1 Introduction

For the demo for the St. Louis Science Center, our team will design and fabricate an interactive exhibit that demonstrates the capabilities of control loops through a thrust-vector-control rocket stand. In our customer interview with Professor Okamoto we narrowed down our target audience, determined features that make an exhibit successful and engaging, and got advice regarding space restrictions and endurance expectations. Our proposed design includes a rocket-shaped body that rotates about a single axis, built so its center of mass is above the pivot point, creating an inherently unstable system. By using sensors and a control loop, we aim to redirect a ducted fan's thrust to keep the body upright. The concept will demonstrate how rockets use active thrust vectoring and introduce the audience to feedback control.

2 Problem Understanding

2.1 Existing Devices

2.1.1 Existing Device #1: Thrust Vectoring EDF Project

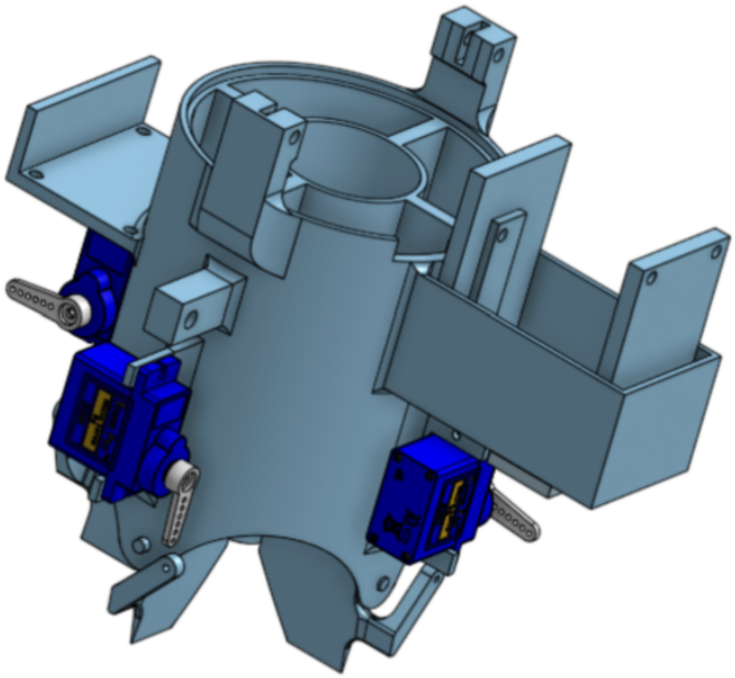


Figure 1: Thurst Vectoring EDF Project (Source: Thrust Vectoring EDF Github)

Link: https://github.com/usedgenes/Thrust-Vectoring-EDF/blob/main/README.md?utm_source=chatgpt.com
Description: The Thrust-Vectoring EDF project is a small hovering device that uses a 64 mm electric ducted fan to produce thrust. Four servos control vanes around the fan to redirect the thrust and

keep the device upright. Most of the structure is 3D printed. An IMU measures orientation, while a power system (ESP32) processes the data and controls the system.

2.1.2 Existing Device #2: Low-Cost 3D-Printed Servo Gimbal

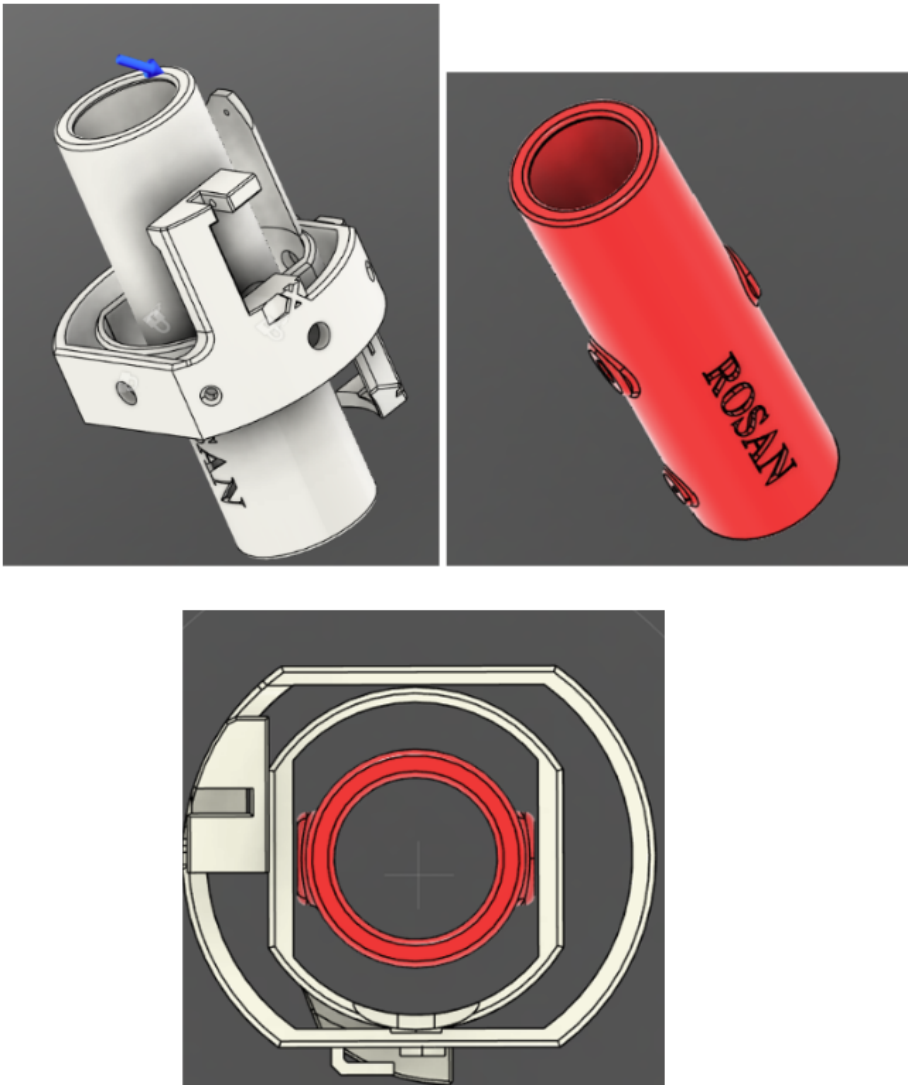


Figure 2: Low-Cost 3D-Printed Servo Gimbal (Source: Thrust Vectoring EDF Github)

Link: https://arxiv.org/abs/2509.00061v1
Description: This thrust vector control gimbal rotation device is designed for low-budget model rocketry applications. The 3D-printable (ABS) design includes a central motor mount with a gimbal frame. Two orthogonal microservos can be mounted to this frame to allow rotation in pitch and yaw (two DOF). The design is intended for a specific motor classification/size, and allows room for pivot joints on the inside of the rocket's airframe.

2.1.3 Existing Device #3: Daedalus Drone Modification & Flight Control

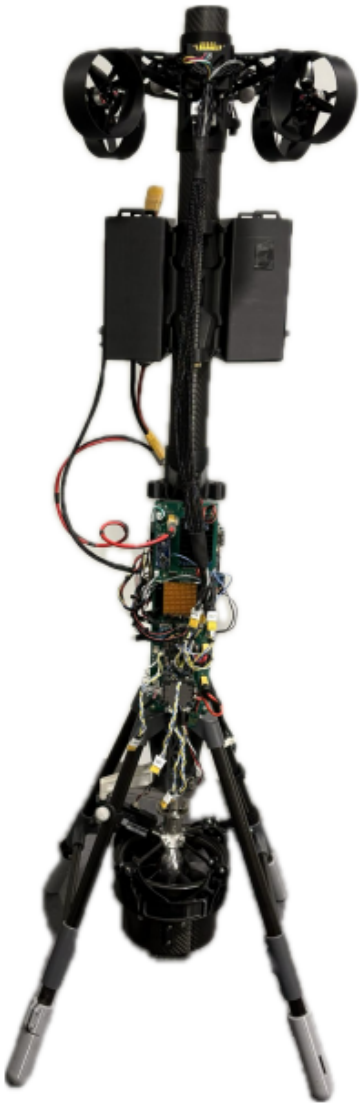


Figure 3: Low-Cost 3D-Printed Servo Gimbal (Source: Thrust Vectoring EDF GitHub)

Link: See Device 3 informational manual attached in references.
Description: This project focused on improving the Daedalus 2 drone and making it a better test platform for lunar lander research. The work included fixing simulation problems, improving flight stability, and creating tools to better understand flight data. Several mechanical parts were also redesigned, including the fan arrays, electronics mount, and actuator supports. Flight testing helped identify power and drifting issues. New software was then developed to create failures and test how the drone could safely recover from them.

2.2 Patents

2.2.1 Single Axis Gimbal Mounted Propulsion System for Aircraft (US11383823)

This patent describes a single-DOF servomotor-driven gimbal assembly and focuses on vertical takeoff and landing (VTOL) aircraft. Each propulsion assembly has a rotor with propellers, and the rotor is attached to a servo-linkage assembly to allow rotation in the range of 10-30 degrees. This allows for flexible maneuverability of the aircraft.

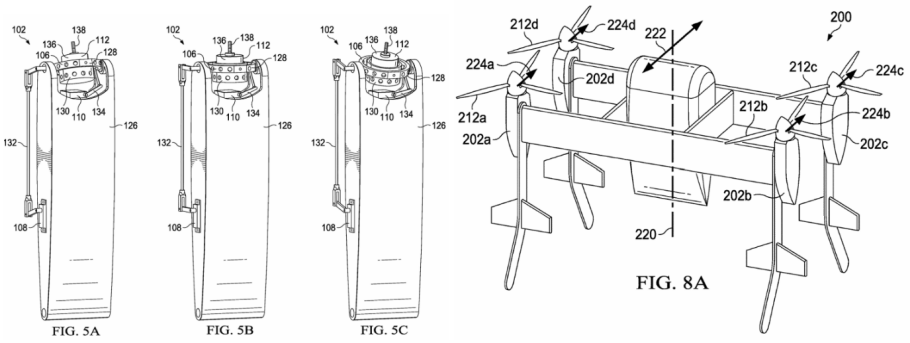


Figure 4: Patent Images for single axis gimbal propulsion system

2.2.2 System and Method for Divert and Attitude Control in Flight Vehicles (US20110082604A1)

This patent outlines a proportional-derivative (PD) controller utilized in Divert and Attitude Control Systems (DACS). The controls architecture outlined takes pitch, yaw, and roll (3 DOF) inputs and outputs thruster controls for fuel-efficient attitude control. It is best suited for asymmetric thrusters with different moment arms and takes into account undesired center-of-gravity shifts in flight.

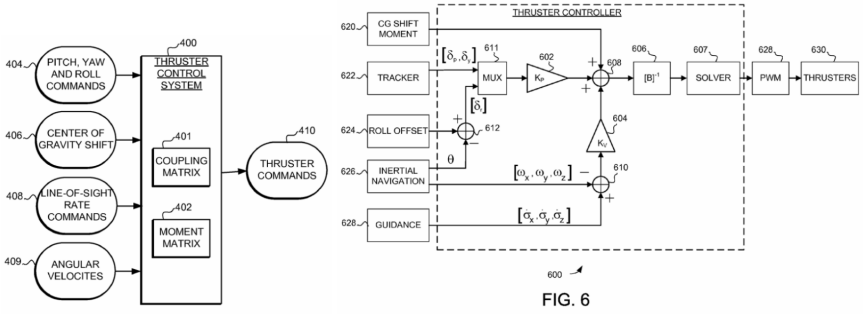


Figure 5: Patent Images for divert & attitude control in flight vehicles

2.3 Codes & Standards

2.3.1 Safety of toys — Part 1: Mechanical and physical properties (SO 8124-1:2022)

This standard specifies the requirements and test methods for children's toys. It deals with products intended for use by children of less than 14 years. It does not apply to specific toys, including but not limited to, toys equipped with combustion engines, toy steam engines, toy slingshots, musical instruments, sports equipment, etc. It focuses on the mechanical and physical properties of toys, not the electrical components. This standard applies to our project because the intended audience of our science demo includes people of all ages, including children less than 14 years old. This standard can ensure that we account for the expected behavior of children, which is important because many times they may lack the same safety reasoning as adults. By using the testing methods provided in this standard we can ensure that the efficacy of our product is completely independent of the user, and that we can include a factor of safety that accounts for unexpected product use.

2.3.2 Household and similar electrical appliances-test code for the determination of airborne acoustical noise-part 1: General requirements (IEC 60704-1:2021)

This standard focuses on the sound hazards that might exist in household appliances and describes the procedures required to determine that noise levels stay within a safe range for daily use. While intended for household appliances, this standard uses methodology to determine noise levels that are directly applicable to our project. By using the provided methodology, we can verify the sound output of the fan and noise makers (if we ultimately decide to incorporate them).

2.4 User Needs

Sed ut perspiciatis unde omnis iste natus error sit voluptatem accusantium doloremque laudantium, totam rem aperiam, eaque ipsa quae ab illo inventore veritatis et quasi architecto beatae vitae dicta sunt explicabo.

2.5 Customer Needs

2.5.1 Customer Interview

Interviewee(s): Ruth Okamoto, Science Center Director
Date & Format: 9/11/2026, In-person Jolley lab meeting
Interview Notes:

- Primary audience is elementary school-aged children and their families, with school groups as a secondary audience
- Successful exhibits in the past use movement, sound, numerical displays, an appealing interface, and immediate feedback
- The exhibit needs to be reliable and robust enough to sustain use for a long time
- We'll have access to wall power (and this is the preferred option over a battery)

- The entire project must fit in a 3 ft by 6 ft makerspace table area with height not exceeding the ceiling
- Moving parts and pinch points have to be enclosed so visitors can't hurt themselves. Clear acrylic is the best option for visibility.
- The explanation should rely mainly on visuals and a small plaque that parents and older students can understand and explain to younger children
- Safety priorities are: preventing injuries, electrical overdraw, overheating, and fire. The exhibit must not involve combustion or explosions.
- Emergency stop is not required.
- The audio has to stay below 70–75 dB and avoid high frequency, high-pitched noises
- A joystick is the preferred control method and could control thrust magnitude and gimbal angle
- A virtual display or sound effects could provide additional feedback and show how the user's inputs affect the system.
- We need to make the connection to rocket control very clear

2.5.2 Interpreted Customer Needs

Table 1: Interpreted Customer Needs

#	Customer Statement	Interpreted Need	Importance (1–5)
1	"Primary audience is elementary school-aged children and their families, with school groups as a secondary audience"	The device shall be engaging for children and families	5
2	"Successful exhibits in the past use movement, sound, numerical displays, an appealing interface, and immediate feedback"	The device shall provide engaging and immediate feedback during interaction	4
3	"The exhibit needs to be reliable and robust enough to sustain use for a long time"	The device shall run reliably during repeated use	5
4	"We'll have access to wall power (and this is the preferred option over a battery)"	The device shall draw power from a wall outlet	5
5	"The entire project must fit in a 3 ft by 6 ft makerspace table area with height not exceeding the ceiling."	The device shall fit in the Makerspace table (and ceiling) constraint.	5

Continued on next page

Table 1 – continued from previous page

#	Customer Statement	Interpreted Need	Importance (1–5)
6	"Moving parts and pinch points have to be enclosed so visitors can't hurt themselves. Clear acrylic is the best option for visibility."	The device shall protect users from injury while keeping the demonstration visible	5
7	"The explanation should rely mainly on visuals and a small plaque that parents and older students can understand and explain to younger children."	The device shall communicate its basic principles with mostly visuals and only small written portions.	3
8	"Safety priorities are: preventing injuries, electrical overdraw, overheating, and fire. The exhibit must not involve combustion or explosions."	The device shall operate without creating fire hazards (in any form)	5
9	"Emergency stop is not required."	The device shall safely come to a resting state without a manual emergency stop	3
10	"The audio has to stay below 70–75 dB and avoid high frequency, high-pitched noises."	The device shall not exceed 70–75 decibels in noise	3
11	"A joystick is the preferred control method and could control thrust magnitude and gimbal angle."	The device shall provide an interactive control experience to engage with the system	5
12	"A virtual display or sound effects could provide additional feedback and show how the user's inputs affect the system."	The device shall combine additional feedback to help the user control the system and immerse in the experience	2
13	"We need to make the connection to rocket control very clear."	The device shall obviously demonstrate rocket control and thrust vectoring for viewers	5

2.6 Target Specifications

1. Mechanical Safety (ISO 8124-1:2022)

The device shall be designed and tested to minimize mechanical hazards to users, particularly children interacting with our demo. All accessible components shall satisfy the applicable requirements of ISO 8124-1:2022 regarding sharp edges, small parts, choking hazards, cords, projectiles, etc. The design will be inspected and tested after use and thoroughly verified so that no mechanical hazards present themselves.

2. Acoustic Safety (IEC 60704-1:2021)

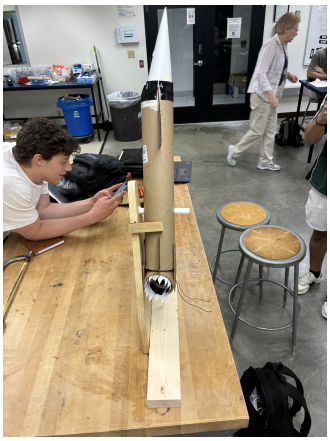
The acoustic output of the demo's components, like the fan, augmented/artificial thrust audio, and any additional noise-making components, shall be in accordance with the measurement ranges specified by IEC 60704-1:2021. The measured sound level will be compared against a project-defined maximum allowable level to ensure that the demonstration does not create an audio hazard for users.

3 Concept Generation

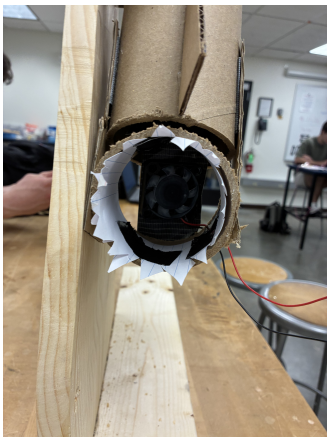
3.1 Mockup Photos



(a) Front view of the mockup.



(b) Side view of the mockup.



(c) Close-up of the thruster and pivot mechanism.

Figure 6: Physical mockup created during the studio session.

Mockup Description and Design Takeaways.

Our group created a thrust-vector-control demo mockup using materials in the studio, including wood, cardboard, paper, PVC pipe, hot glue, wood screws, metal pins, and a dummy fan. We learned that alignment is an important design constraint to keep in mind - the single degree of freedom in the servo-controlled gimbal rotation must align very well with the single degree of freedom of the rocket's rotation about the pivot. Mechanically, the stops that we use to constrain the rocket's rotation must be carefully placed (and ideally adjustable) to allow for a reasonable window of rotation - we learned that it might be hard to place the stop where only the top or the bottom of the rocket will catch, and not the other side. A simple pivot will likely work for our purposes, and the high friction on the pivot led us to the decision to use ball bearings (or something with similar functionality) at that rotation point.

3.2 Functional Decomposition

The function tree shown in Figure 7 breaks down our thrust vectoring science demo into the smaller functions that would be required for functionality and safely exhibit operation. There are a lot of subfunctions but these were the most important ones we thought of throughout our thought process.

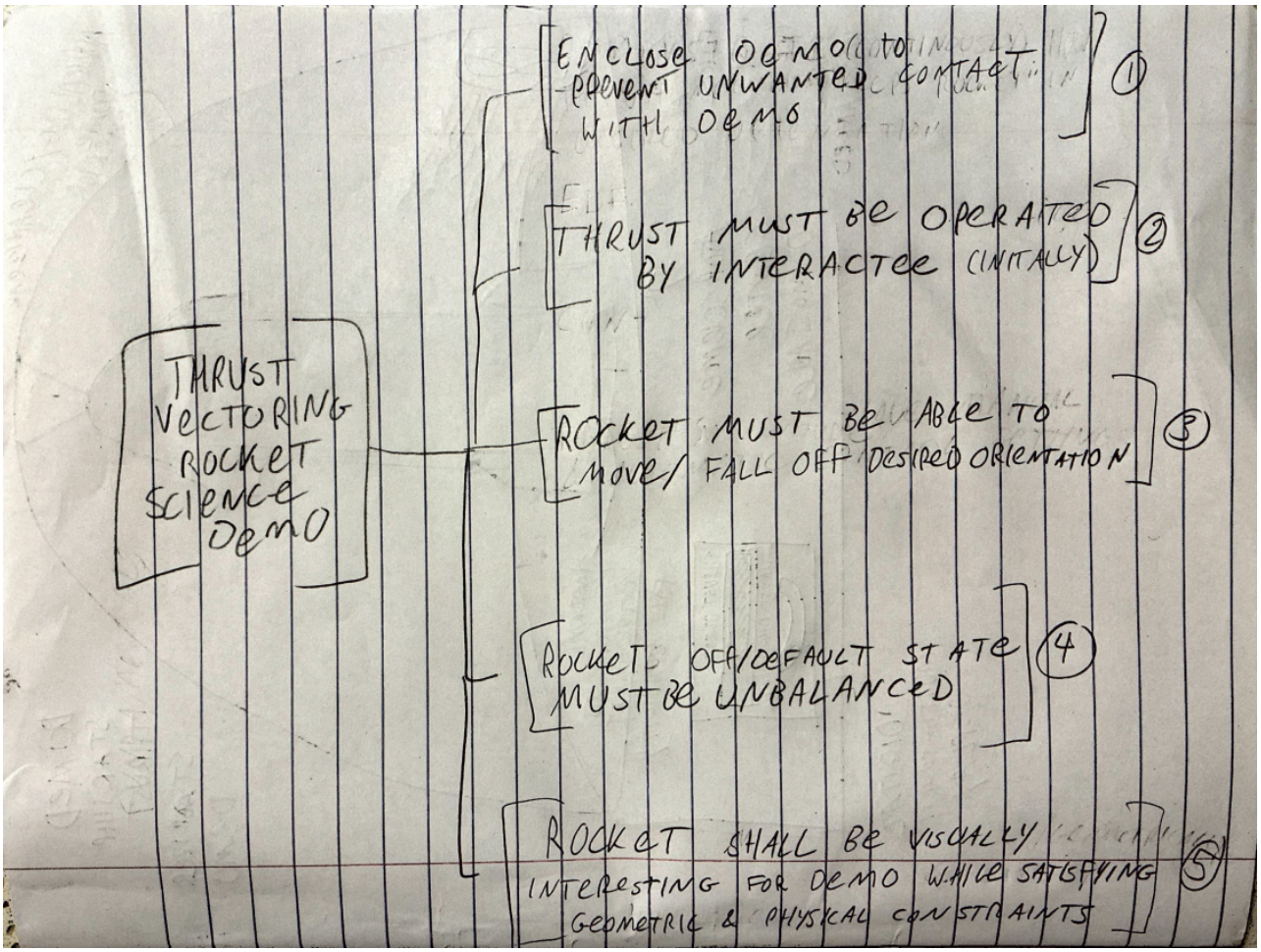


Figure 7: Function tree for the interactive thrust vector control demonstration.

The primary functional areas are as shown. Together, this ensures our project is enclosed and users are safe from moving parts, thrust is controllable, the rocket is prevented from becoming too unstable, the off state has to be unbalanced (the system must be inherently unstable), and the demo should be visually appealing and interesting.

3.3 Morphological Chart

The morphological chart in Figure 8 presents 14 solutions for the device's major subfunctions. These options were combined in different ways to develop the four design concepts presented in Section 3.4.

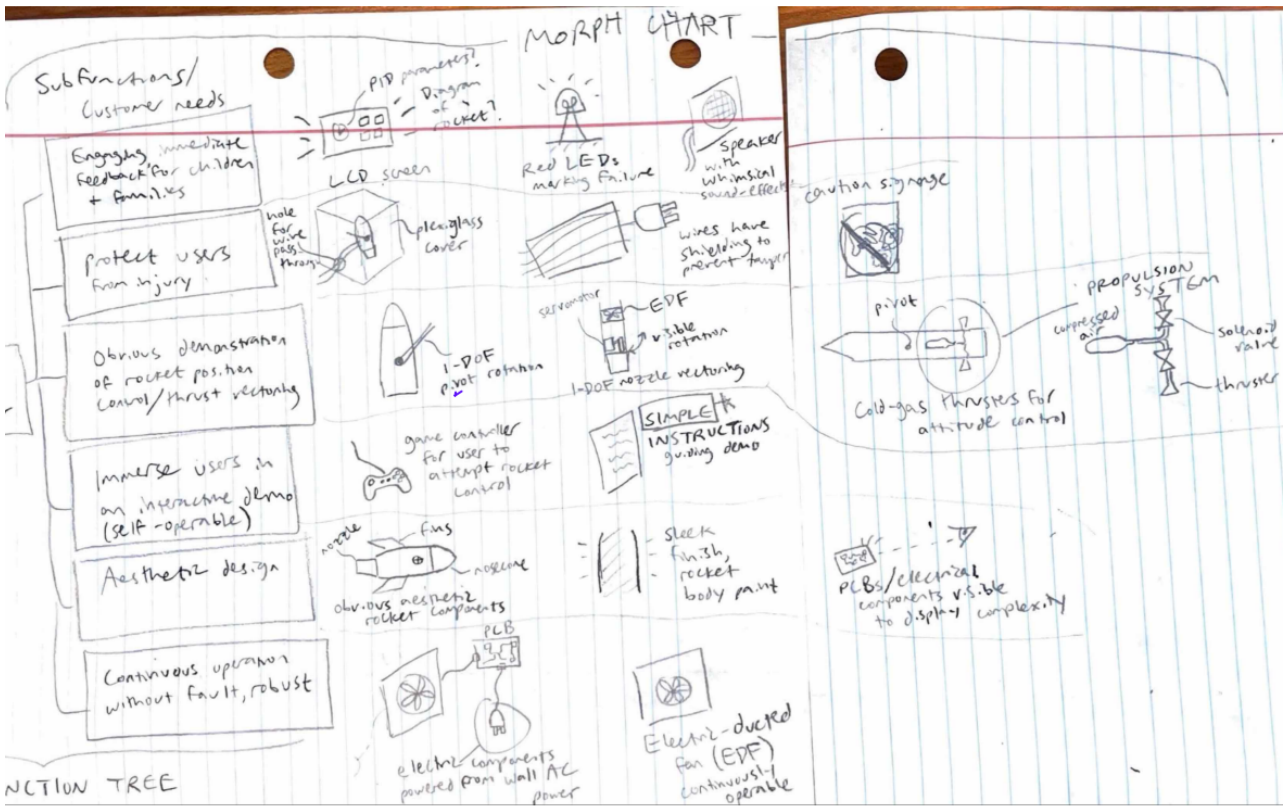


Figure 8: Morphological chart for the interactive thrust vector control demonstration.

The solution options were essentially a massive brain dump of all the various ways the specified subfunctions could be combined to get to a functional, safe, and intriguing demo.

3.4 Alternative Design Concepts

Each of us went through the process of concept generation, so our four concepts combine ideas from the four of us. Each concept provides a different way we can go about building this project and now we have options to downselect towards our specific architecture.

3.4.1 Concept #1: Alec's Concept

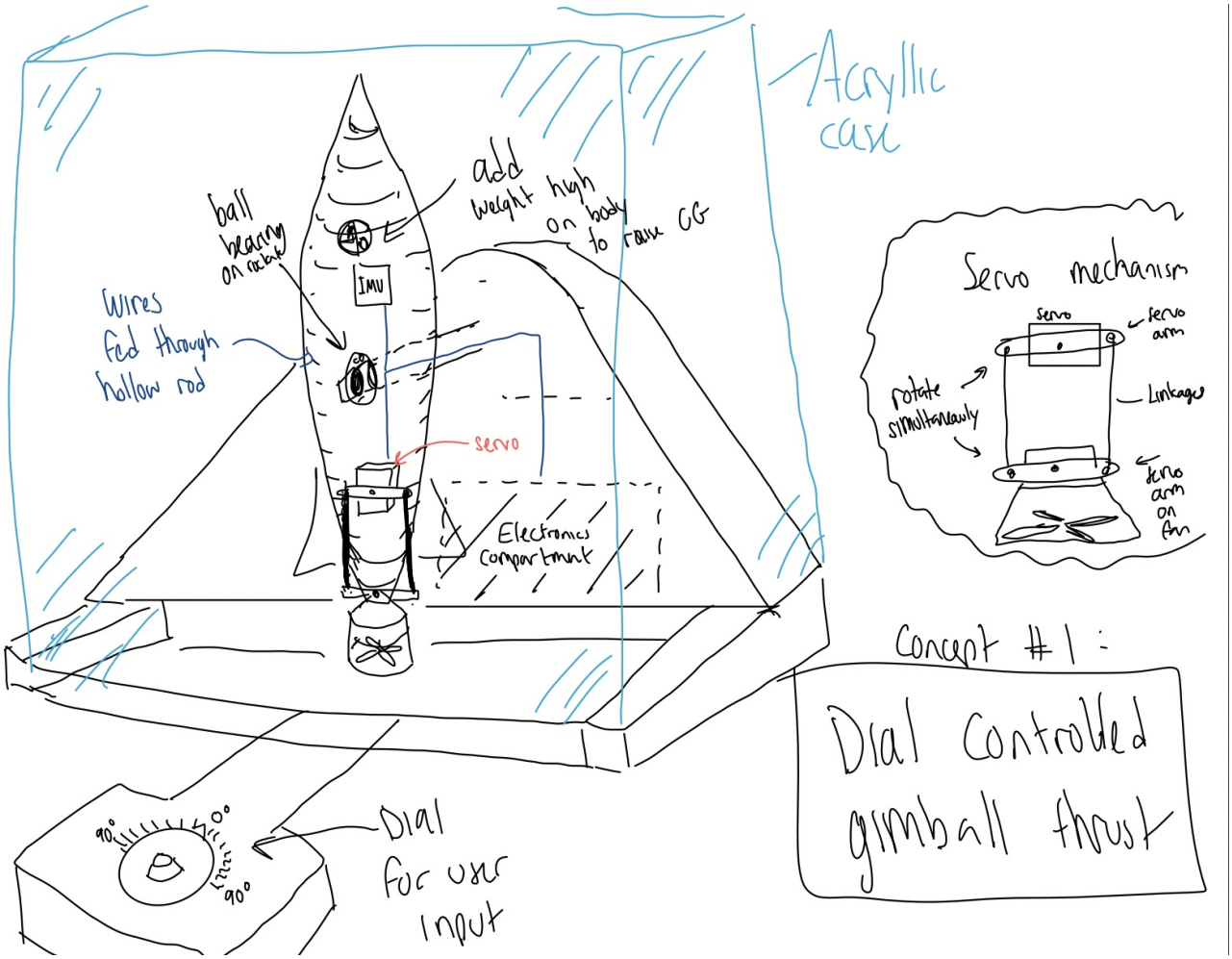


Figure 9: Concept 1: Alec's in depth implementation strategies for TVC

Description. Concept 1 incorporates a rocket body that is cone-shaped and secured to a pivot point via a ball bearing attachment. This joint should reduce friction and allow the system to react to input immediately. The rocket body rotates around this point. An IMU mounted inside the body will sense the rockets orientation, which will provide our control loop with feedback in order to make any corrections. We will add a compartment to quickly add any weight to the rocket body above the pivot point, providing control over the location of the center of gravity, an important parameter for our control loop. A servo near the bottom of the rocket will act as motor to tilt our fan, giving us control over the direction of thrust. The mechanics of the servo mechanism are detailed in the figure, demonstrating the use of servo arms and linkages to provide immediate feedback. An electronics component will be designed into the base to keep the demonstration clean. The system will also be connected to a user input source, a dial, which would allow the user to control the angle of the thrust. An acrylic case will also enclose the demo to avoid unwanted user manipulation.

3.4.2 Concept #2: Nate's Concept

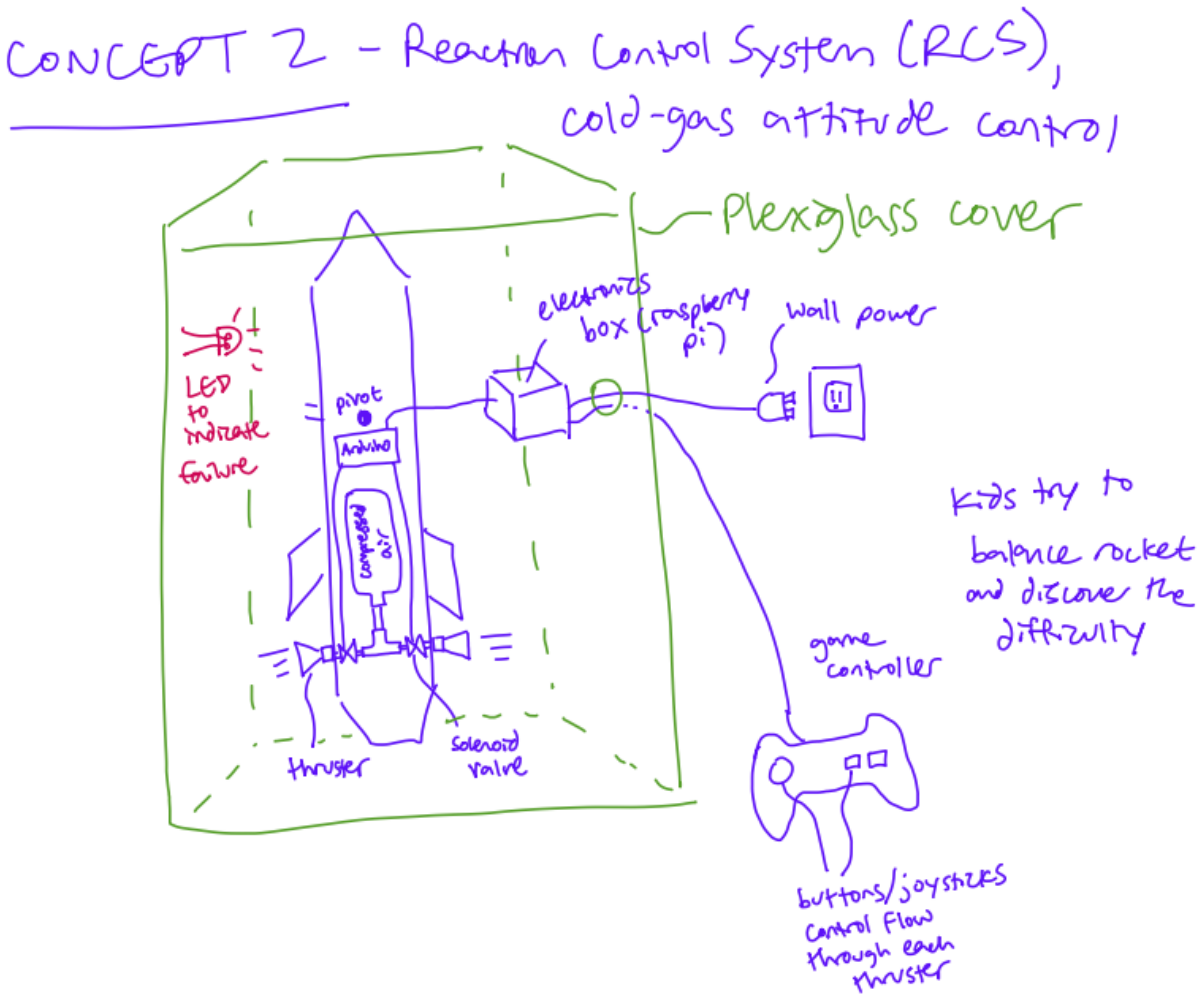


Figure 10: Concept 2: Nate's Cold Gas Attitude Control System

Description. Concept 2 is a reaction control system that uses compressed air to control our system. The rocket body pivotes about a single point, and incorporates an arduino and small compressed air canister within the body. This compressed air is hooked up to two exhaust ports, controlled by solenoid valves. In this version, the thrust direction is fixed and our control is done through controlled bursts of air, instead of a fan, allowing us for stronger thrust. This concept is inspired by real spacecraft, which use a reaction control system (RCS) for attitude control. Users would be able to control this rocket with a modified game controller which uses buttons and joystick to control the flow through each air output. A red LED in the enclosure will indicate a failure when the user can not control the rocket sufficiently with manual input. Electronics will be housed in a separate box, which will include the Rasberry Pi, which will deal with the user input. The entire demo will be enclosed by a plexiglass cover to keep visitors away from the moving parts.

3.4.3 Concept #3: Warren's Concept

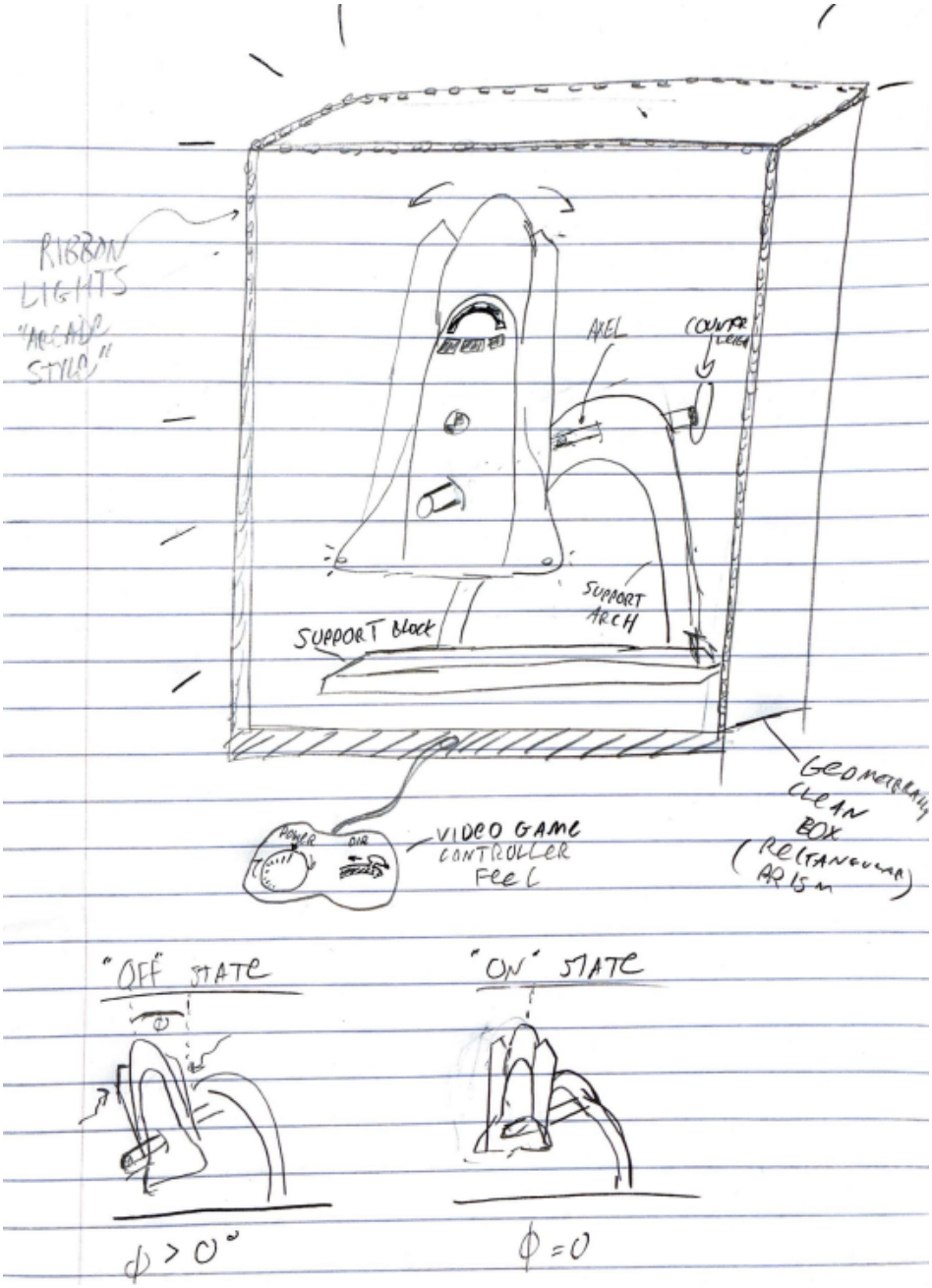


Figure 11: Concept 3: Warren's Visually Appealing Ideas

Description. Concept 3 shows the setup for mounting the decorated rocket (that resembles a space shuttle) on a pin and support arch for optimal structural support and maneuverability. It also adds a lot of visually appealing components to make the exhibit look even better and more appealing to a science center viewer. Ribbon lights, cool decorations within the demo, and a video game controller make it a prime target for kids interested in the topic. It also demonstrates the On and Off states. In the off state, the rocket is off balance and unstable, but once the system is on and the control system is active, the rocket is meant to right itself to a vertical position.

3.4.4 Concept #4: Kailash's Concept

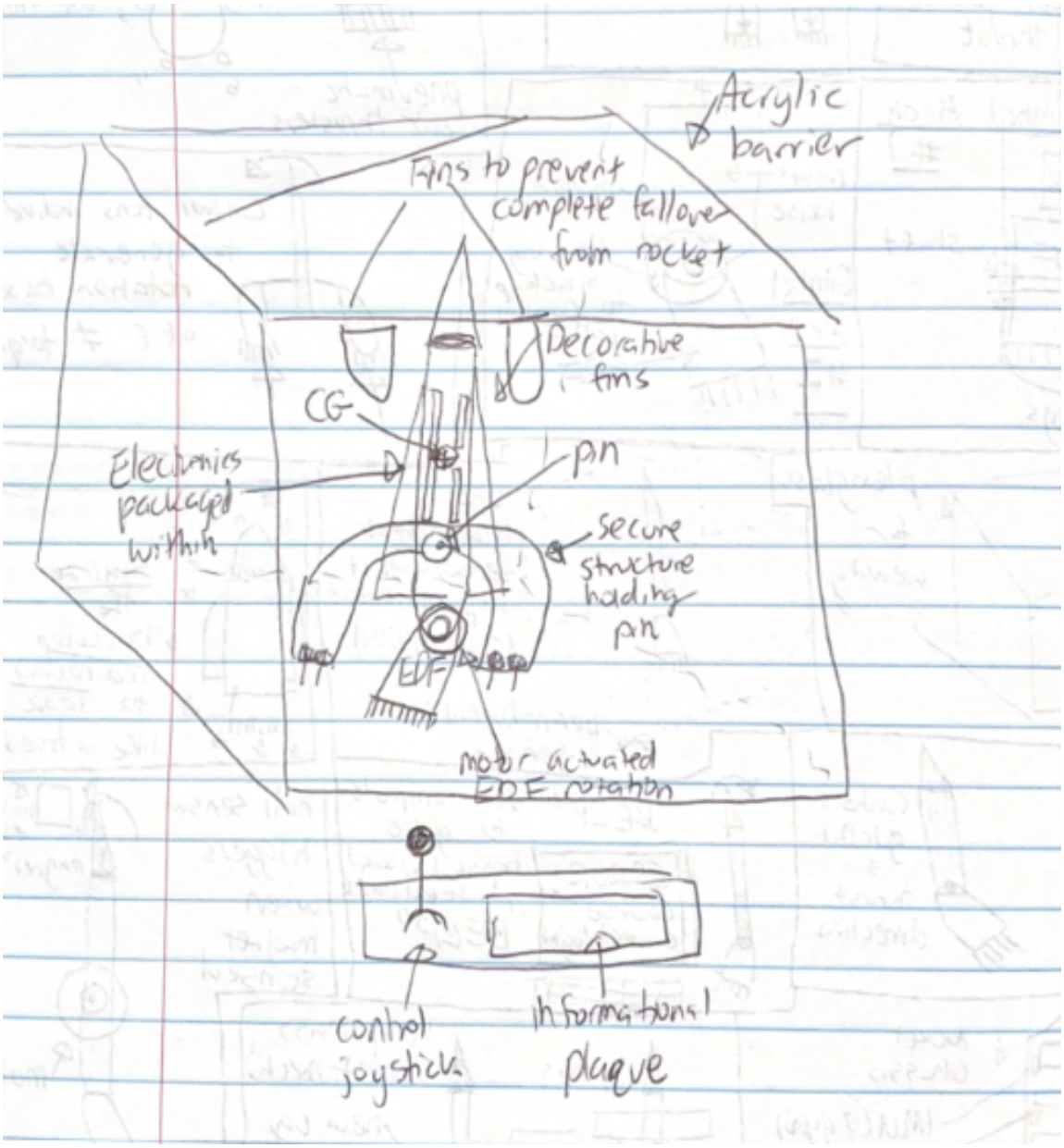


Figure 12: Concept 4: Kailash's Gimbal TVC Design Concept

Description. This idea involves a pinned rocket with a center of gravity above the pivot point so the rocket is inherently unstable. There are fins next to the rocket to limit how far it can fall (because our control system will only work if it has small angles to correct (and not massive changes). Electronics packaged within the rocket allow for position, velocity, and acceleration tracking, and the EDF is mounted on a shaft that can be operated with a motor. User interaction relies on a joystick and an informational plaque about thrust vector control in reality. Finally, the entire thing is packaged in acrylic for safety and visibility.

4 Concept Selection

4.1 Selection Criteria

Five selection criteria were used to compare the proposed concepts: ease of manufacturing/assembly, accuracy/precision, durability, aesthetics/entertainment value, and affordability of components. These criteria reflect the most important requirements for the demonstration, including its educational value, performance, and practicality.

The Analytic Hierarchy Process (AHP) was used to determine the relative importance of these criteria. Each criterion was compared with every other criterion, and the resulting comparisons were used to calculate normalized weights. Figure 13 shows the comparison table and the resulting weights.

	Ease of manufacturing/assembly	Accuracy/precision	Durability	Aesthetics/entertainment value	Affordability of components	Row Total	Weight Value	Weight (%)
Ease of manufacturing/assembly	1.00	0.20	0.33	0.20	1.00	2.73	0.06	5.58
Accuracy/precision	5.00	1.00	3.00	1.00	5.00	15.00	0.31	30.65
Durability	0.20	3.00	1.00	0.33	3.00	7.53	0.15	15.39
Aesthetics/entertainment value	0.33	3.00	0.14	1.00	5.00	9.48	0.19	19.36
Affordability of components	3.00	5.00	5.00	0.20	1.00	14.20	0.29	29.01
					Column Total:	**48.94**	**1.00**	**100.00**

Figure 13: Analytic Hierarchy Process comparison table for the five selection criteria and their normalized weights.

4.2 Concept Evaluation

The proposed concepts were evaluated using a Weighted Scoring Matrix (WSM), shown in Figure 14. The matrix uses the same five criteria and the weights calculated through the AHP. Each concept was assigned a score from 1 to 5 for each criterion, with higher scores indicating better performance.

The weighted total for each concept was calculated as

$$S_j = \sum_{i=1}^{5} w_i s_{ij}, \tag{1}$$

where S_j is the total weighted score for concept j, w_i is the normalized weight of criterion i, and s_{ij} is the score assigned to concept j for criterion i. The weights satisfy $\sum_{i=1}^{5} w_i = 1$.

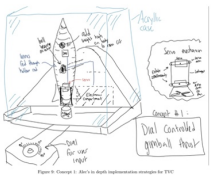
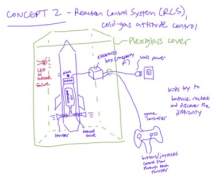
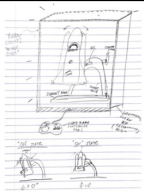
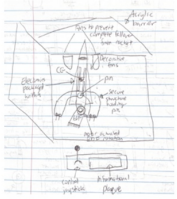
Alternative Design Concepts		Concept #1		Concept #2		Concept #3		Concept #4	
									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Ease of manufacturing/assembly	5.58	4	0.22	4	0.22	4	0.22	5	0.28
Accuracy/precision	13.34	4	0.53	5	0.67	4	0.53	4	0.53
Durability	22.15	5	1.11	5	1.11	5	1.11	5	1.11
Aesthetics/entertainment value	18.41	4	0.74	5	0.92	5	0.92	3	0.55
Affordability of components	27.59	5	1.38	2	0.55	3	0.83	4	1.10
	Total score	**3.980**		**3.470**		**3.612**		**3.576**	
	Rank	**1**		**4**		**2**		**3**	

Figure 14: Weighted Scoring Matrix comparing the proposed concepts using the weights calculated from the AHP.

4.3 Evaluation Results

The highest-ranked concept was Concept #1, the dial-controlled gimbal thrust design, with a total weighted score of 4.444. This concept consists of a cone-shaped rocket body that pivots about a ball-bearing joint partway up its length, with a ducted fan mounted on a servo-actuated gimbal near the base. An IMU inside the body senses orientation, a counterweight compartment above the pivot sets the center of gravity, and a visitor-operated dial commands the target tilt angle, which a closed-loop PID controller tracks by rotating the fan. The entire mechanism is enclosed in an acrylic case. Its ranking reflects how these specific features address the five selection criteria.

For ease of manufacturing/assembly, the concept received a score of 4 because the servo-arm linkage, requires careful alignment during assembly. In particular, the linkage geometry must be set precisely so the fan's commanded angle matches the servo's actual rotation, which adds a level of difficulty beyond simply bolting parts together.

For accuracy/precision, the score of 4 reflects the use of closed-loop IMU feedback with a tuned PID controller. This would allow the device to continuously correct for disturbances and sensor noise, though the achievable precision is still limited by IMU noise and servo accuracy rather than being perfect.

For durability, the concept earned 5 because the ball-bearing pivot and the rigid acrylic enclosure are both built to withstand repeated public interaction. However, the servo and its linkage remain the components most susceptible to damage over many cycles

For aesthetics/entertainment value, the score of 4 was based on the visible rocket silhouette and the direct dial control, which clearly communicates input and feedback to a visitor. This feature would let visitors immediately connect turning the dial to the rocket's response, though it scored slightly below concepts using more visually dynamic feedback such as game controllers or fault-indicator lighting.

Finally, for affordability of components, the concept received 5 because it relies entirely on low-cost hardware rather than items such as compressed-air canisters and solenoid valves used in other concepts. Overall, the combination of a proven, low-friction pivot mechanism, low-cost electronics, and a closed-loop control architecture already validated in simulation makes this concept the most

practical choice for the demonstration.

4.4 Engineering Models/Relationships

4.4.1 Model 1: Sum of Moments About the Pivot

This model describes the rotational equation of motion of the rocket body about its fixed pivot, capturing both the destabilizing gravitational torque and the restoring torque produced by the vectored fan thrust.

$$I_o\ddot{\theta} = mg\, r_0 \sin\theta - F_t(t)\, R \sin\phi \tag{2}$$

Symbols and units:

- θ: angle of the rocket body from vertical [rad].
- $\ddot{\theta}$: angular acceleration of the body [rad/s^2].
- I_o: mass moment of inertia of the rocket body about the pivot [kg·m^2].
- m: mass of the rocket body [kg].
- g: gravitational acceleration, 9.81 [m/s^2].
- r_0: distance from the pivot to the body's center of gravity [m].
- $F_t(t)$: thrust force produced by the ducted fan at time t [N].
- R: distance from the pivot to the fan [m].
- ϕ: gimbal angle of the fan relative to the body's long axis [rad].

Given quantities: m, r_0, I_o, and R from the CAD assembly, and $F_t(t)$ from the selected fan's thrust.
Quantity to determine: The angular acceleration $\ddot{\theta}$, which is used to predict $\theta(t)$, the body's response to a given thrust and gimbal input.
Design application: This equation is the same relationship simulated in Simulink and in a MATLAB model to validate PID gains before any hardware was built. The $F_t R \sin\phi$ term sets how much control authority the fan and servo must provide to counteract the instability of the high center of gravity. This directly informs the required thrust-to-weight ratio of the selected EDF and how aggressively the controller must react. Because I_o depends on final CAD geometry, the model will be evaluated once the physical assembly is finalized.

4.4.2 Model 2: Closed-Loop PID Control System

This model describes how the controller converts a measured orientation error into a commanded actuator input, forming the feedback loop that stabilizes the otherwise unstable rocket body.

$$u(t) = K_p\, e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt} \tag{3}$$

Symbols and units:

- $u(t)$: controller output commanding the servo/fan gimbal angle [rad, or equivalent actuator units].
- $e(t) = \theta_{des} - \theta_{act}$: orientation error between desired and measured angle [rad].
- K_p, K_i, K_d: proportional, integral, and derivative gains [unitless/appropriately scaled].
- θ_{des}: desired orientation, set by the visitor dial [rad].
- θ_{act}: measured orientation from the IMU [rad].

Given quantities: The visitor-commanded setpoint θ_{des} and the IMU-measured feedback θ_{act}, sampled at the microcontroller's control loop rate.
Quantity to determine: The control signal $u(t)$ sent to the servo actuating the fan gimbal.
Design application: This model determines how the system translates sensor feedback into a stabilizing actuator command, and is the basis for every gain-tuning exercise performed so far, including use of MATLAB's PID Tuner against the linearized plant from Model 1 and a discrete-time simulation incorporating simulated IMU noise and a derivative filter. The K_p, K_i, and K_d values are optimized specifically for this system's fast natural response, and the model also exposed the need for a low-pass filter ahead of the derivative term, since sensor will have noise. This model will guide final gain selection once real hardware response (servo lag, IMU noise characteristics) replaces the simulated estimates.

4.4.3 Model 3: Gimbal Servo Torque Sizing

This model describes the torque a servo must deliver to move the ducted fan through a required range within a target response time, treating the fan as a uniform cylinder rotating about one end.

$$\tau = \left(\frac{1}{4}mR^2 + \frac{1}{3}mL^2\right)\frac{4\theta_{total}}{\Delta t^2} \tag{4}$$

Symbols and units:

- τ: required servo torque [N·m].
- m: mass of the ducted fan unit [kg].
- R: fan radius, $R = D/2$ [m].
- L: axial length of the fan [m].
- θ_{total}: total angular sweep required, e.g. $\pi/2$ for a 90° range [rad].
- Δt: time allotted to complete the sweep [s].

Given quantities: m, R, and L from the selected fan's datasheet/CAD model. θ_{total} and Δt from the target responsiveness requirement.
Quantity to determine: The minimum required servo torque τ at the needed rotational speed.
Design application: This model supports the servo selection. It computes the actual torque needed given the fan's real inertia and the team's target response time, assuming constant angular acceleration over the first half of the sweep and constant deceleration over the second half. A servo must be chosen whose torque at the required speed exceeds this value, with a safety margin to account for friction not captured by the idealized model.