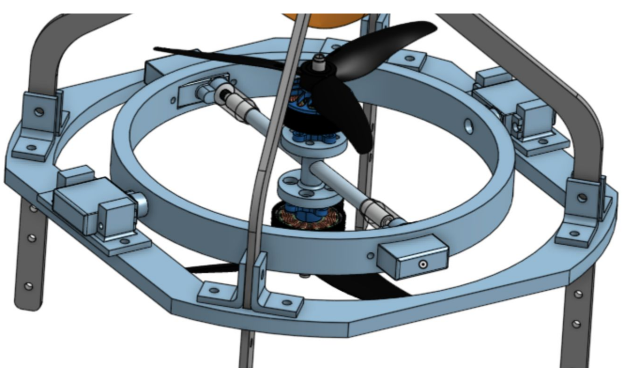
Thrust Vector Control (TVC)

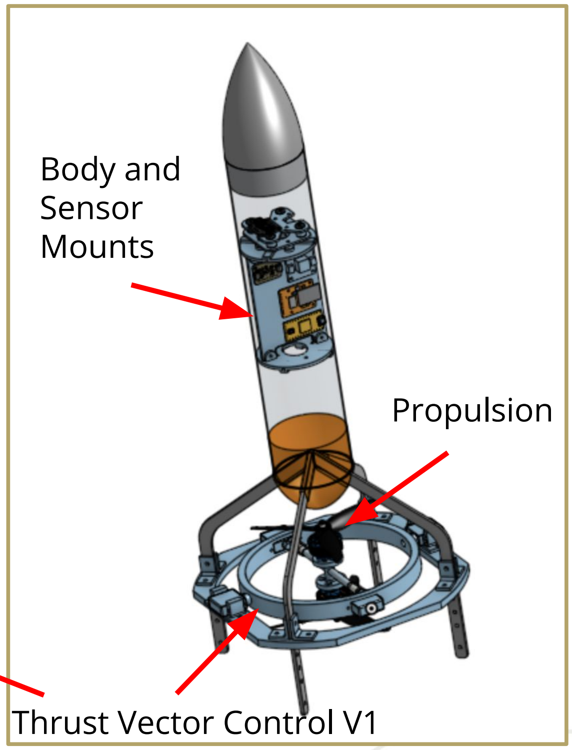
Area of analysis



Version 1 Prototype

- Have had two major designs so far
- Most changes relate to the TVC mechanism, however updates have been made to all subsystems

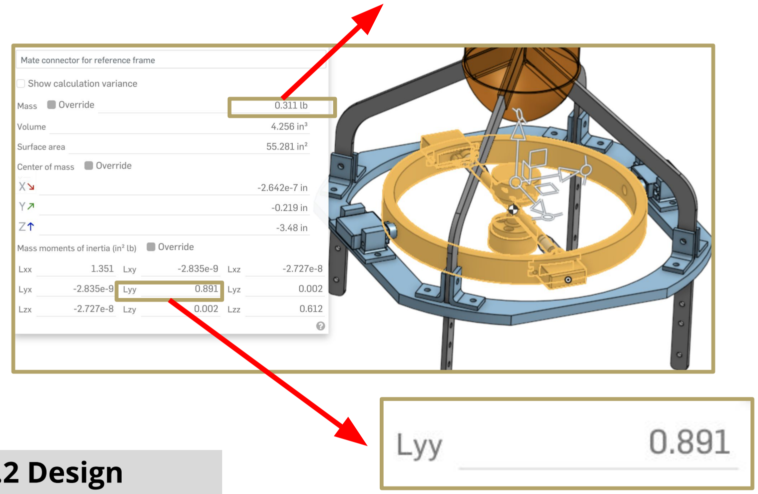




Version 1 TVC Mechanism

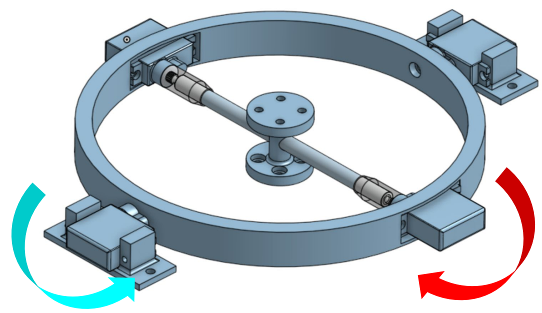
- Moment of inertia of .891 in^2*lb
- Design has weight problems
- Shaft is coupled to motors using epoxy and dual motor mount
- Outer servos couple directly to ring by using a heat insert of the servo spline

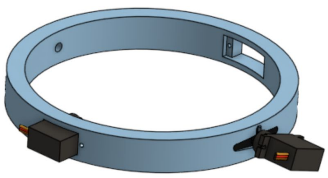
Mass = 141 grams



(260.74 Kg mm^2)

V1.2 Design





V1.1 Design

Version 1 TVC Mechanism

- Moment of inertia of .891 in^2*lb
- Design has weight problems
- Shaft is coupled to motors using epoxy and dual motor mount
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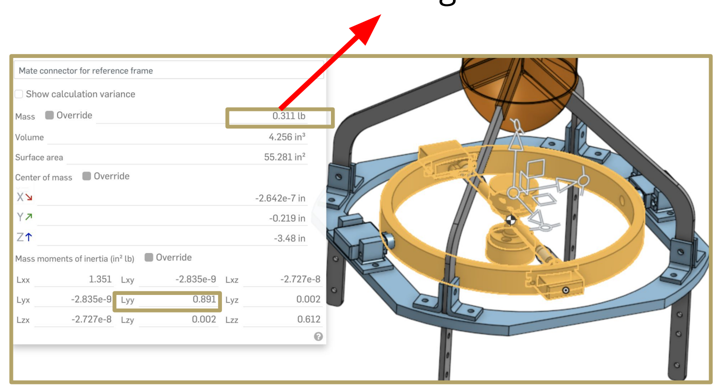
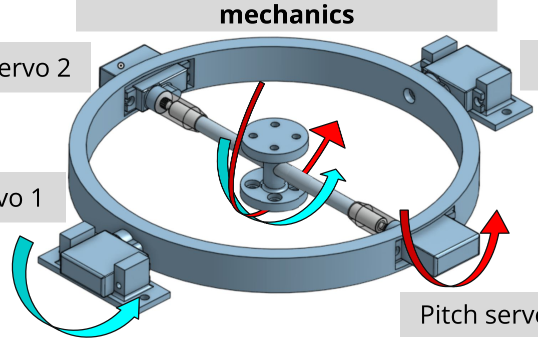
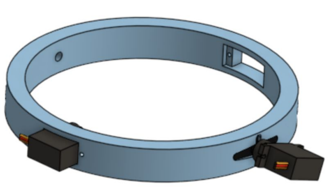
Mass = 141 grams



Pitch/roll actuation mechanics

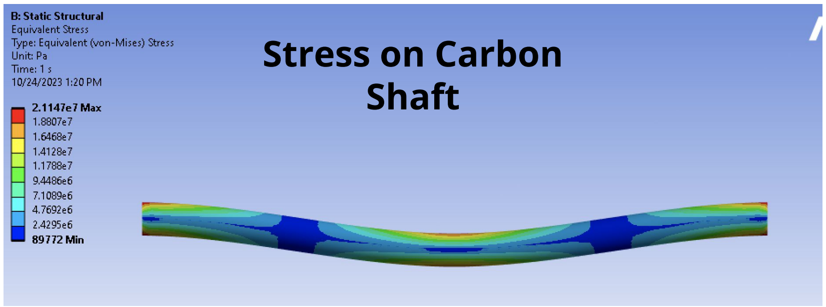


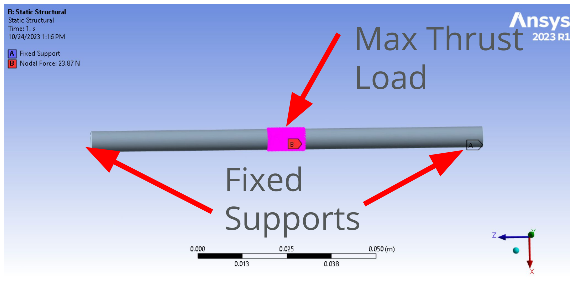


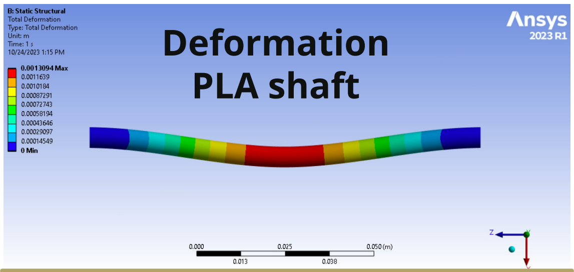
V1.1 Design

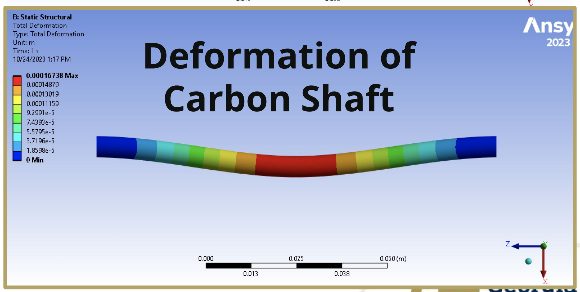
First shaft Bending Analysis

- Profiles of shafts look similar, however max deformation of carbon tube is .16mm while PLA is 1.3mm
- Max stress of PLA is about half that of critical stress, while carbon is about 4 magnitudes off





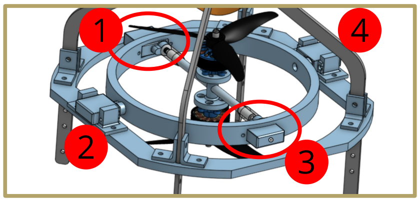




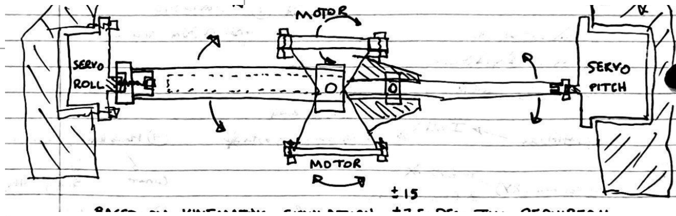
TVC Iteration Rationale

Benefits/Issues with V1 TVC mechanism:

Benefits	Issues
Low mechanical backlash/play	Increased rotational inertia (reduced TVC mechanical bandwidth - BAD!)
Low friction rotation (utilizes internal servo bearings)	Increased system frontal area (increased vehicle drag)
Superior torque due to multiple actuators per axis	Multiple actuators (4x servos total)
Isolated/independent actuation of roll/pitch	Increased system mass

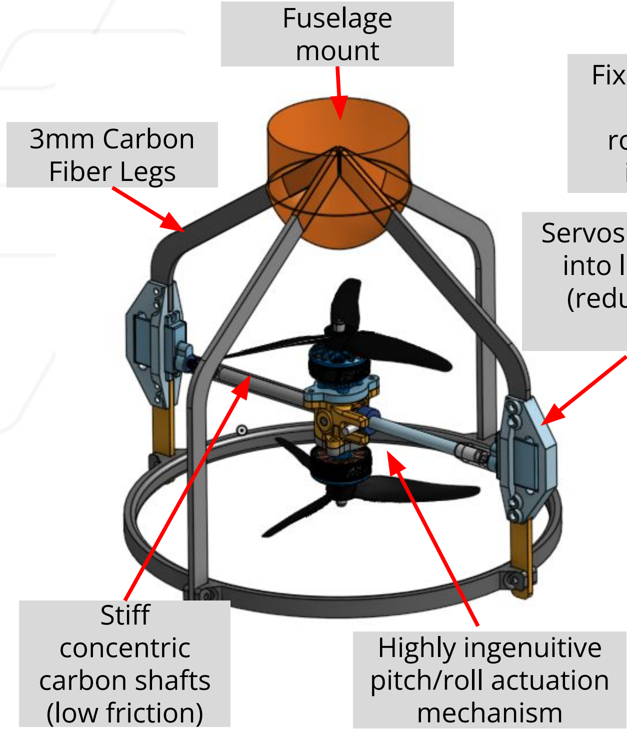


Can a TVC mechanism be designed that reduces system rotational inertia, frontal area, actuator complexity, mass?

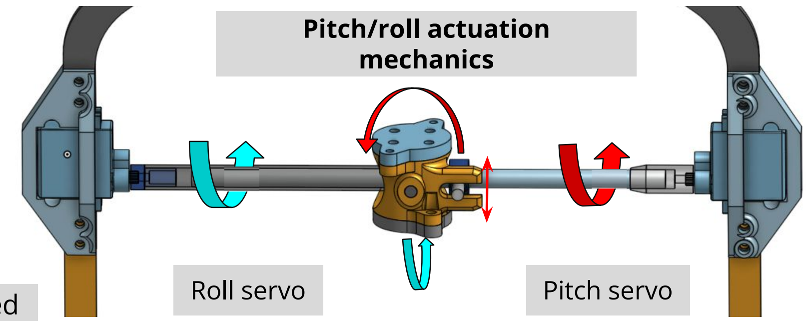


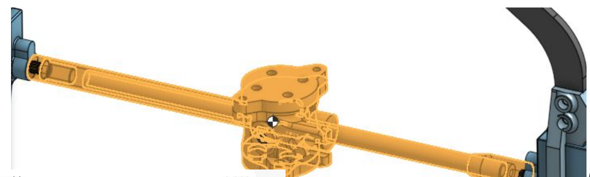
Yes! Interesting mechanism capable of meeting all requirements!

Version 2 TVC Mechanisr

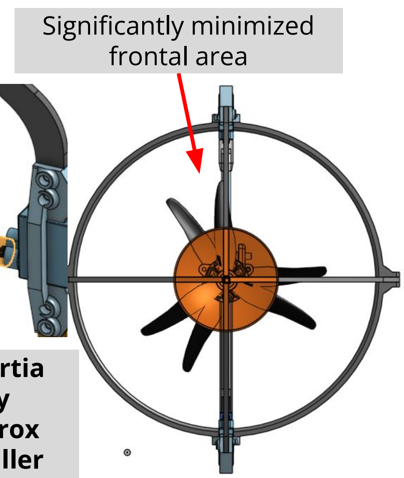


Clearance for up to 6” propellers





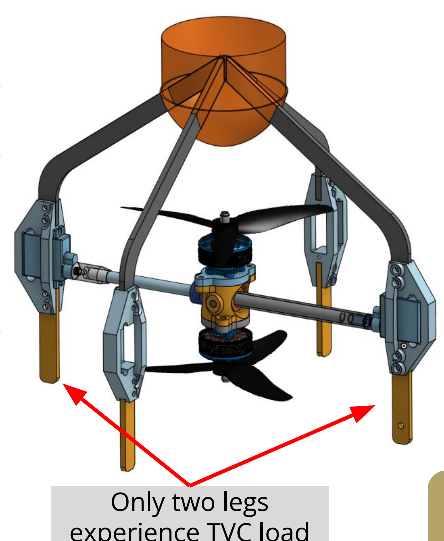
Mass	Override				0.022 kg
Volume					16765.848 mm³
Surface area					20602.495 mm²
Center of mass	Override				
X					6.022 mm
Y					-5.001 mm
Z					107.675 mm
Mass moments of inertia (kg mm²)	Override				
Lxx	23.243	Lxy	-0.001	Lxz	-4.157e-4
Lyx	-0.001	Lyy	23.391	Lyz	0.151
Lzx	-4.157e-4	Lzy	0.151	Lzz	2.104

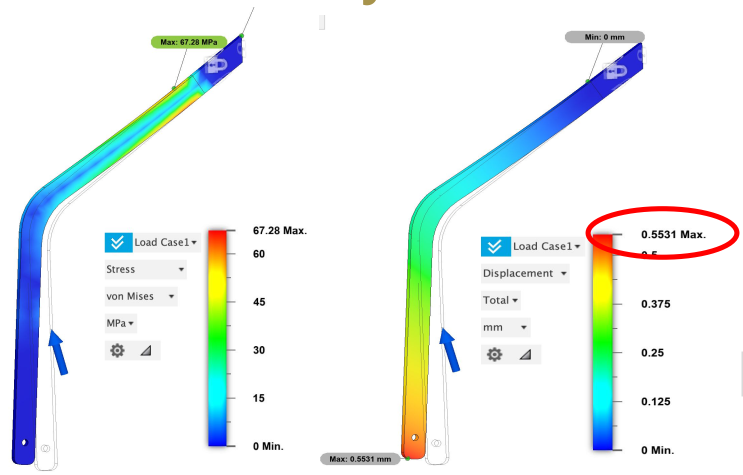


Rotational inertia significantly reduced - approx 123 times smaller than V1 TVC!

Landing Gear Stiffness Analysis

V2.1 Design





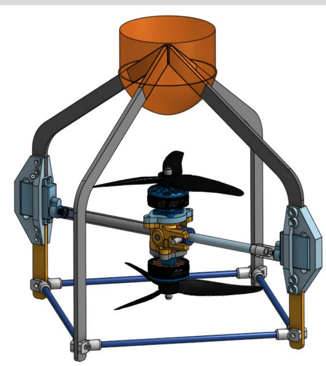
FEA max deflection: 0.5531mm vs. Hand calc deflection: 0.361mm

$$\delta_A = \frac{FL^3}{A \times EI}$$

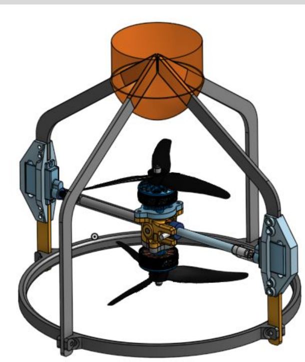
Where A=2 when legs coupled together

Adding rigid body between legs **reduces landing gear deflection and stress by 50%**

V2.2 Stiffener



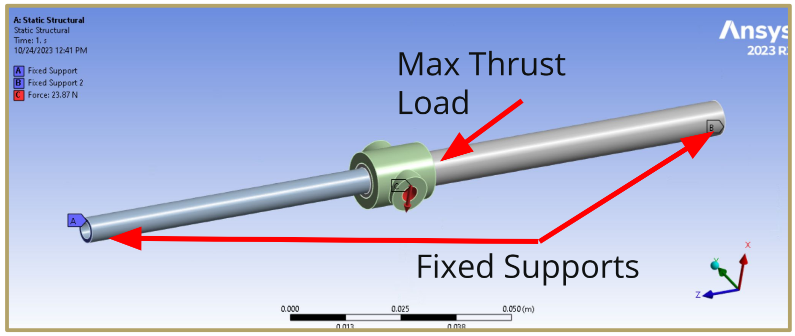
V2.3 Stiffener

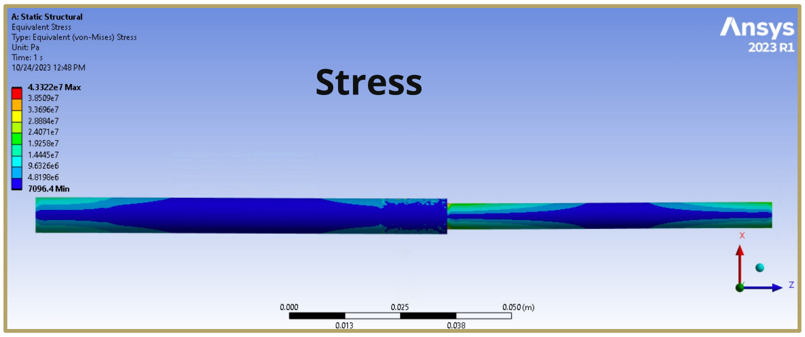


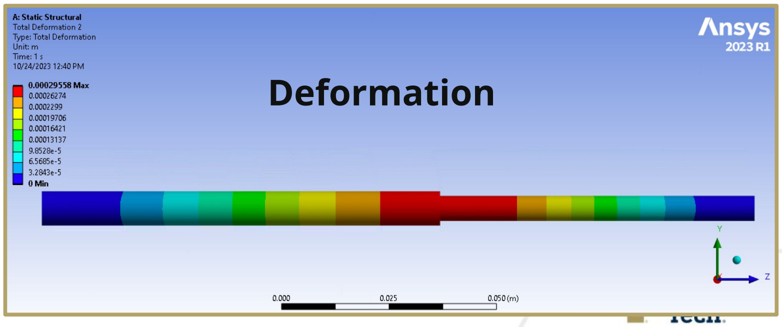
Outstanding alignment between hand calcs and FEA analysis! Very little deflection

Concentric Shaft Bending Analysis

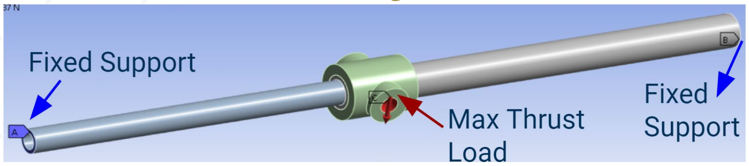
- FEA shows max deformation of .3 mm for carbon tubes
- Shows max stress of .043 GPa (About **4 magnitudes** away from critical stress)

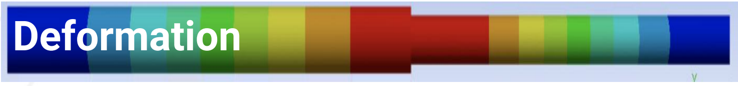






FEA Summary

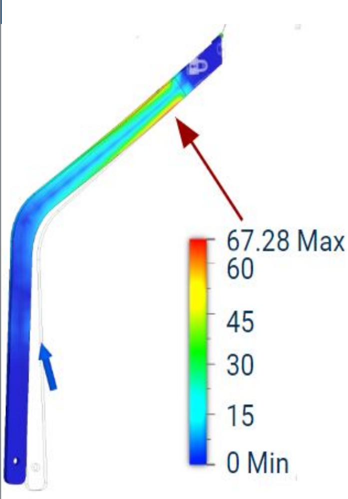


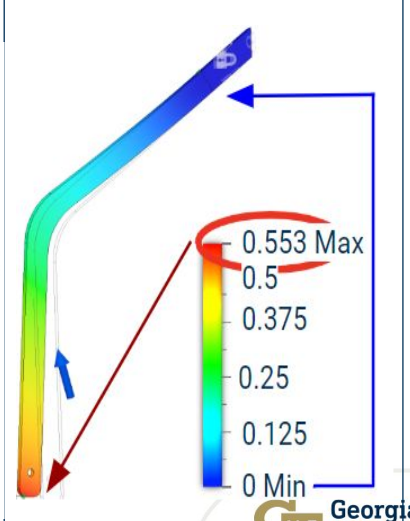


Material	Max Deformation of Tubes (mm)	Max Stress in Tubes(% of Crit.)
PLA	1.3	50 %
Carbon Fiber	0.3	0.016 %

FEA max deflection of .553 mm vs .361mm by hand calculations

Stress	Deflection





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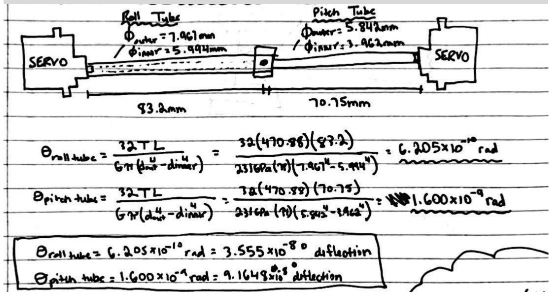
TVC Backlash Calculations

Operating in semi-open loop servo control, so **minimization of mechanical backlash/play is critical!**

V1 TVC

Version 1: Traditional Concentric Ring TVC Mechanism			
		Roll Axis	
Roll shaft angular deflection	9.25E-10	rad	Beam under torsion equation
Roll shaft angular deflection	5.30E-08	deg	Conversion
Combined total roll backlash	0.10	deg	Sum of individual mechanism component deflections
Backlash percent of total travel	0.67%	%	Backlash compared to total axis angular deflection
		Pitch Axis	
Pitch shaft angular deflection	9.25E-10	rad	Beam under torsion calculation
Pitch shaft angular deflection	5.30E-08	deg	Conversion
Combined pitch backlash	1.00E-01	deg	Sum of individual mechanism component deflections
Backlash percent of total travel	0.67%	%	Backlash compared to total axis angular deflection

Shaft angular deflection calcs



V2.3 TVC

Version 2: Double Pivot Concentric Shaft TVC Mechanism			
		Roll Axis	
Roll shaft angular deflection	6.31E-10	rad	Beam under torsion equation
Roll shaft angular deflection	3.62E-08	deg	Conversion
Backlash center coupler joint	0.00506	rad	Caclulated based on pivot joint tolerance
Backlash center coupler joint	0.290	deg	Conversion
Combined total roll backlash	0.39	deg	Sum of individual mechanism component deflections
Backlash percent of total travel	2.60%	%	Backlash compared to expected max angular deflection
		Pitch Axis	
Pitch shaft angular deflection	1.88E-09	rad	Beam under torsion calculation
Pitch shaft angular deflection	1.08E-07	deg	Conversion
Backlash center coupler joint	0.01	rad	Caclulated based on pivot joint tolerance
Backlash center coupler joint	0.29	deg	Conversion
Backlash sliding pitch coupler	0.003199989077	rad	
Backlash sliding pitch coupler	0.1833458686	deg	Conversion
Combined pitch backlash	0.57	deg	Sum of individual mechanism component deflections
Backlash percent of total travel	3.82%	%	Backlash compared to expected max angular deflection

V2.3 TVC has 3x larger backlash (primarily due to increased mechanical complexity) than V1 TVC. ***However, total backlash of both mechanisms is less than 4% of expected angular deflection (+/- 15 deg).***

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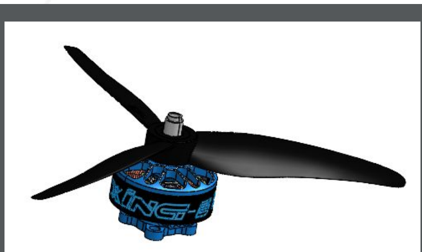
TVC Backlash Calculations Summary

Key Performance Indicators		Spec.
Roll Backlash %	**2.6%**	**≤4%**
Pitch Backlash %	**3.92%**	**≤4%**

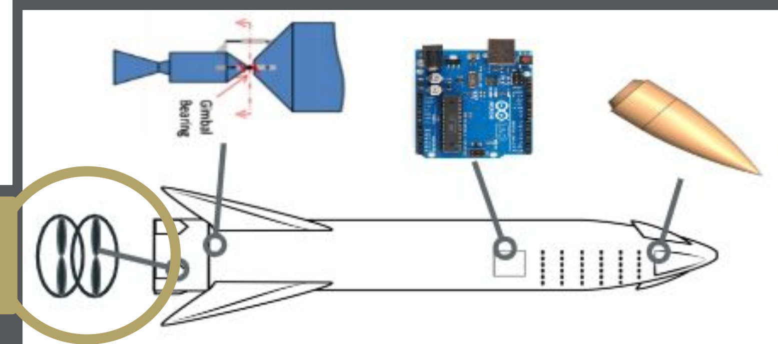
V2.3 TVC has 3x larger backlash (primarily due to increased mechanical complexity) than V1 TVC. ***However, total backlash of both mechanisms is less than 4% of expected angular deflection (+/- 15 deg).***

Georgia Tech

Propulsion



Area of analysis



Propulsion

V1: XING-E Pro 2207 2-6S FPV Motor

V2: XING2 2207 4S 6S FPV Motor

	Max. Thrust	Efficiency at ~1390g thrust
V1	1391 g	2.437 g/W
V2	1576 g	2.551 g/W

V1/V2: 51466 Tri-Blade 5.1" Prop

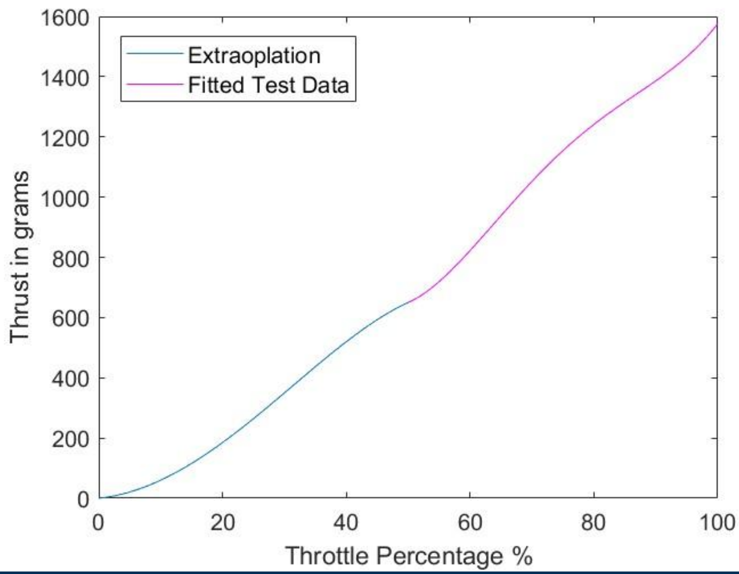
- Compatible with motor

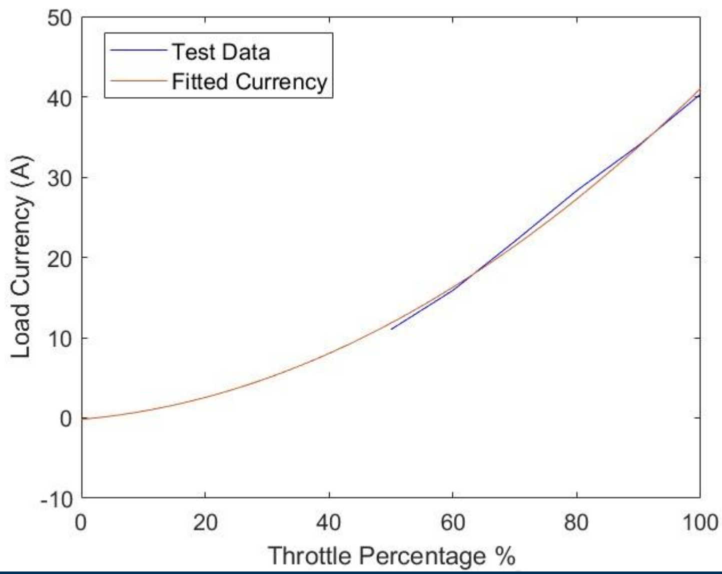
V1/V2: Tattu R-Line 1050mAh 95C 4S1P Lipo Battery Pack With XT60 Plug

- 72.5mm Length x 35.5mm Width x 24.5mm Height
- 119.5g

Propulsion Analysis - 1 Motor

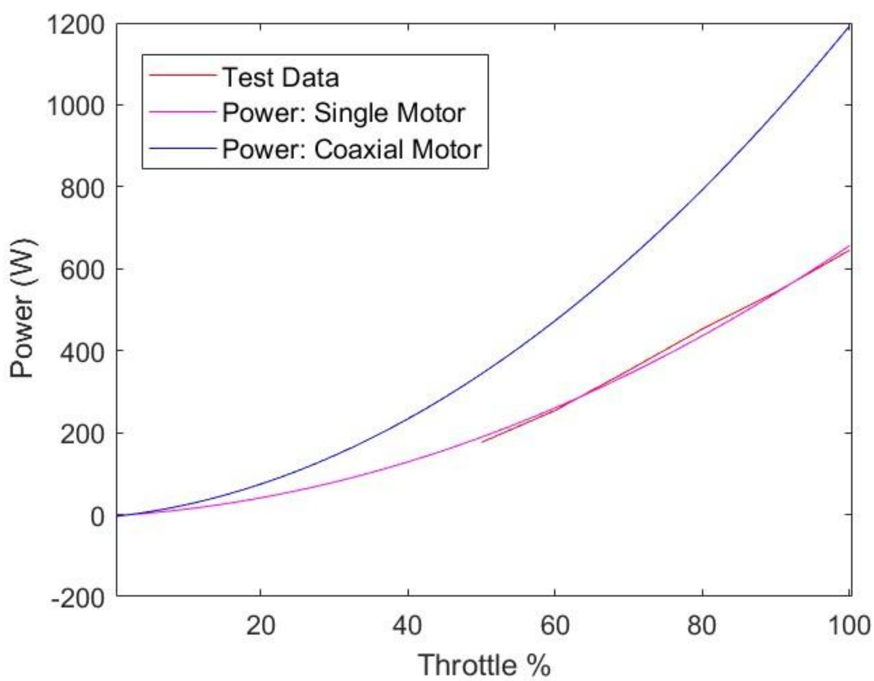
- Throttle % vs
  - Thrust in grams conversion
- Currency Estimate





Propulsion - 2 motors

- Throttle % vs
  - Single motor & coaxial motor : propeller power produced



- Thrust to Weight Ratio:

$$\frac{Efficiency\ Factor\ of\ 2\ motors \times Maximum\ Thrust}{Weight\ of\ Entire\ System} = \frac{1.8116 \times 1576g}{461.96g} = 6.18$$

Georgia Tech

Propulsion Calculations

$$Flight\ Time = \frac{Battery\ Ah\ Rating}{Load\ Currency\ \times number\ of\ motors}$$

$$@\ 100\%\ Throttle\ = \frac{1.05\ Ah}{40.35\ A\ \times 2}\frac{60\ mins}{1\ h} = 0.78\ mins$$

$$@\ 50\%\ Throttle = \frac{1.05\ Ah}{11.02\ A\ \times 2}\frac{60\ mins}{1\ h} = 2.86\ mins$$

$$@\ 33\%\ Throttle(Hover) = \frac{1.05\ Ah}{8\ A\ \times 2}\frac{60\ mins}{1\ h} = 7.875\ mins$$

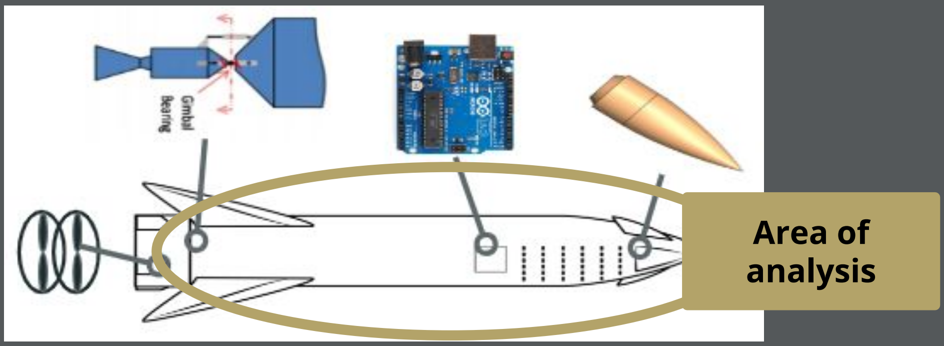
$$Linearized\ deceleration\ (0-33\%\ Throttle): \frac{1.05\ Ah}{5.5\ A\ \times 2}\frac{60\ mins}{1\ h} = 11.455\ mins$$

$$Total\ Estimated\ Flight\ Time =$$

$$0.78\min(10\%) + 2.86mins(40\%) + 7.875mins(30-50\%) + 11.455mins(0-20\%) =$$

$$5.876\ mins\ \ -5.16\ mins$$

Rocket Structure/Mounts



Body Tube Selection

- Transparent frame
- Large enough diameter to comfortably fit all required components
  - > 43mm diameter
- Minimize frontal area
- Length considerations

V1.0 Fuselage (76mm)

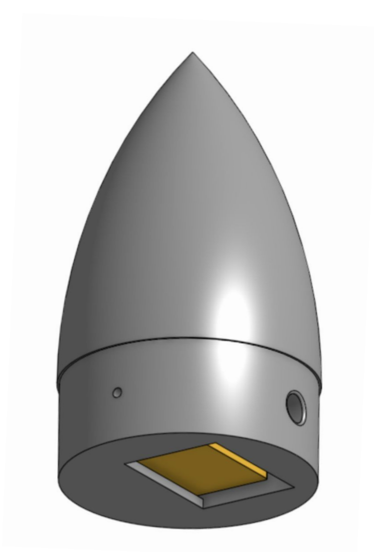
V1.1 Fuselage (66mm)

Fuselage Frontal Area Calculations			
Variable	Value	Units	Notes
Minimium tube diameter for battery	43.13351365	mm	Based on Tattu 1050mAh 4s battery pack
76mm Fuselage Tube			
66mm tube outer diameter	76.2	mm	From Apogee Rockets spec sheet
66mm tube inner diameter	74.4	mm	From Apogee Rockets spec sheet
66mm tube wall thickness	0.90	mm	Beam under torsion equation
Frontal Area	4,560.37	mm^2	Based on fuselage tube area
Does it fit the battery?	Yes		
Frontal Area Comparison			
66m Fuselage Tube			
BT70 tube outer diameter	66	mm	From Apogee Rockets spec sheet
BT70 tube inner diameter	65	mm	From Apogee Rockets spec sheet
BT70 tube wall thickness	0.50	mm	Beam under torsion equation
Frontal Area	3,421.19	mm^2	Based on fuselage tube area
Does it fit the battery?	Yes		
Comparison of frontal area difference	1,139.17	mm^2	BT70 as compared to origional 66mm tube
Percent frontal area reduction	24.98%	%	BT70 as compared to origional 66mm tube
For this reason, the 66m fuselage tube is the ideal solution for this application!			

Nose Cone

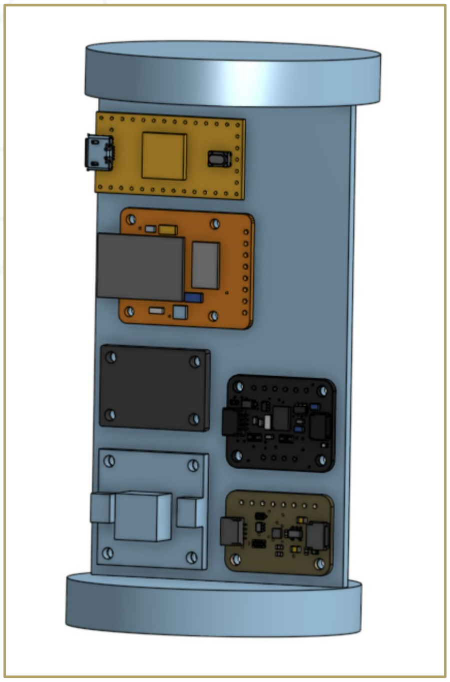
V1.0 Nose Cone

V1.2 Nose Cone



- Reduced size
- 55.035 g vs 86.462 g
- Bolt holes for mounting
- Press fit battery storage
  - Enhanced CG placement
- Battery heating → ~9.95 W operating at maximum discharge rate
  - Inconsequential thermal expansion less than 1/500 of original dimensions

Sensor Mount V1



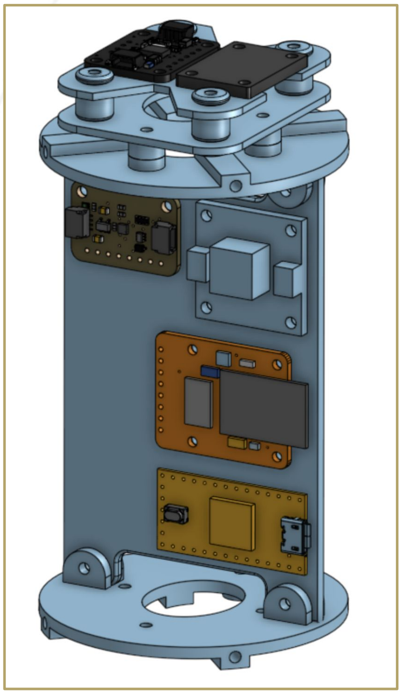
Goal:

- Provide accessible mount containing all sensors in one central package

Determined flaws:

- IMUs require **vibration dampening**
- Difficult to 3D print as one structure
- Risk of **structure failure** when mounting into rocket
- Poor wiring compatibility
- Limits modularity

Sensor Mount V1.2



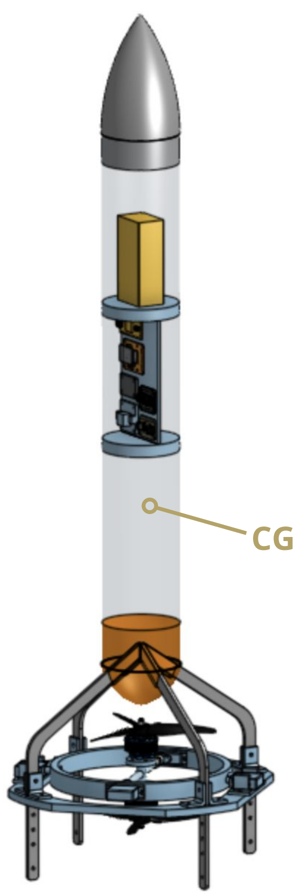
- Provides IMU vibration dampening with silicon rubber spacers
- Reduction in part weight from 25.9675 g to 13.0267 g
- Ease of 3D-printing with individual components
- Provided wire conduits
- Bolt connections allow for modularity of part

Final CAD Assembly

Final Structure

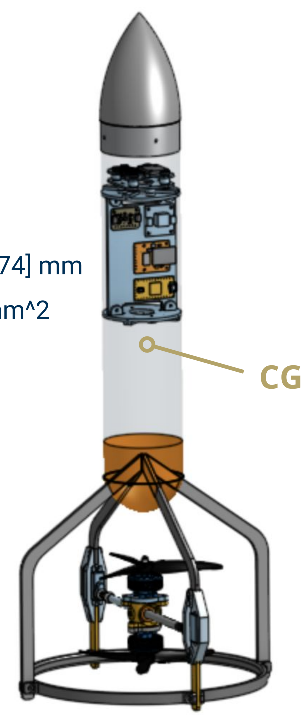
Preliminary Design:

- 574.207 g
- Cg = [-0.3472, 0.2441, 346.5941] mm
- Gimbal Moment: 260.74 Kg*mm^2



Final Design:

- 461.9586 g
- Cg = [0.1302, 0.0713, 303.9474] mm
- Gimbal Moment: 2.104 Kg*mm^2



Rapid Prototyping

Phase III

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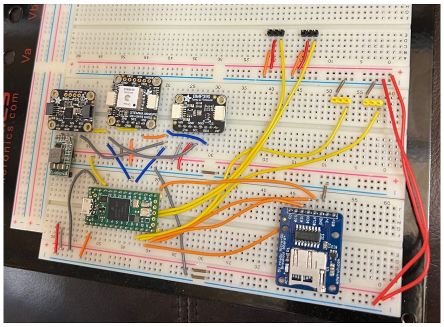
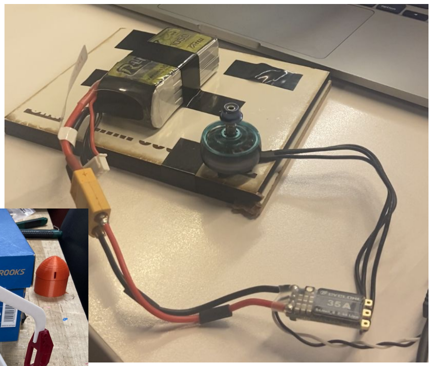
Prototyping Philosophy

Segment the prototyping/validation into simpler units that allow for validation of individual subsystems followed by a final whole vehicle validation

- Assemble sub-systems
- Validate function of sub-systems through testing
- Integrate systems
- Entire vehicle validation/testing





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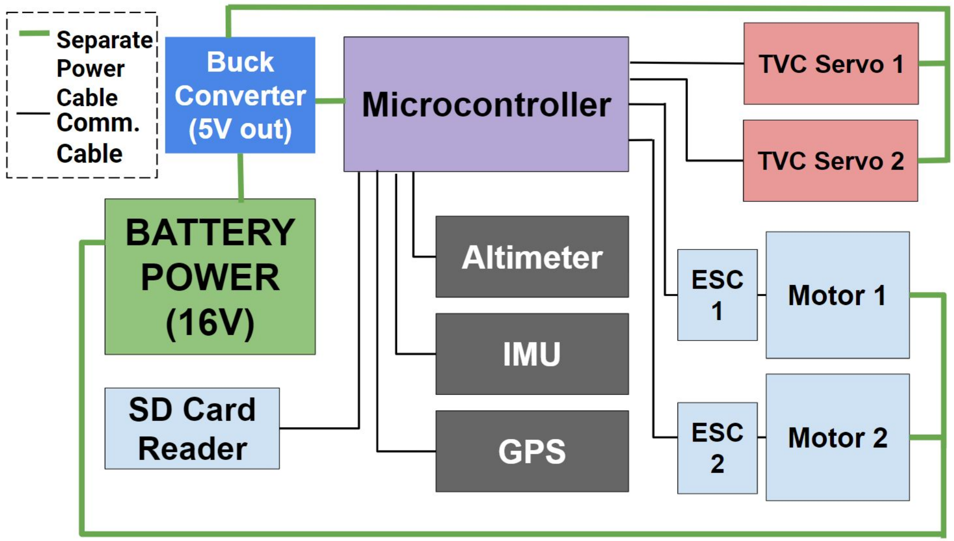
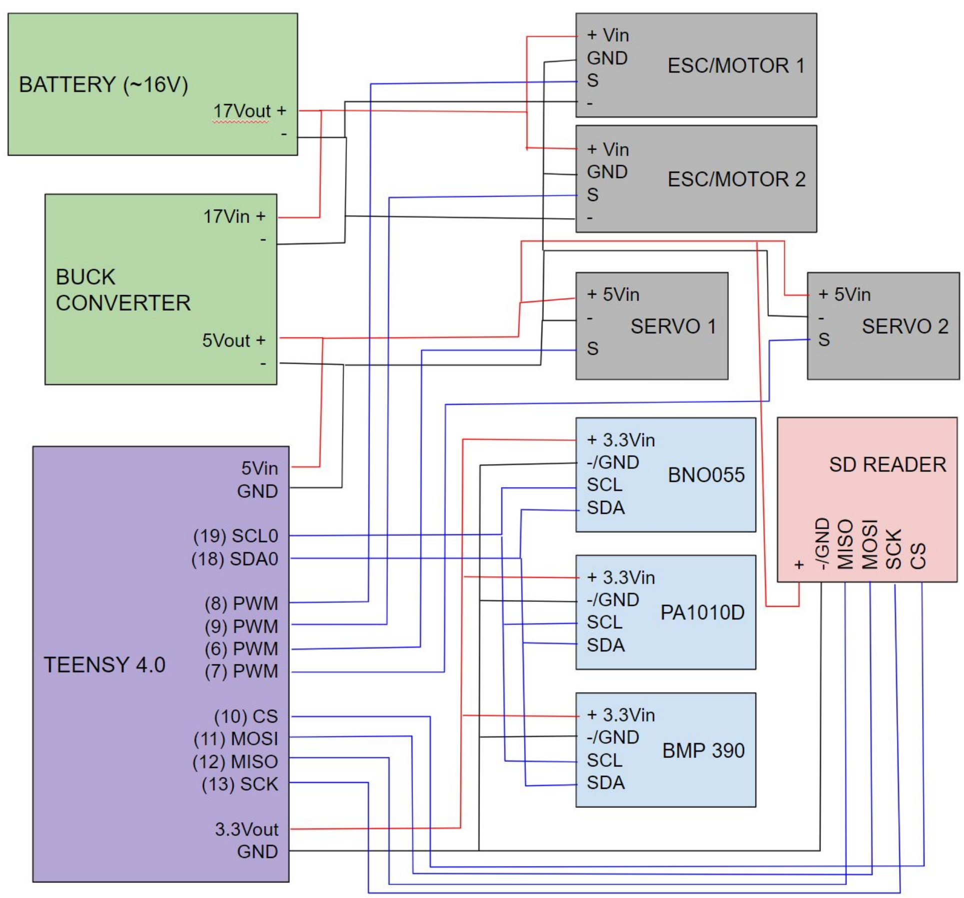
Electronics/Sensors

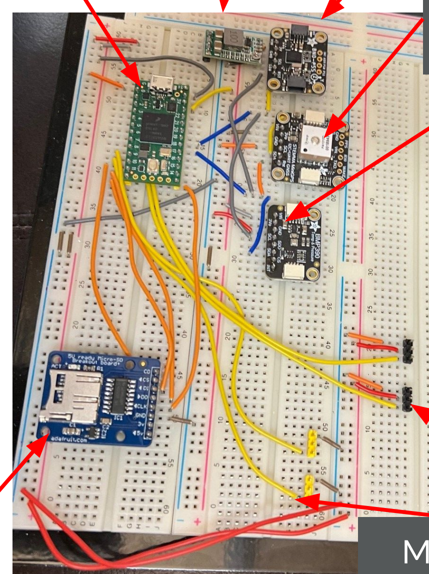


Detailed Wiring Schematic

- Integrates all necessary data components, power supplies
- Outlines specific pins and communications
- Allows for data to be processed at central location and stored



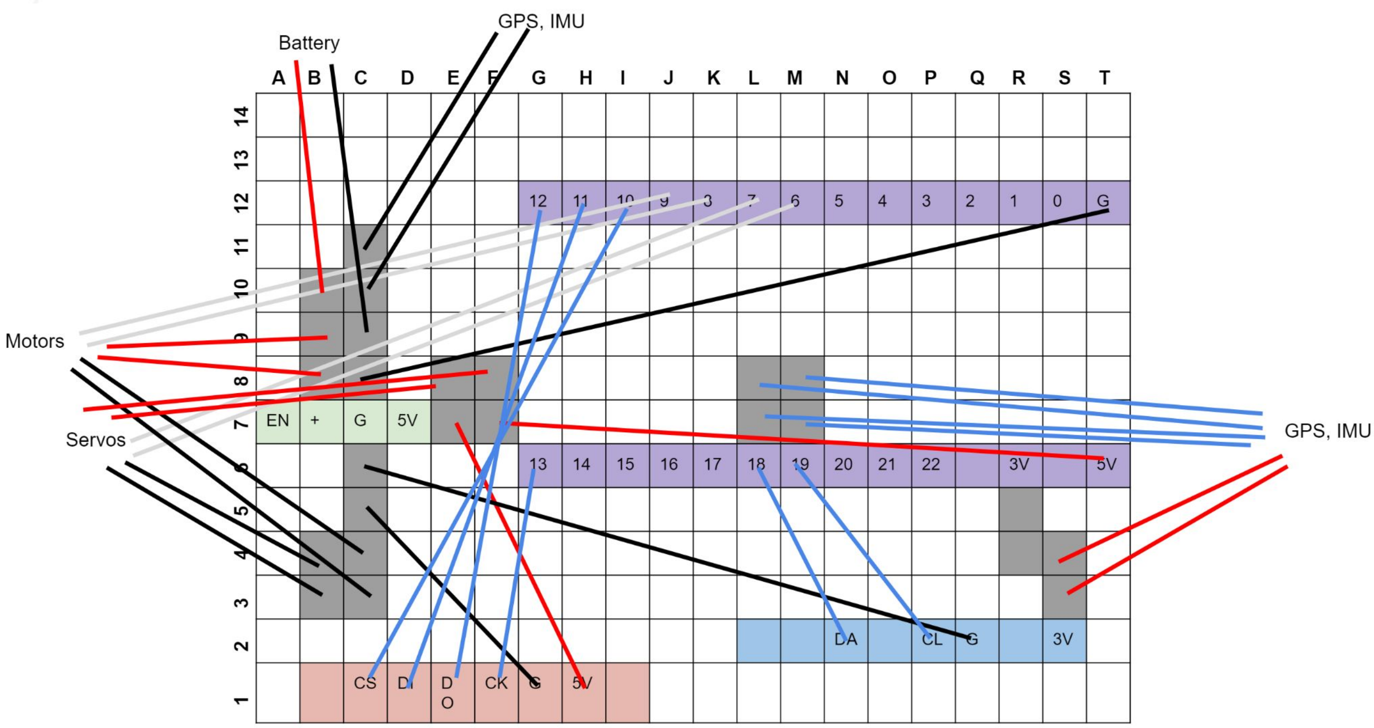
- Used solderless breadboard to test connections
- Developed basic code to feed data from all sensors
- Sample output of IMU, altimeter data shown on right
- Should allow for integration of raw data into any flight control algorithm



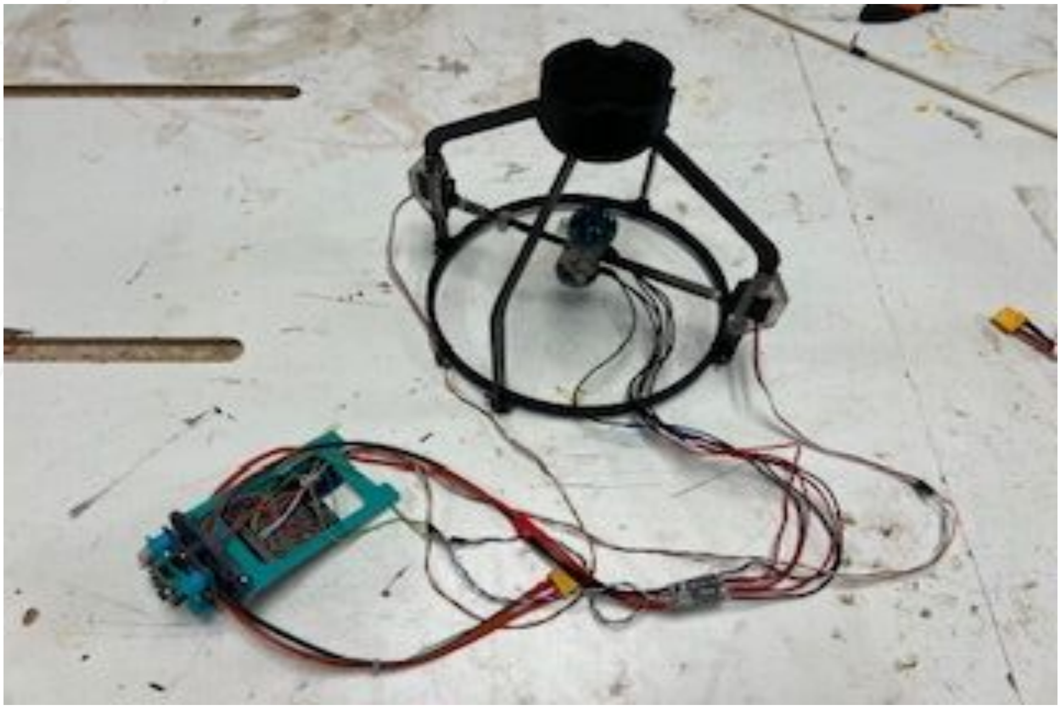
Example Communications

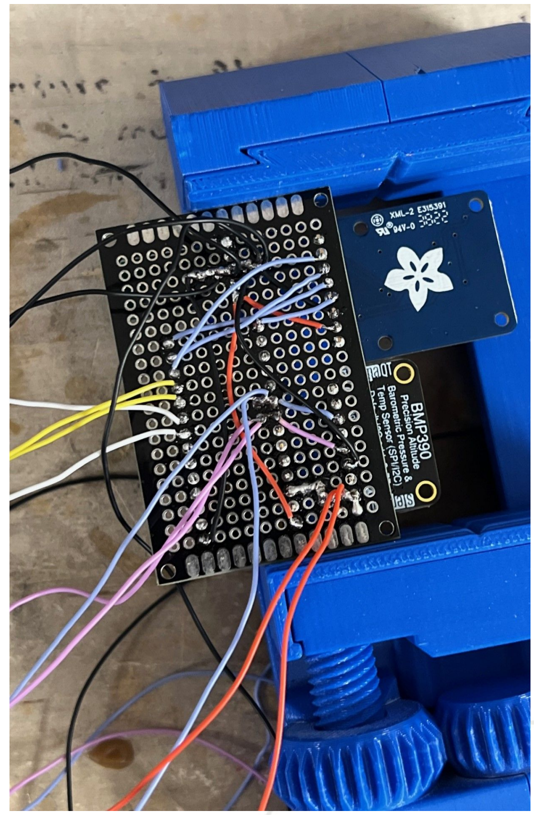
```
Orientation: 0.00, 0.00, 0.00
Temperature: 25.00 °C
Pressure: 98794.03 Pa
Orientation: 359.87, -4.87, 10.75
Temperature: 25.01 °C
Pressure: 98802.99 Pa
Orientation: 359.69, -5.19, 10.63
Temperature: 25.03 °C
Pressure: 98799.12 Pa
Orientation: 2.06, -17.62, 3.69
Temperature: 25.03 °C
Pressure: 98800.18 Pa
Orientation: 357.25, -8.25, -9.94
Temperature: 25.05 °C
Pressure: 98801.02 Pa
Orientation: 1.75, -2.81, 21.75
Temperature: 25.06 °C
Pressure: 98796.08 Pa
Orientation: 358.87, -9.63, 8.06
```

Iteration 2 (Soldering Schematic)



Prototyping Iteration 2

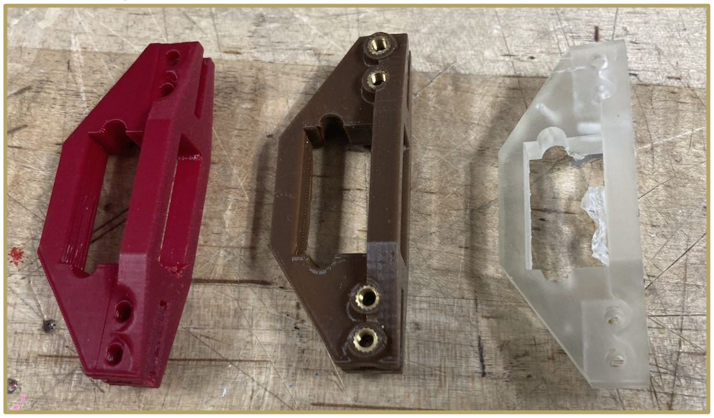


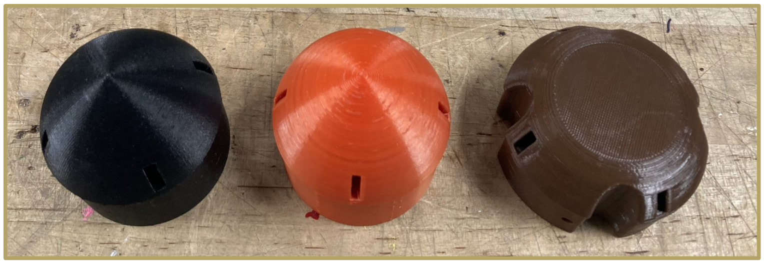


Thrust Vector Control (TVC)

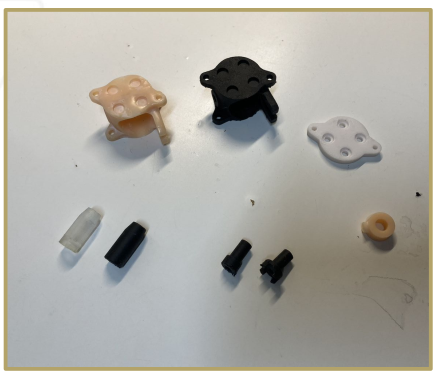
TVC Iteration

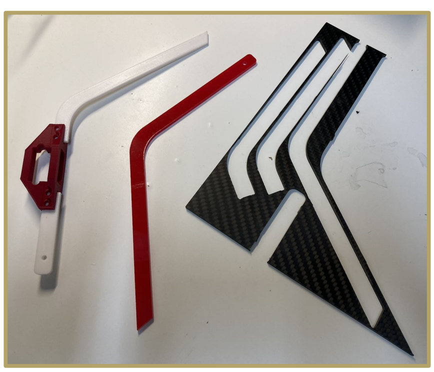
Given the mechanical complexity of the TVC system, extensive prototyping and iteration occurred…





More Iteration





Pitch/Roll

- Two servos mounted directly across from each other
- Creates two axis of freedom with lever arm on smaller shaft (Purple arrows)

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Pitch/Roll

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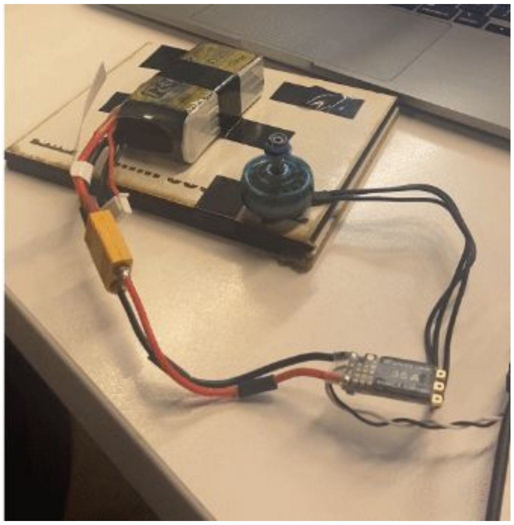
Propulsion

Sub-system Testing: Motor Testbed

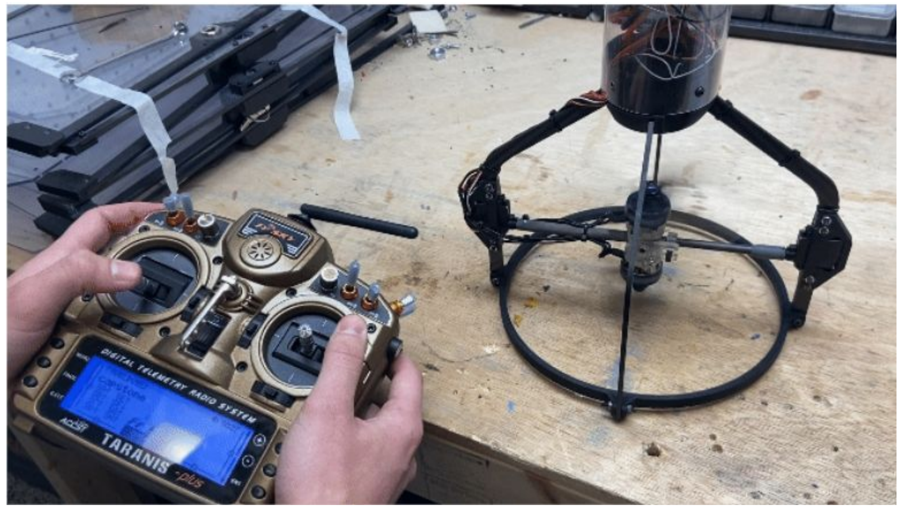
- Allows for independent bring up of motor/ESC controls without needing the full vehicle
- **Validation:**
  - Compatibility with battery, microcontroller, & ESC
    - Were unsure if BL_Heli ESC's compatible with PWM communication
  - Software integration
    - High fidelity control of motor velocity via PWM



Sub-system Testing: Propulsion Testing

Validation:

- Propulsion system (propellers, motors, ESC, LIPO battery) performs as expected
- Co-axial propellers capable of yaw control



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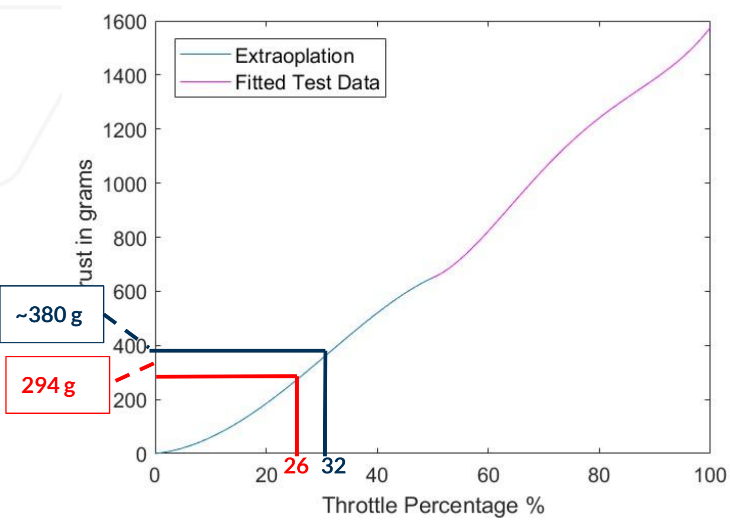
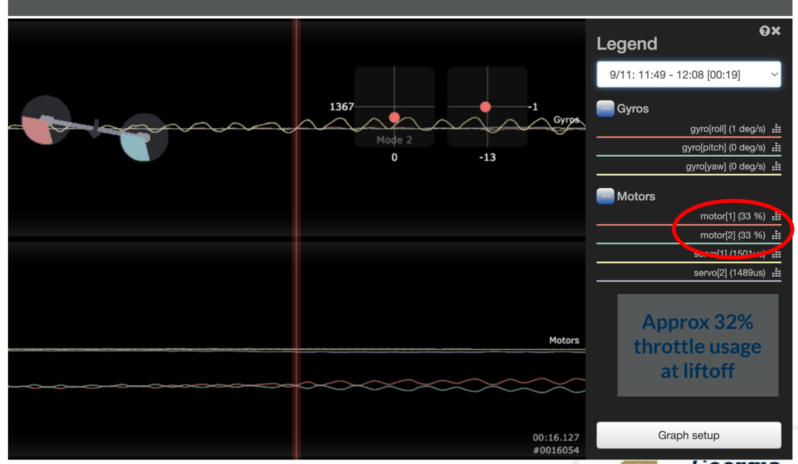
Expected vs. Actual Throttle % Needed for Lift-off

Expected Throttle Curves



Flight Testing Data Logging Analysis At Liftoff



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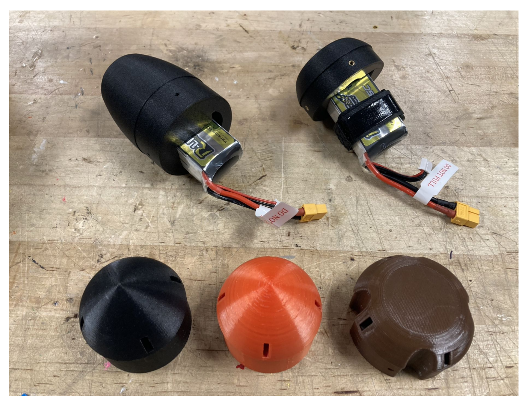
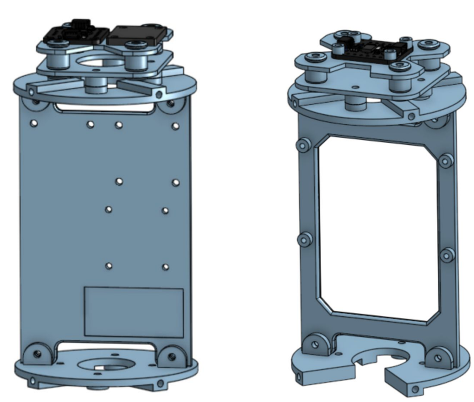
Rocket Body & Assembly

Rocket Fuselage Prototyping





- Change in material of large parts (Standard PLA → Light weight PLA)
  - Weight reduction of 87 g
- Modified nose cone to reduce size + better fit wired battery
- Altered TVC fuselage mount to provide ample wire routing passages
- Sensor mount changed to fit full proto-board + allow for better wiring
- Incorporation of heat-set inserts (reduces chances of stripping/cross threading plastic)

Final Product

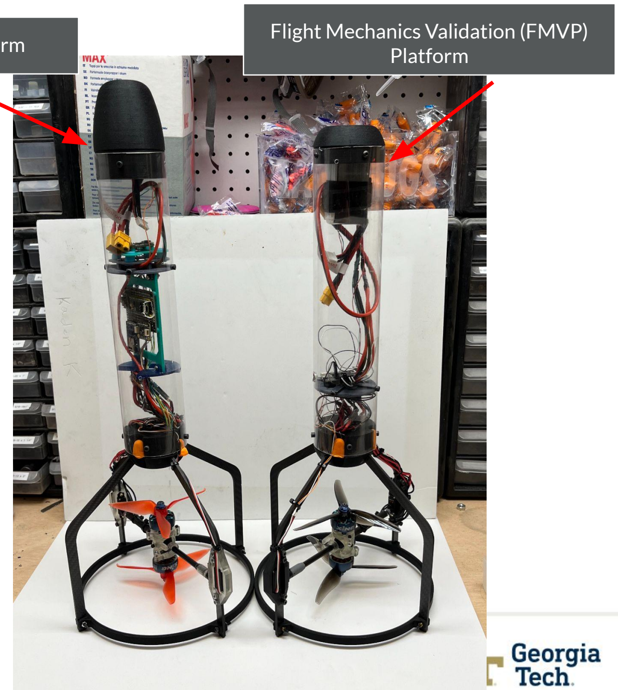
The Need For Two Rockets!

Background:

- Electronics bring-up highly intensive and complicated
  - Tumultuous debugging and iteration of code to get desired actuator outputs

Rationale:

- Needed a way to **parallel process** electronics bring-up and validation of the TVC mechanics + first flight
- Used an highly modified off the shelf multirotor flight controller (Flip 32 F4) and open source firmware (initially BetaFlight then iNAV)
  - Extensive actuator mixing required



Experimentation of Flight Mechanics Platform (FMVP)

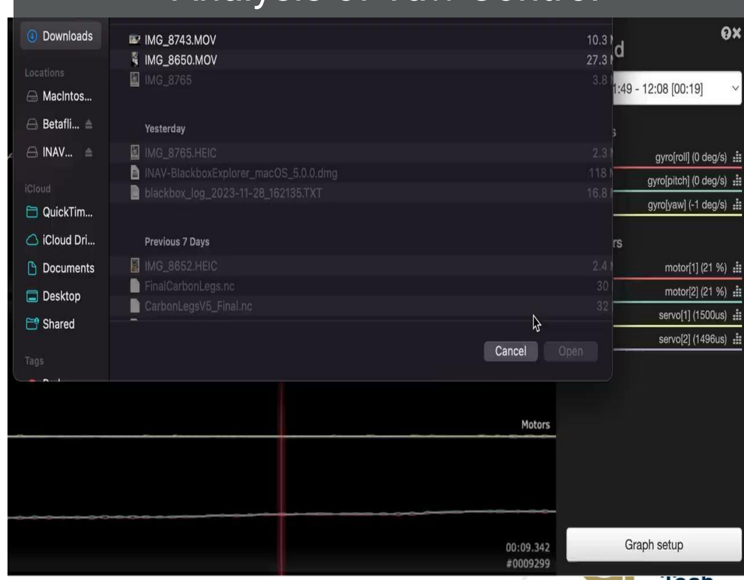
Initial Platform Testing

Rough Tuning

Analysis of Flight Logs (iNAV Blackbox Explorer)

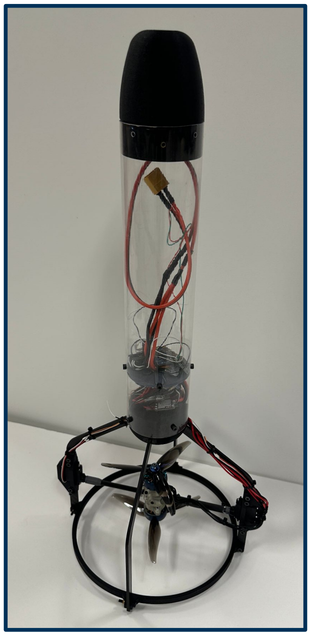
Analysis of Roll/Pitch Control

Analysis of Yaw Control



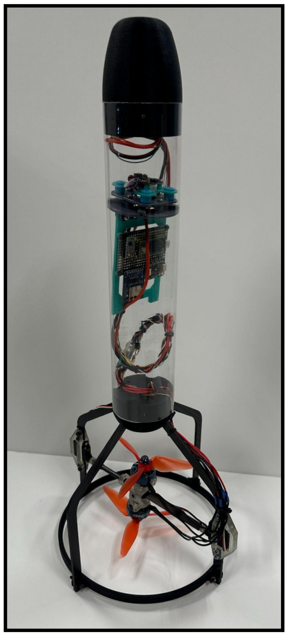
Compared Rocket Final Platforms

Flight Mechanics Validation Platform



Testing flight through open source flight controller and firmware

Combined Rocket Platform



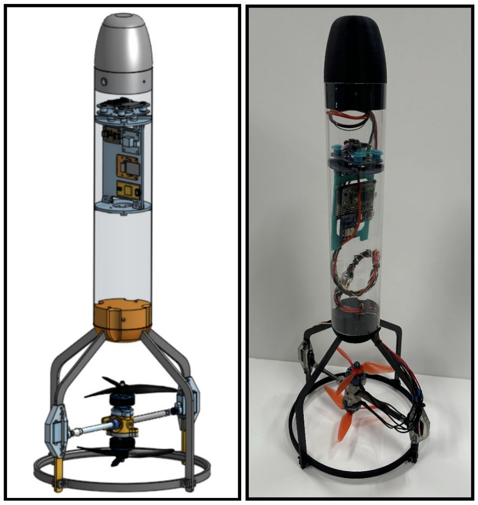
Identical to FMCP system but with more ideal custom electronics

Platform Accessibility

Github Page

Project Description

The goal of this project is to provide research groups and hobbyists with an open source, drone motor, rocket build that they can copy and modify to implement control algorithms. This page contains details on the required materials and tools as well as build instructions.



Fabrication Techniques and Materials

The following machines will be needed for fabrication

1. FDM Printer
2. Resin Printer
3. Desktop CNC Router
4. Soldering Iron
5. Drill
6. Dremel

Additionally, a full list of materials with links to purchasing sites can be found here(insert link to excel)

Build/Assembly

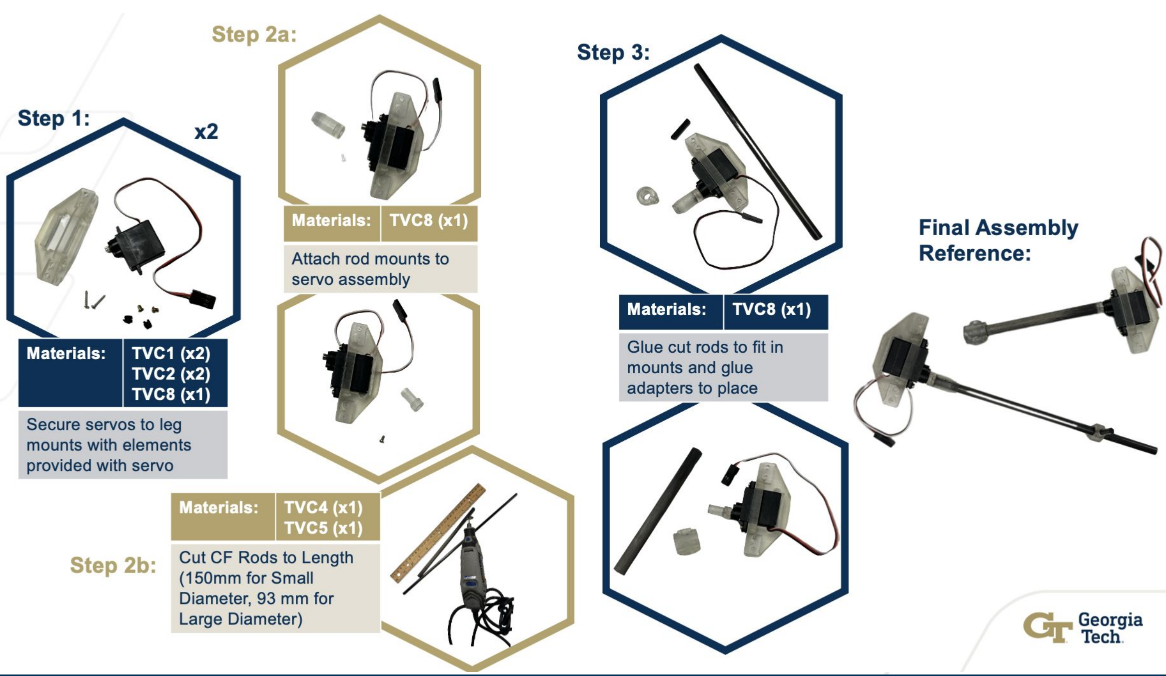
There are three main components to this build. The first is machining, printing and cutting parts. The second is soldering the circuit schematic together and the third is epoxying and bolting together the full assembly.

Step 1: Machining, Printing and Cutting

The parts to print are seperated into resin and FDM parts and can be found here(insert link to stls). The resin parts require higher fidelity; for example, the servo couplers which need to mate to a spline which has teeth size on the order of a single millimeter. The FDM parts are generally larger and require less fidelity. A lightweight material called (insert name of robbie material) was used with low infill to reduce the wieght of these larger parts.

Instruction Manual

- Downloadable and print-friendly assembly manual
- Contains 3D prints, part orders, bill of materials, required tools and step-by-step assembly



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Bill of Materials

Component Number	Body Structure [BS]	Sensors and Battery [S&B]	TVC Mechanism [TVC]	Thrust [TR]
1	56 mm X 10" Clear Tube (x1)	Tattu R-Line 1050mAh 95C 4S1P Lipo Battery Pack (x1)	Corona DS-843MG (x2)	iFlight XING2 2207 4-6S Brushless Motor (x2)
2	Sensor mount plate (x1)	Adafruit Mini GPS PA1010D - UART and I2C - STEMMA QT (x1)	Provided Servo Connectors (x2)	Electric Speed Controller (x2)
3	Sensor mount connector (x2)	Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout - BNO055 (x1)	Carbon Fiber Sheet 300x400x3MM (x1)	Propellers (x2)
4	3D Printed Nose Cone (x1)	Adafruit BMP390 - Precision Barometric Pressure and Altimeter (x1)	Large Diameter Carbon Fiber Rod (x1)	
5	M2 x 6mm (x12)	MicroSD card breakout board+ (x1)	Small Diameter Carbon Fiber Rod (x1)	
6	M3 x 4mm (x8)	PJRC Teensy 4.0 USB Development Board (x1)	M3 x 4mm (x8)	
7	M3 heat set inserts (x8)	Adafruit MPU-6050 6-DoF Accel and Gyro Sensor (x1)	M3 Nuts (x4)	
8	3D Printed TVC Mount (x1)	Wire spool (x1)	SLA Printed Part Sheet (x1)	
9	Zip Ties (x25)	Universal Proto-board PCBs 4cm x 6cm (x1)	3D Printed Leg Connector (x1)	

Purpose	Vendor	Amount
TVC servos	Amazon	$115.00
TVC carbon fiber tubes	McMaster	$79.15
LIPO Batteries	Tattu	$61.77
Motors + Propellers + ESC	Amazon	$161.00
Micro controller, IMU, GPS, Pressure sensor	Combined Adafruit	$231.17
Flight Microcontroller	Amazon	$24.59
Body Structure	Apogee Components	$37.20
Structural Carbon Fiber Sheets	Amazon	$91.98
Buck Converter, Breadboard	Amazon	$61.99
Microusb cable	Amazon	$7.48
30 awg wire	Amazon	$21.37
		$892.70
Project Budget		$1,000.00
Percent of Total Budged Used		89.27%

** Only $395 spent within final assembly

Prototypes vs. Requirements

Key Performance Indicators		Specification
Total Cost	**$395**	**≤$500**
Flight Time	**5.16-5.88 mins**	**≥4 minutes**
Thrust/Weight Ratio	**5.4:1**	**≥ 4:1**
Roll Backlash %	**2.6%**	**≤4%**
Pitch Backlash %	**3.92%**	**≤4%**