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Team 515: Haptic Robot

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Abstract

Disclaimer

A portion of the editing of this document was completed with OpenAI’s ChatGPT. This currently includes the condensing of team-generated writing. Specific usage of this is noted. All text has been reviewed by the team and edited if needed~~.~~.

Acknowledgements

Team 515 would like to thank Dr. Carl Moore, the National Science Foundation, and the National Research Institute for sponsoring this project, which has furthered the team’s education and experience in mechanical design.

Team 515 would also like to thank Dr. Carl Moore and Dr. Shayne McConomy of the FAMU-FSU College of Engineering for advising the team both technically and instructionally.

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1.1 Project Scope

Project Description

Team 515 is tasked with designing an educational device to demonstrate the use of Continuous Variable Transmission (CVT) technology in robotics. The device aims to engage student audiences by highlighting the smooth movement characteristics of CVTs. If significant technological development is made, the devices could serve as a subsystem in a larger haptic feedback collaborative robot (cobot) for remote tele-operation (OpenAI, 2024). (No Change)

Key Goals

The main goal of this project is to utilize CVT technology to engage with potentially STEM-curious students by outputting ~~output~~ a desired two-dimensional path. ~~that engages students~~. The working principle of the CVT technology ~~involved in the movement of the device~~ used is intended to be displayed and explained, while its effectiveness in producing clear motion is intended to be entertaining and thought provoking. The device is also intended to highlight the autonomous characteristics of robots, so a single input provided by the user is desired to produce the path. Once the input is provided by the user, the desired path can be drawn autonomously by the device. The device's ~~size~~ output area is intended to be ~~large enough~~ maximized to maximize classroom engagement, while the overall device footprint is intended to be minimized for transportability.~~engage with a typical classroom size.~~

Intended Markets

The primary market for the device is intended to be STEM educational institutions (schools, museums, research, etc.). Examples include public and private schools, the Challenger Learning Center, the National High Magnetic Field Laboratory, and outreach programs such as Young Engineers Tallahassee. Secondary markets involve ndustries where haptic robotics can be beneficial, such as hazardous enviroments~~include industries where haptic robots could be implemented, such as hazardous environments~~ (e.g., space, nuclear, or underwater environments), remote surgery, and VR gaming. Given that the device is a smaller part within a larger cobot project it is meant to showcase further applications of CVTs within haptic robotics. Tackling both markets will further enhance the education and development of CVTs in robotics.

Assumptions

The assumptions team 515 will be operating under during the project include:

- While the sponsored research project involves applications in haptics, the device itself is not a haptic device (will not incorporate physical human interaction/interface).
- While there is no physical control of the device, it will incorporate a user interface for choosing desired motion output.
- The device will output planar/2D motion using a Continuously Variable Transmission.
- Existing motor and control hardware are allowed.
- Use of existing control methods are allowed.
- Device will build on past prototypes/designs
- Access to conventional sources of electricity is available.

Stakeholders

Stakeholders who would benefit from the success of this project include:

- Dr. Shayne McConomy
- Dr. Carl Moore
- The National Science Foundation (NSF)
- The National Research Institute (NRI)

- Shape-Based Remote Manipulation (SBRM), consisting of Northwestern University and the FAMU-FSU College of Engineering
- Prairie View A&M University, a host of a similar capstone project
- Human Augmentation via Dexterity Engineering Research Center (HAND ERC)

1.2 Customer Needs

Investigating Needs

Once the scope of this project was established, the team had to identify the customer's needs. To do this, various questions were asked of the assigned customer, Dr. Moore. The proposed questions were formulated to get a general concept of what the customer anticipated the design and characteristics of the product to be like. After recording the responses, the team then discussed ways to answer the customer’s needs in the design. The table below outlines the questions, answers, and interpreted needs

Table 1: *Customer Needs*

Questions	Provided Answers	Interpreted Need
If this is an educational tool, what audience are you intending to reach with this device? (elementary, middle, high, college)	High schools.	Any mathematical concepts plotted are within a high school educational level.
How large of an audience do you intend to display the device to at a time?	30 High Schoolers.	The device is large enough to display to 30 high schoolers at a time.

Where do you intend to display the device?	Science museums and classrooms.	The robot may require a layer of protection to prevent damage from over-excited/irresponsible viewers
How do you intend to transport the device?	By car.	The device can fit into a car to be transported.
How much time do you expect to have with the audience?	An hour.	The robot can be easily run and reset (if applicable) to accommodate this schedule
Would you discuss smaller steps of achieving the output to the audience? Would you like to focus on displaying the steps as well as the output?	Both steps and output are important. Demonstrate this as a robot to help students understand mathematical concepts and engineering concepts. Some concepts may be too complicated.	Given the robot will be demonstrated to a high school audience within an hour, basic mathematical/engineering concepts can be briefly explained. This may also depend on the device's running time.
What is the most important aspect of the device to you?	An endpoint following a curve.	The device can follow a curve.
Would you discuss and then showcase? Or would you like to showcase while you discuss? Would you like the device to stop at various steps for explanation?	Constant movement is desired.	The device can transition continuously from input to output.
It has been discussed that a 10x10 footprint is an acceptable size. Do you have a target output area?	The 10x10 footprint is not a packaging area footprint. The footprint is the output space, which is now 8.5 in x 11 in.	The device can output an area of 8.5 in x 11 in.

How much student interaction are you seeking? Do you intend for immediate student interaction/interface?	Direct student interaction is not an immediate concern, but changing of mathematical parameters is desired.	While direct student interaction may be incorporated into the design, the input parameters are the priority.
What do you dislike about similar models?	Former models or attempts were designed to be too rigid.	The product’s mechanism will be adjustable.

Explanation of Results

Team 515 engaged with the customer during discussions and follow-up emails to clarify their needs for an educational tool for high school students. The customer intends to use this device in science museums and classrooms to demonstrate mathematical and engineering concepts to groups of around 30 students at a time. The device must fit into a car for easy transportation, designed to run continuously for approximately one hour. The primary focus is on ~~showcasing~~displaying the process and output, with both steps and the endpoint (following a curve) being crucial elements. Although direct student interaction is not the main priority, the ability to change mathematical parameters is essential. The device's footprint will be 8.5 inches by 11 inches, and it needs to be simple enough for brief explanations while demonstrating core concepts~~.~~ .

1.3 Functional Decomposition

Introduction

The CVT robot’s functionalities will now be explored using functional decomposition. Functional decomposition is a systems approach to understanding the lowest level functionalities required for a solution to an engineering problem. These functionalities are customer driven and reside under larger systems. Determining such low-level functionalities aids in identifying key systems that will work in tandem to solve the desired problem. Identifying functionalities will also aid in determining benchmarking factors for selecting an acceptable design.

Data Generation and Functional Hierarchy

Team 515 met multiple times to brainstorm functionalities. The first brainstorming session involved confirming the most important customer need – continuous, precise, and customizable two-dimensional output. This allowed the team to discuss a series of high-level actions from start to finish. These high-level actions involve inputting a desired set of curve parameters, creating a nominal set of movement parameters, beginning actuation, validating movement, and correcting movement. All these actions are occurring while the output is being displayed. This allowed for the realization of three main systems. Further brainstorming sessions refined the content within these three systems. The refined hierarchal structure of the systems, subsystems and functions is shown below.

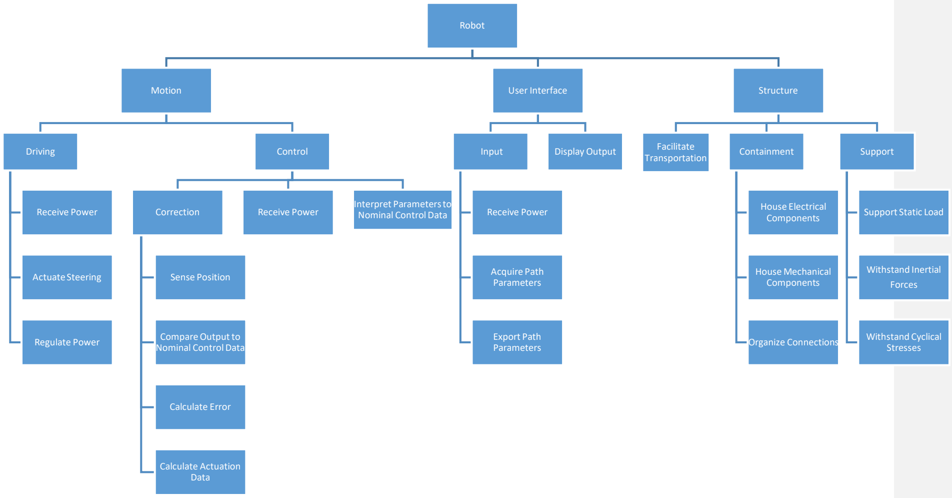


Figure 1: *Functional Hierarchy Chart*

The functional hierarchy chart highlights three main systems: structure, user interface, and motion. The structure system plays a key role in maintaining the device's integrity against movement forces, provides packaging of components, and facilitates transport of the device.

The user interface system handles interactions with the user. This was realized from the customer need for education and interactivity. It manages user-defined path parameters and displays the desired path to the user. As this was identified as the most important need for the customer, output functionality is left simplified to allow for an open solution space.

The motion system is responsible for processing and initiating movements that will be displayed as output. This involves realizing the path parameters taken from the user interface in to control data, actuating motion, and controlling the motion to match that of the input. A major customer-driven need for a continuous transition between input and output realized this system.

Connection To Systems

The device has 3 main systems: structure, motion, and user interface. Each system has identifiable subsystems that aid in achieving its desired purpose.

The structural system involves two subsystems – support and containment. The support subsystem involves ensuring the device's ability to withstand static and dynamic loading and prevent effects from inertial forces, such as unwanted translation or rotation. The containment subsystem involves general packaging, which includes accepting mechanical and electrical components, and organizing connections. These two subsystems aid in contributing to each other's success and provide clear identifiers of success in meeting the customer's need for output visibility. If the device is not well packaged, for example, unwanted mechanical forces may not be mitigated. Loose mechanical components such as motors could create vibrations. If the devices are not well supported, packaging may come undone. The optimization of packaging and support subsystems could also aid in facilitating transportation. A densely packed and light structure could allow for the device to be carried, lifted, or rolled to its destination much easier.

The motion system involves two subsystems – control and driving. The control subsystem involves determining the necessary actuations to take to achieve the desired output motion. This includes creating nominal control parameters, sensing position, comparing it to the nominal, calculating error, and setting the correct actuation data. The drive subsystem involves performing the necessary actuations to achieve the desired output motion based off the actuation data received from the control subsystem. These two subsystems are key in ~~showcasing~~highlighting the effective movement characteristics of CVTs. Without the control subsystem, the device would have no logic to perform the desired movement. Without the driving system, the device would not be able to physically move a point in space. Optimizing these two together will aid in gaining smooth, precise two-dimensional output, which will clearly be displayed to the audience.

The user interface system is comprised of a smaller input subsystem. This allows for the acquisition, storage, and communication of desired output path parameters to the rest of the device. The function of displaying output may become a subsystem in future work. As previously stated, it was left at a high level of functionality to allow for an open solution space. Once a solution is determined, however, displaying the output will need lower-level functionality. The relationship between the input subsystem and the output functionality of the device is of key importance to its educational worth. Without an input, a curve could not be set or changed, severely reducing interactivity. Without a proper output, the desired curve may not be realized, also reducing interactivity. Input and output functionality are important to the project's success and should work together to increase audience interactivity.

The Functional Cross Reference Table

Each of the lowest level functions is then compared against the systems to rank each function's importance in system relationship. This is shown in the table below. An “X” is marked under a system (column) that a function relates to (row)~~.~~.

Table 2: *Functional Cross Reference Table*

	Systems		
Functions	User Interface	Motion	Structure
Receive Power	X	X	
Acquire Path Parameters	x		
Export Path Parameters	X	X	
Display Output	X	X	X
Sense Position		X	

Compare Output to Nominal Data	X	X	
Calculate Error		X	
Calculate Actuation Data		X	
Interpret Parameters to Nominal Control Data	X	X	
Actuate Steering		X	X
Regulate Power		X	
Support Static Load			X
Withstand Inertial Forces		X	X

Withstand Cyclical Stresses		X	X
Organize Connections			X
House Electrical Components	X	X	X
House Mechanical Components		X	X
Facilitate Transportation			X

Smart Integration

The interaction between the systems is key to the overall functionality of the device. Each system connects to some other system between lower-level functions. The realization of this can identify areas for system integration and optimization of design parameters to ensure that all systems work holistically with each other.

From the cross-reference table, display output functionality has the most system relations. It involves parameters defined from the user interface, processed by the control subsystem, and realized by the motion subsystem. The realized motion directly affects the actual structure, while showing results, as dynamic forces are formed. This highlights a clear path from input to output through every system and implies that the design of each system will affect the output of the device. This is useful information when prototyping and testing because it is likely that a design choice may affect the output motion.

The realization of other areas of integration can be seen from functions of lower relationships. The function of exporting user determined path parameters, interpreting parameters to control data, and comparing the output to the nominal data involves both the user interface and the motion system. Data flows from the user interface, which is interpreted by the control subsystem, and is realized as actuation data. This means that proper communication between both the user interface and the motion system through the control subsystem is of importance. Streamlining where control and user data collection take place may help with this. Control and data collection may be done within one software environment, for example.

Motion and structure systems are also related. The ability of the structure to withstand inertial forces and cyclical stresses determines its effectiveness. However, this also affects the ability of the device to control and actuate motion. The structure failing due to its inability to withstand mechanical loading may add additional loading to mechanical components. Actuators such as electrical motors also have mechanical limits and may not operate correctly if this occurs. This implies that the housing of mechanical components is helped by the structural system and affects the motion system, as improper housing could lead to additional mechanical stresses and vibrations. It is also important to note that the ability to house electrical components affects all systems, as motion and user interface may include electrical systems. The structure can therefore take form with other systems. Sizing components through simulations and ample testing can help identify mounting needs. Testing mounting needs and motion characteristics can help improve this relationship.

Action and Outcome

The primary action of this project is to highlight the heightened resolution and accuracy that a Continuous Variable Transmission (CVT) based robotic device can execute. The customer needs this device to be an educational tool for secondary education aged students to show the capabilities of robotics and how far robotics development has come. The device powers on, reaching the appropriate angular velocity (ω) and torque to compensate for the contact preload, allowing the cylinder to drive the wheels through frictional contact, with the rolling axes initially parallel. It then receives a set of instructions that define a path function and dimension parameters within the bounds of the output medium. The software converts these instructions from output area coordinates into corresponding wheel distance parameters. These parameters are communicated to the microcontroller, which calculates the steering angle (ϕ) required for the friction-driven wheels to achieve the desired distance at a predetermined velocity, using the relation $v = r\omega\tan(\phi)$. Finally, the device executes the list of steering angles to accurately reproduce the initial path function and dimension parameters onto the output medium.

Function Resolution

It is important to discuss the resolution that describes the current functionality of the design. From the current customer needs, it has been desired that a continuous transition from user defined path parameters to an output curve is necessary. This process will highlight the unique movement characteristics of CVTs. The knowledge of this need led to the current understanding of functionality, with the understanding that the most important basic functionality is setting movement data, actuating movement, controlling that movement, and displaying it. The functionality of the device, therefore, relies on data transference. The user interface allows desired output data to be generated, recorded, and exported in the form of path parameters. The motion system then receives this data as control data with the formation of nominal control variables. The control data is then realized as movement data through comparisons with the nominal control variables. The movement data is then transferred back to the user interface system as visible output motion. The structure system ensures that the motion system and user interface system can effectively communicate this data by proper housing and mechanical support.

1.4 Targets & Metrics

To ensure functionality outlined during the functional decomposition process, metrics were applied to each function to provide a quantitative method of validating performance. When applicable, a target value was added. The team's functional hierarchy and cross-reference table were used to establish these, drawing from customer needs and feasible technical goals. The metrics and targets assigned to each function are detailed in both the table below and Appendix C.

Table 3: *Target Summary*

Function	**Metric**	**Target**
Acquire Path Parameters	Time Delay Between Interface and Motion Systems (sec)	0.5-1 sec
Export Path Parameters		
Interpret Parameters to Nominal Control Data		
Sense Position	Translation Measurement Error	< 0.05 in
Compare Output to Nominal Control Data	Desired Control Time Constant (sec)	0.5 sec
Calculate Error	Desired Steady State Output Error (in)	± 0.1 in
Calculate Actuation Data	Frequency of New Data Generation (Hz)	-

Actuate Steering	Maximum Actuation Torque (lb*ft)	-
	Desired Steering Coefficient of Kinetic Friction	0.215
Display Output	Display Output area (in^2)	8.5 in x11 in
	Desired Completion Time (sec)	60 sec
Withstand Static Load	Total Mass (~~lb~~lb.)	22 ~~lb~~lb.
Withstand Inertial Forces	Ratio of Base Mass to Linkage Mass	2
Withstand Cyclical Stresses	Life Cycle (years)	5 years
House Mechanical Components	Available Volume (in^3)	32 in x 28 in x 55 in
House Electrical Components		
Organize Connections		
Facilitate Transportation	Total Mass (~~lb~~lb.)	22 ~~lb~~lb.
Receive Power	Input Voltage (V)	120V AC

Regulate Power	Output Voltage Range (V)	5V to 24V DC

Critical Targets & Metrics

The CVT educational device, designed primarily for high school educational environments, involves several critical functionalities that ensure basic operation. The following table provides a summary of these critical functions and their associated metrics and targets.

Table 4: *Critical Targets and Metrics*

Function	**Metric**	**Target**
Receive Power	Input Voltage (V)	120 V
Acquire Path Parameters	Time Delay Between Interface and Motion Systems (sec)	0.5-1 sec
Export Path Parameters		
Interpret Parameters to Nominal Control Data		
Sense Position	Translation Measurement Error	± 0.05 in
Compare Output to Nominal Data	Desired Control Time Constant (sec)	0.5 sec
Calculate Error	Desired Steady State Output Error (in)	± 0.1 in
Calculate Actuation Data	Frequency of New Data Generation (Hz)	100 kHz

Actuate Steering	Maximum Actuation Torque (~~lb~~lb.*ft)	-
	Desired Steering Coefficient of Kinetic Friction	0.215
Display Output	Display output area (in^2)	8.5 in x 11 in
	Desired completion time (sec)	60 sec

Generation of Critical Metrics and Targets

The functions, metrics, and target values above were deemed critical using the previous discussion of the basic flow of information between the major systems (the generation of path data and the transformation of path data into control, ~~actuation~~actuation, and output data).

Path Parameter Acquisition and Handling

To measure the functionality of receiving, exporting, and interpreting path parameters, the metric of time delay can be used, as a quantifiable time between user input and motion will automatically ensure these functions are completed. This is targeted to be 0.5-1 sec to provide a customer driven efficient experience. It is important to note that this may be changed if a more reasonable value is determined with specific hardware.

Position Sensing

The metric involved with sensing position is critical in controlling motion. Without the knowledge of a current position, a new position cannot be realized. The necessary sensor would be a passive, proprioceptive sensor because it will be measuring values internal to the robot and will be able to do so by measuring ambient environmental energy as opposed to emitting energy and measuring a reaction. The target for accuracy of sensing the robot's position is expected to be within 0.05 inches of the actual position. This was determined based on research of product specifications of a possible sensor to use for measurement. It is also more accurate than the required level of accuracy stated by the customer. A nominal position value for the robot will be determined analytically.

Comparison of Data and Error Calculation

Once a position is sensed, that sensed data and path data are expected to be compared together to produce control data. If accurate control data has been created, then some mitigated steady state error should be present. The steady state output error quantifies the control subsystem's ability to quantify errors from this comparison. This was determined to be ± 0.1 in and was specified by the customer. The time constant required to achieve this error measures the efficiency at which sensed data and nominal path data can be compared. This was determined to be 0.5 sec to provide the efficient, accurate motion needed by the customer. However, this is expected to change with hardware, and a more realistic value will ~~likely be~~be applied.

Calculation of Actuation Data

After control data has been created, actuation data is generated at a rate of 100kHz after calculation. ~~The ability of the motion system to generate actuation data efficiently to match the generation of control data can be used to quantify the extent to which this functionality is completed.~~The motion system's ability to generate actuation data efficiently to match the generation of control data can be used to quantify how much this functionality is completed. If actuation data is not generated efficiently, a bottleneck of information flow will occur. Therefore, the frequency of new actuation data generation can be used to determine the extent of this bottleneck. No value has been determined, as this is hardware specific. A specific quantity will eventually be realized.

Steering Actuation

After actuation data is generated, actuation can occur. As this is a physical action, physical metrics can be used to quantify if this action can occur. These were determined by realizing the limiting conditions present in a CVT. The desired steering coefficient of friction and the maximum actuation torque determined by it are critical to the project, because if these are not met, steering may not be able to occur. The desired steering coefficient of kinetic friction is critical. If friction is too low, accurate motion may be lost due to excessive slip. However, if friction is too high, not enough slip can be generated, preventing steering. Therefore, two extremes were taken and averaged – oiled steel on oiled steel for a low friction situation and rubber on wet concrete for a high friction application (Moebs et al., 2016). This averaged value was determined to be 0.215. Note that wet concrete was used instead of dry concrete, as dry concrete was determined to have too high friction. The torque required to steer the wheels under this average condition is important to determine, as insufficient torque will result in loss of steering. This value was left to be determined with high fidelity simulation. ~~This was due to other loading conditions that are unknown at this time and will be determined once some high-fidelity concepts are generated.~~This was due to other loading conditions unknown and will be determined once high-fidelity concepts are generated.

Output of Motion

Displaying output is critical to the project because it determines the ability of the device to engage with students. The output area was deemed a critical method of measuring this functionality, as it was specified by the customer and will affect the audience size. This has a target value of 8.5 in x 11 in but may change if needed. It is also important to measure the efficiency with which output is displayed, given the time constraints specified by the customer. The total path completion time was then created as a metric with a target value of 60 seconds to maintain interaction with 30 individuals within a one-hour period.

Receiving Power

For the data flow to occur, power must be received to components such as actuation and control hardware. The input electrical voltage is then used as a metric to gauge if power can be supplied. This was determined to be the standard 120V AC standard voltage found in North American infrastructure. This ensures compatibility with common power outlets in schools and museums.

Measurement and Validation of Critical Metrics

To measure and validate the critical functions, metrics and targets for the team's device, a series of specific testing and validation methods will be employed. These methods will ensure the design meets the functional requirements and performs reliably in educational settings.

To test the handline of path parameters, the time delay between user input and motion initiation can be measured using an integrated timer. The target of 0.5–1 second ensures quick responsiveness, critical for maintaining engagement in a classroom demonstration. This can be validated by conducting timed response tests with varying input conditions and ensuring the system consistently meets the target time. A software environment can be created and timed runs can be performed.

To test the device's ability to sense position, a position sensor can be used to measure the current location of the device in real time. This can be validated in software by a collection of positions over time. The sensed data can be compared to the desired path data, and error can be measured. This can be done physically by plotting test curves and measuring their deviation, or by creating a software environment that tracks control data over time. This control data can be compared over time to determine if the steady state error reaches the desired value. Additionally, the software environment can be utilized to track the time necessary to reach a desired steady state error~~.~~.

To validate the steering ability of the device, physical and virtual testing environments can be created. A virtual computer aided design (CAD) model can be simulated with proper material values to determine the torque necessary to make movements. This can be done iteratively with new material combinations and motor specifications to achieve better target values. Physical validation can be performed by running tests with varying loads and materials and analyzing the error in the output (as explained earlier). ~~The steering coefficient of kinetic friction could be measured using a tribometer or alternatively through a manual friction test during prototyping utilizing a spring scale.~~The steering coefficient of kinetic friction could be measured using a tribometer or through a manual friction test during prototyping using a spring scale.

The robot's ability to trace a visible path within an 8.5 in x 11 in area will be verified by measuring the output area with a ruler or similar tool. This can be done in tests where a rectangle is drawn around the working boundary, and the rectangle is measured. Additionally, the path completion time of 60 seconds will be validated through timed trials to ensure the device can engage an audience.

A multimeter will be used to verify the 120V AC input voltage for Receiving Power. The regulated output voltage, which aims to produce power between 5 and 24 V DC, will be tested across several components to verify reliable and secure power delivery while maintaining compatibility with normal classroom outlets.

Summary of Targets & Metrics

A comprehensive list of all the project's targets and metrics can be found within Appendix C. As prototypes are developed and tested, some targets may be refined to reflect real-world conditions. These targets serve as performance benchmarks, ensuring alignment with customer objectives and managing project costs. While subject to adjustment, they provide a clear framework for tracking progress and guiding design decisions.

1.5 Concept Generation

Concept generation is a critical phase in the design process, as it fosters the development of innovative ideas that can address complex problems effectively. By leveraging a range of concept selection techniques, our team was able to craft a broad array of distinctive ideas. Combining our targets and constraints, we ultimately generated a list of 100 potential concepts for the project, as detailed in Table 1 of Appendix E.

Concept Generation Tools

To spark and refine ideas, the team employed various tools, including brainstorming, SCAMPER, and a morphological chart. We started concept generation within our Sponsor's Office, creating a collaborative space where everyone could contribute freely, facilitating an inclusive atmosphere for exploring diverse ideas that could meet the essential functions identified in the project's functional decomposition.

The team created a morphological chart to map significant functions derived from the functional decomposition. By organizing various categories and their corresponding options in this structured chart, we systematically combined options from ~~different categories~~various categories, leading to unique design configurations. This chart is shown in Table of Appendix E.

Finally, team members used SCAMPER and Biomimicry methods to explore other unique characteristics that might enhance the final design. SCAMPER expands on existing ideas by using actions represented in its acronym: Substitute, Combine, Adapt, Modify (Magnify, Minify), Put to another use, Eliminate, Rearrange, and Reverse. ~~Biomimicry, on the other hand, draws inspiration from natural forms and functions found in plants and animals.~~Biomimicry, however, draws inspiration from natural forms and functions found in plants and animals.

Concept Fidelity

To streamline concept selection, the team identified five medium-fidelity concepts and four high-fidelity concepts.

1.5.1.1 Medium Fidelities

To evaluate key features of our design while staying within the project constraints, we selected medium-fidelity concepts that highlight specific functions without fully integrating all target features. Each of these concepts has been tailored to test certain aspects of the CVT system, user interaction, and device control, providing us with valuable insights before moving to high-fidelity models.

Projectile Trajectory Game (Button-Controlled)

This concept centers on a simple projectile trajectory game using an external endpoint friction contact drive. It allows users to select from a set of button options to adjust launch parameters, demonstrating basic user control and feedback. The system utilizes nylon wheels on an aluminum cylinder, with an inverted crank linkage to adjust trajectory angles. ~~This medium-fidelity prototype aims to test the feasibility of friction contact for maintaining control under varying conditions, as well as to evaluate the responsiveness of the button-controlled interface.~~This medium-fidelity prototype aims to test the feasibility of friction contact for maintaining control under varying conditions and to evaluate the responsiveness of the button-controlled interface.

Racecar Game (Potentiometer-Controlled)

This version of the Racecar Game uses an internal endpoint friction contact drive and a linear/string potentiometer with absolute or incremental encoders to sense position. Like the Projectile Trajectory Game, it features nylon wheels on an aluminum cylinder with an inverted crank linkage to modulate wheel positioning. The potentiometer control offers continuous feedback, helping us assess accuracy and speed modulation capabilities. This prototype will test the CVT system’s ability to dynamically adjust speed, allowing us to refine frictional engagement and wheel adjustments.

Projectile Trajectory Game with PID Control

Another Projectile Trajectory Game variant, this design implements a PID control system to achieve precise trajectory adjustments. Using an external endpoint friction contact drive, the game incorporates nylon wheels on an aluminum cylinder and an inverted crank linkage. The PID control feature allows for real-time adjustments in response to changes in trajectory angle and speed. This prototype is valuable for evaluating how well the CVT system maintains stability under varying conditions and for testing the accuracy of the friction drive paired with PID feedback.

Roller Coaster Potential Energy Study

This concept investigates energy dynamics using an external total lengthwise friction contact drive, with a rotary potentiometer to measure position along a simulated roller coaster path. Constructed with nylon wheels on a PVC cylinder, the design integrates a high-precision gear linkage to adjust wheel positioning smoothly along the track. This concept will help us understand energy transfer and potential energy conservation, testing CVT's role in modulating speed along a variable incline.

Gridded Paper Curve Plotting

The Gridded Paper Curve Plotting concept is a drawing interaction tool, using a clamp-coupled direct drive system to trace paths on gridded paper. Controlled through a draw pad interaction interface, it uses polypropylene wheels on a powder-coated aluminum cylinder, connected via a magnetic carriage linkage for smoother operation. By testing precision and stability in curve plotting, this concept explores CVT application in steady, continuous motion and ensures that user inputs translate accurately into consistent movement.

1.5.1.2 High Fidelity

Our high-fidelity concepts incorporate essential features that most closely align with the project's primary goals and customer requirements. These four designs will be integral to the concept selection process, as they represent the most complete embodiments of the functions necessary to fulfill the project objectives. Each concept focuses on dynamic interactions, control precision, and educational engagement, providing a comprehensive test of our CVT-based design capabilities.

Optimal Path Simulation for Racecar Game (Concept 1)

This high-fidelity concept allows users to explore the optimal path on a simulated racecar course. Users can draw their perceived fastest path on a chosen course, after which the robot attempts to recreate the optimal path for comparison. The user interface includes a simple menu with button controls to select various track options. Distance sensing is facilitated by string potentiometers, while stepper motors power the CVT wheels. The system operates with a belt drive and external tensioner to simulate frictional interactions, using polyurethane wheels on a steel cylinder. The linkage and carriage interaction are controlled by an inverted crank-slider pin connection. This concept teaches users about efficient path planning and helps visualize how CVT adjustments impact path accuracy and speed control.

Long Exposure Drawing Guessing Game (Concept 2)

This concept presents a guessing game that utilizes long-exposure drawing to reveal portions of a hidden shape, encouraging the user to identify the form as the robot draws. Users select a complex shape from the interface, and the robot uses a laser to draw on a photosensitive screen, momentarily illuminating individual parts of the shape. The interface is operated by a simple button input, with a string potentiometer used for distance sensing. Rack and pinion devices actuate the CVT wheels, while an internal endpoint friction contact drive moves the laser, with polyurethane wheels on a PVC cylinder for smooth interaction. The linkage and carriage are connected by a pivoting linkage, providing precision in shape tracing. This concept illustrates the precision and adaptive qualities of CVT in a dynamic, interactive environment, enhancing users' understanding of position control and incremental exposure techniques.

Projectile Trajectory Game (Concept 3)

This device simulates a projectile trajectory game to demonstrate fundamental robotics and physics principles, particularly projectile motion. The game is centered around teaching users about the effects of adjusting initial velocity and launch angle to hit a target. The curve of each projectile follows a parabolic path, which is plotted on a whiteboard with erasable markers. A pivoting linkage arm, guided by nylon wheels on an aluminum cylinder, controls the projectile's trajectory. The aluminum cylinder operates through an external endpoint friction contact drive, while servo motors provide precise steering, and rotary encoders measure position. Controlled by a PID feedback system, the device offers an interactive user interface, allowing users to input values such as launch speed and angle via a keyboard. This setup provides a detailed exploration of motion dynamics, helping users gain a hands-on understanding of how continuous variable transmission impacts movement.

Waveform Interaction Study

This concept is designed to educate users on waveform properties by allowing them to control and interact with two sine waves, adjusting amplitude, frequency, and phase difference. The device plots wave interactions on a decorated whiteboard using erasable markers, helping visualize constructive and destructive interference. It uses a pivoting linkage arm driven by nylon wheels on an aluminum cylinder and powered by an external endpoint friction contact drive. Servo motors enable smooth control of wave adjustments, while rotary encoders sense position and ensure accurate wave representations. A PID controller provides real-time adjustments, and users can interact with the system via a keyboard-based interface. This setup not only teaches fundamental concepts in wave theory but also highlights CVT functionality through continuous modulation of motion parameters.

Each high-fidelity concept has been carefully crafted to support the technical goals of demonstrating CVT principles, user engagement, and educational outcomes. These prototypes provide a clear pathway to evaluate which design best meets the project’s specifications and customer requirements, offering hands-on interaction, real-time feedback, and a comprehensive exploration of CVT applications.

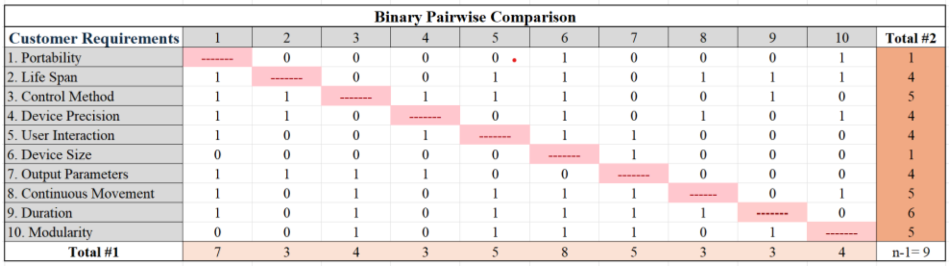
1.6 Concept Selection

Once the five medium fidelity and three high fidelity concepts were determined to break down and choose the best concept, using specific tools to narrow down the concepts. The point of implanting these tools is to erase biased opinions and give a fair and discrete rating system, alloying the idea of having a fair assessment. Make sure that the team chooses the final concept based on objective reasoning. The tools used to determine this are the Binary Pairwise Comparison, House of Quality, Pugh charts, and the Analytical Hierarchy Process.

1.6.1 Binary Pairwise Comparison

Within the Binary Pairwise Comparison, the team has a list of requirements the customer gives for the device to operate. These requirements are compared and ranked on a scale of 1-0. Reading the scale from the row to a column, if a requirement in that row was given one compared to the column it is being compared to, it means that the requirement has a higher priority over the other, and the reverse happens when given a 0. Once filled, a score for each requirement will be added based on the scores in each section, making a weight factor score that will be used later with the House of Quality.

Table 8: *Binary Pairwise Comparison*

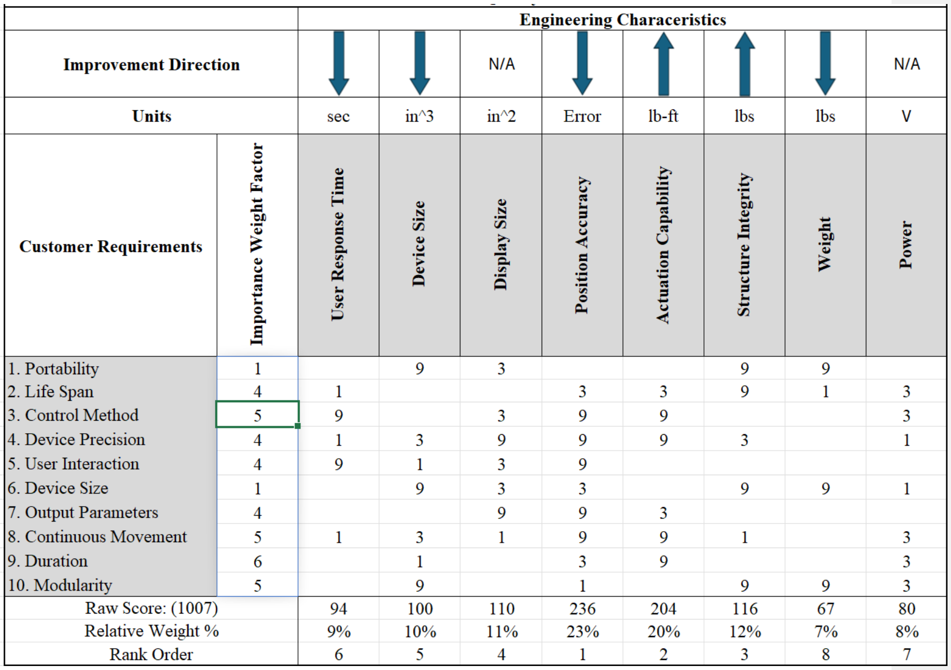


Binary Pairwise Comparison											
Customer Requirements	1	2	3	4	5	6	7	8	9	10	**Total #2**
1. Portability	-------	0	0	0	0	1	0	0	0	1	1
2. Life Span	1	-------	0	0	1	1	0	1	1	1	4
3. Control Method	1	1	-------	1	1	1	0	0	1	0	5
4. Device Precision	1	1	0	-------	0	1	0	1	0	1	4
5. User Interaction	1	0	0	1	-------	1	1	0	0	0	4
6. Device Size	0	0	0	0	0	-------	1	0	0	0	1
7. Output Parameters	1	1	1	1	0	0	-------	0	0	0	4
8. Continuous Movement	1	0	1	0	1	1	1	------	0	1	5
9. Duration	1	0	1	0	1	1	1	1	-------	0	6
10. Modularity	0	0	1	0	1	1	1	0	1	-------	5
Total #1	7	3	4	3	5	8	5	3	3	4	n-1= 9

1.6.2 House of Quality

The House of Quality process focused on determining the primary customer needs to guide the design. The team identified and clarified vital requirements through a systematic comparison, ensuring that each design aspect aligns with these priorities. Weighted scores evaluated how various design features meet customer needs, emphasizing those most crucial for safety and functionality. This structured approach allowed the team to balance all requirements objectively, ensuring that critical and secondary elements are addressed in the final design framework.

Table 9: *House of Quality*



		Engineering Characeristics							
Improvement Direction		↓	↓	N/A	↓	↑	↑	↓	N/A
Units		sec	in^3	in^2	Error	lb-ft	lbs	lbs	V
Customer Requirements	**Importance Weight Factor**	**User Response Time**	**Device Size**	**Display Size**	**Position Accuracy**	**Actuation Capability**	**Structure Integrity**	**Weight**	**Power**
1. Portability	1		9	3			9	9	
2. Life Span	4	1			3	3	9	1	3
3. Control Method	5	9		3	9	9			3
4. Device Precision	4	1	3	9	9	9	3		1
5. User Interaction	4	9	1	3	9				
6. Device Size	1		9	3	3		9	9	1
7. Output Parameters	4			9	9	3			
8. Continuous Movement	5	1	3	1	9	9	1		3
9. Duration	6		1		3	9			3
10. Modularity	5		9		1		9	9	3
Raw Score: (1007)		94	100	110	236	204	116	67	80
Relative Weight %		9%	10%	11%	23%	20%	12%	7%	8%
Rank Order		6	5	4	1	2	3	8	7

1.6.3 Pugh Charts

The five medium-fidelity and three high-fidelity concepts outlined in Table 10 below are compared in a Pugh Chart to assess the effectiveness of their functional characteristics. The concepts are represented in columns, while the engineering characteristics, identified from the House of Quality, are listed in rows. To initiate the Pugh analysis, a reference point, or "datum," is selected, serving as a baseline against which all other concepts are evaluated. The chart employs a rating system of pluses (+), minuses (-), and satisfactory (S) to gauge comparative performance. This system translates qualitative aspects—such as concept features and requirements—into quantifiable data, enabling weighted analysis to identify the optimal choice based on the chart's results.

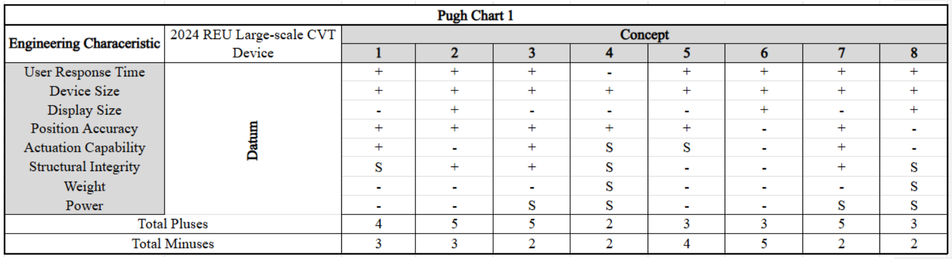
Table 10: Concepts Table

Concept	**Description**
1	**Optimal Path Simulation for Racecar Game**
2	**Long Exposure Drawing Guessing Game**
3	**Projectile Trajectory Game**
4	**Waveform Interaction Study**
5	**Projectile Trajectory Game (Button-Controlled)**
6	**Racecar Game (Potentiometer-Controlled)**
7	**Projectile Trajectory Game with PID Control**
8	**Roller Coaster Potential Energy Study**

Table 11 presents the initial Pugh Chart, with a pre-existing CVT model, developed by a previous research student under Dr. Moore, chosen as the datum. This CVT model provides the foundational baseline for evaluating the remaining seven concepts based on the top five prioritized engineering characteristics. In this first iteration of the Pugh Chart, concepts 2, 3, and

7 achieved the top positive scores. All concepts scoring positively in the first iteration were carried forward to the next stage of evaluation.

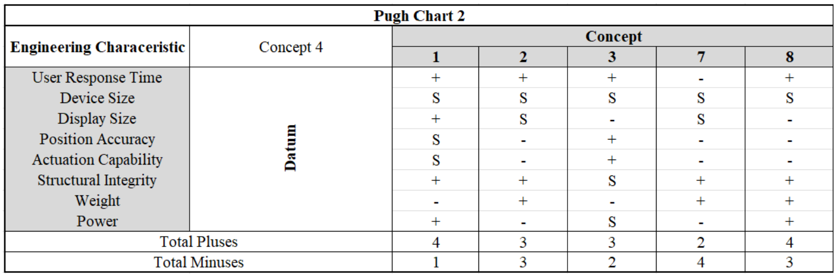
Table 11: Pugh Chart 1 Iteration



Pugh Chart 1									
Engineering Characeristic	2024 REU Large-scale CVT Device	Concept							
		1	2	3	4	5	6	7	8
User Response Time	Datum	+	+	+	-	+	+	+	+
Device Size		+	+	+	+	+	+	+	+
Display Size		-	+	-	-	-	+	-	+
Position Accuracy		+	+	+	+	+	-	+	-
Actuation Capability		+	-	+	S	S	-	+	-
Structural Integrity		S	+	+	S	-	-	+	S
Weight		-	-	-	S	-	-	-	S
Power		-	-	S	S	-	-	S	S
Total Pluses		4	5	5	2	3	3	5	3
Total Minuses		3	3	2	2	4	5	2	2

The second iteration of our Pugh Chart is shown in Table 11. In this round, Concept 4 was chosen as the datum, as it provided a balanced reference point based on its prior performance. After completing the chart, Concept 8 and 1 emerged with a score of +4, the highest in this iteration, followed closely by Concepts 2 and 3. Concept 7, however, had the lowest score, suggesting lower suitability relative to the datum.

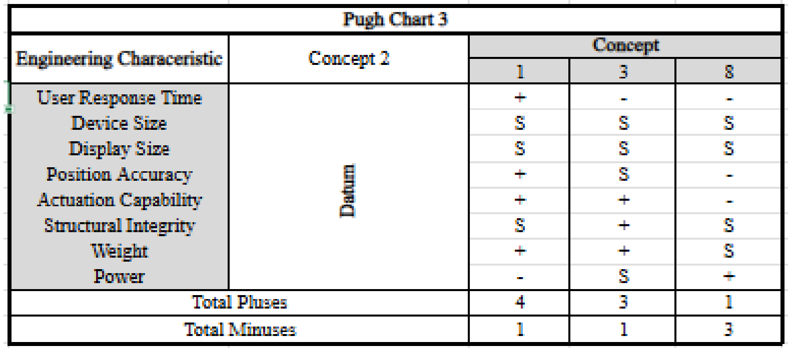
Table 12: Pugh Chart 2 Iteration



Pugh Chart 2						
Engineering Characeristic	Concept 4	Concept				
		1	2	3	7	8
User Response Time	Datum	+	+	+	-	+
Device Size		S	S	S	S	S
Display Size		+	S	-	S	-
Position Accuracy		S	-	+	-	-
Actuation Capability		S	-	+	-	-
Structural Integrity		+	+	S	+	+
Weight		-	+	-	+	+
Power		+	-	S	-	+
Total Pluses		4	3	3	2	4
Total Minuses		1	3	2	4	3

Our final Pugh Chart is presented in Table 12, where Concept 2 was selected as the datum to compare the top-performing concepts from previous iterations: Concepts 1, 3, and 8. Each engineering characteristic was evaluated against this baseline, and as a result, Concept 1 achieved a score of +4, while Concept 3 scored +3. Concept 8, with a score of +1, showed relatively lower potential. These final rankings will inform the selection process in the concluding rating matrix, leading to our choice of the optimal concept.

Table 12: Pugh Chart 3 Iteration



Pugh Chart 3				
Engineering Characeristic	Concept 2	Concept		
		1	3	8
User Response Time	Datum	+	-	-
Device Size		S	S	S
Display Size		S	S	S
Position Accuracy		+	S	-
Actuation Capability		+	+	-
Structural Integrity		S	+	S
Weight		+	+	S
Power		-	S	+
Total Pluses		4	3	1
Total Minuses		1	1	3

The top three concepts based on the final iteration are Concept 2, Concept 1, and Concept 3.

1.6.4 Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) was applied to prioritize the engineering characteristics most crucial for the project's success. The process entails comparing each characteristic against all others to establish a relative importance ranking. A scale of 1, 3, 5, 7, and 9 was used, where 1 signifies equal importance between two characteristics, and 9 indicates one characteristic is significantly more important than the other. The corresponding cell on the opposite side of the matrix receives the inverse value of the original score. Cells comparing a characteristic to itself are marked with a 1.

Once the comparisons were completed, the scores were summed vertically. Each cell was then normalized by dividing it by the column's total, producing a normalized matrix. To verify the accuracy and impartiality of these rankings, a consistency check was performed. If the consistency ratio was below 0.1, the rankings were considered unbiased. A higher ratio indicated inconsistency, requiring adjustments to the ranking. Table 13 presents the initial AHP matrix for the engineering characteristics which can be found in ~~the Appendix~~Appendix E.

1.6.5 Final Concept Selection

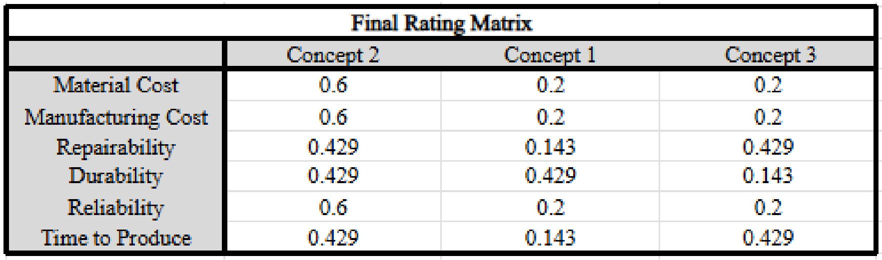
Based on the results from our Final Rating Matrix in ~~the Appendix~~Appendix E, Concept 2, the "Long Exposure Drawing Guessing Game," stands out as the top choice, meeting the key criteria from our previous analysis most effectively. This concept is designed as an interactive guessing game that combines long-exposure drawing with a unique educational experience. It invites users to identify hidden shapes gradually revealed as the robot uses a laser to draw on a photosensitive screen. Users select a shape through the interface, and the robot illuminates sections of it in stages, allowing users to guess the shape incrementally.

The drawing process is powered by a CVT-controlled system that includes servo motors ~~rack-and-pinion devices~~ for actuating the wheels and an endpoint friction drive to move the laser with precision. Polyurethane wheels roll on a PVC cylinder for smooth, stable movement, while a pivoting linkage ensures accurate shape tracing. Rotary encoders in tandem with string potentiometers will sense the position of the wheels along the cylinder. A [blank] controller will interpret the input from the user and will control the steering of the wheels by modeling dynamics of motion. Input will be registered from the user through an LCD screen and button interface. This setup effectively demonstrates the adaptability of CVT systems and their role in maintaining precise position control. Additionally, distance is measured by a string potentiometer, and users operate the game via a straightforward button input, ensuring an intuitive experience.

This concept was chosen as it best fulfills the critical characteristics identified in the AHP matrix. The matrix highlighted the importance of repairability, durability, and reliability. Concept 2’s design, which leverages long-exposure drawing and a controlled, guided movement, aligns well with these characteristics. Although this concept will require additional sensors and fine-tuned controls for maintaining consistent drawing speed and accuracy, it presents significant advantages in user engagement and educational value.

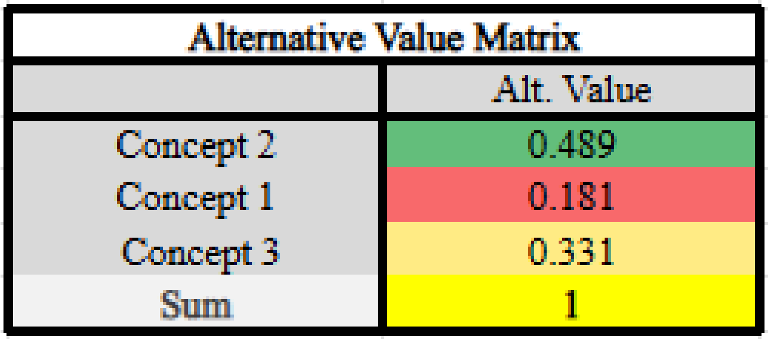
By offering a dynamic, visually engaging way to understand the CVT principle, Concept 2 provides a practical demonstration of precision control and incremental exposure techniques, making it an ideal choice to meet customer needs. The interactive format and educational focus of this concept ~~fulfill~~fulfills both the technical requirements and the experiential goals of the project, making it the most advantageous solution among the options evaluated.

Table 13: Final Rating Matrix



Final Rating Matrix			
	Concept 2	Concept 1	Concept 3
Material Cost	0.6	0.2	0.2
Manufacturing Cost	0.6	0.2	0.2
Repairability	0.429	0.143	0.429
Durability	0.429	0.429	0.143
Reliability	0.6	0.2	0.2
Time to Produce	0.429	0.143	0.429

Table ~~14 :~~14: Alternative Value Matrix



Alternative Value Matrix	
	Alt. Value
Concept 2	0.489
Concept 1	0.181
Concept 3	0.331
Sum	1

Appendices

Appendix A: Code of Conduct

This document serves as a binding contract for members of FAMU-FSU College of Engineering Senior Design Team 515 effective Fall 2024 to Spring 2025.

Project Description

Team 515 is tasked with designing an educational device to demonstrate the use of Continuous Variable Transmission (CVT) technology in robotics. The device aims to engage student audiences by highlighting the smooth movement characteristics of CVTs. If significant technological development is made, the devices could serve as a subsystem in a larger haptic feedback collaborative robot (cobot) for remote tele-operation (OpenAI, 2024).

Mission Statement

Team 515's objective is to collaboratively design a mechanical device for robotic education. The team will apply engineering design strategies and knowledge in a professional and ethical manner, ensuring the representation of the FAMU-FSU College of Engineering with respect and integrity.

Outside Obligations

Team 515 intends for team and sponsor meetings to occur during hours that best align with each party's schedule. To do so effectively, each member's schedule was considered when selecting meeting times. Absences will be discussed in the Attendance section. The following are known outside obligations:

- Kemani Harris: Undergraduate research, Organization meetings and events
- Aaron Havener: Work (schedule varies weekly)
- Jacob Hernandez: AME Undergraduate Research, Organization Obligations
- Aliya Hutley: NASA Langley Research Center M-F ~~MagLab & HPMI Research~~
- Cade Watson: ASC undergraduate research ~~on Monday, Wednesday, and Friday; Corresponding Secretary obligations for~~ Tau Beta Pi involvement occurring throughout each week; ~~C~~church obligations on Sunday and Tuesday

Team Roles

The following table outlines the agreed roles for each team member, which may be reassigned or adjusted as needed. Additional roles may be assigned during the project, and any changes will be discussed with the team.

~~Table~~ ~~5:~~Table: *Team Roles*

Team Member	Role
Kemani Harris	Dynamic Systems Engineer – responsible for work on the kinematics and forces interacting with the system
Aaron Havener	Controls Engineer – responsible for incorporating electrical components and control system ~~programming with~~ in the motion of the mechanism. Aid and support systems engineer with performing tests.
Jacob Hernandez	Design Engineer – responsible for incorporating kinematic, materials, and testing feedback into the iterative design process to produce the most feasible, high-fidelity prototype
Aliya Hutley	System Engineer & POC – Responsible for developing test procedure and documentation. Focus on writing and optimizing code,

	collaborating remotely with the Controls Engineer, and ensuring the system functions cohesively with the overall device. Provide support across design and coordinate meetings with Advisor while tracking progress. ~~Testing Engineer & POC – Responsible for conducting and documenting tests, analyzing performance, troubleshoot issues, etc.~~
Cade Watson	Materials Engineer – Responsible for selecting proper engineering materials and material modeling

Communication

Team communication is expected to be conducted using both Microsoft Teams and text messaging. Microsoft Teams and other similar shared workspace suites will be used to discuss technical content, assign tasks, and track progress. ~~while t~~Text messaging will be used for ~~meeting~~ ~~planning~~ more informal and rapid discussion. Each team member is expected to be responsive during scheduled meeting times. Normal communication hours are Monday-Friday between 8:00 AM and 10:00 PM with a maximum of 24 hours between chat responses. Members are expected to communicate in a respectful and professional tone during professional meetings with sponsors, advisors, teaching staff, and stakeholders.

Dress Code

For team and sponsor meetings, casual attire is appropriate unless specified. However, for Virtual Design Reviews (VDRs), team members are expected to dress in business casual, which would consist of khakis and polo/button-down shirts. On Senior Design Day, a business professional dress code is required.

Attendance Policy

Regularly scheduled team meetings have been agreed to occur during Senior Design class following the lecture. Currently this is scheduled for Tuesday and Thursday from 3:30 PM – 7:45 PM. Sponsor/Advisor meetings are tentatively scheduled ~~biweekly on Monday at 3:00 PM~~ for Wednesdays at 4:45 PM. For these meetings, absences should be stated within 1 hour of the meeting time. The previous meeting is expected to be discussed in the following meeting. If a notification is not given or attendance is missed at the following meeting, an infraction will be incurred (refer to Intervention Policy). If a notification is not given and attendance is missed at the following meeting, a strike will be incurred.

Commented [AH1]: Refer to When2Meet for new possible time

Commented [AH2R1]: Additionally, adding Hybrid Meeting Option for remote members.

Additional team meetings are scheduled at least 12 hours prior to the desired date. Notification of attendance should be provided using the same minimum window. Failure to do so will result in an infraction. Design Reviews require mandatory attendance. If missed, an automatic 2 strikes are incurred.

Task Tracking and Accountability

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To ensure project completion and timely submission of Canvas Assignments, the team will use Microsoft Teams Planner App for task management. During Team 515's Weekly Meeting, typically held on Tuesdays, tasks will be created and planned for the next 1 to 2 weeks, aligning with project deadlines, milestones, and Canvas Submission due dates. Tasks will be assigned in rotations among team members, with each person taking responsibility for ~~specific~~a specific task. ~~If necessary, team members may exchange responsibilities, provided that the change is communicated in advance and the shift is validated by the team.~~If necessary, team members may exchange responsibilities, provided the change is communicated in advance and validated by the team. Each task will be clearly defined with specific objectives and due dates. An individual will also be responsible for submitting each Canvas Assignment, ensuring ~~accountability~~accountability, and reducing the risk of missed deadlines. Team members will be expected to regularly check the Planner App to track their progress and provide updates during meetings. This system will help the Team stay organized, accountable, and on track.

To hold each member accountable for their tasks, the intervention policy (refer to Intervention Policy) will be employed. If the team deems that a member has not met their tasks sufficiently, an infraction will be incurred at the first occurrence. At the second occurrence, a strike will be incurred, and a proactive meeting will be held during class time to determine corrective actions. Each of the following occurrences will incur a strike. Note that if the team determines the member was not at fault, punitive measures may be reversed.

Intervention Policy

Team 515 will use an intervention policy constituting smaller infractions and larger strikes. Three infractions constitute one strike. Two strikes will result in a team intervention. This involves a meeting with the team to discuss preventative measures. Communication about the meeting will be provided via text message and e-mail. Note that failure to attend the intervention will result in a third strike. Upon the incursion of a third strike, a meeting with Dr. McConomy will be scheduled via email seeking a team-wide meeting to discuss punitive measures. The team agrees that emergencies, as determined by a member's respective school, absolve a team member of any potential strike. When meeting with Dr. McConomy, the team seeks guidance on how to address the situation and requests support in facilitating a resolution, which may include mediation or formal intervention to ensure the team can move forward productively.

Amendment Policy

Amendments to this contract are allowed but must be passed by a unanimous decision of group members.

Statement of Understanding

I acknowledge the guidelines outlined in the Code of Conduct and shared on the Microsoft Teams page. I understand it is my responsibility to follow these procedures and agree to the policies and any consequences determined by the team for non-compliance.

Code of Conduct Acknowledgement

Kimani Harris

Aaron J. Havener

Gabriel Cecil

Alinya Hutley

Appendix B: Work Breakdown Structure

~~Table 6:~~Table: *Work Breakdown Structure*

Milestone	**Task**	**Subtasks (Packets)**	**Managing Team Member**	**Status**	**Due Date**	**Date Completed**
VDR1			-	Not started	10/8/2024	
	Project Scope		-	Completed	9/20/2024	9/20/2024
		Set meeting time with sponsor(s)	Aliya	Completed		9/13/2024
		Perform background research on sponsors and previous work	Aaron	Completed		9/16/2024
		Form questions for the sponsor about the purpose, goals, and previous progress of the project	Aaron	Completed		9/16/2024
		Discuss questions with sponsor and take meeting notes	Jacob	Completed		9/16/2024
		Discuss meeting notes as a group and refine	Cade	Completed		9/19/2024

		As a group, identify a clear project description, goals, markets, stakeholders, and assumptions	Kemani	Completed		9/19/2024
		Write the document	Aliya	Completed		9/19/2024
		Edit the document	Cade	Completed		9/20/2024
		Submit the document	Cade	Completed		9/20/2024
	Customer Needs		-	Not started	9/27/2024	
		Set meeting time with sponsor(s)	Aliya	Completed		9/20/2024
		Perform background research on customer and end user behavior	Aaron	Completed		9/22/2024
		Form questions for the sponsor regarding the customers and end users	Cade	Completed		9/22/2024
		Discuss questions with sponsor and take meeting notes	Kemani	Completed		9/24/2024

		Discuss meeting notes as a group and form a list of questions and answers	Jacob	Completed		9/28/2024
		Interpret engineering needs from the sponsor's answers	Aaron	Completed		9/30/2024
		If needed, perform additional supplementary technical research	Aliya	Not started		-
		Write the document	Kemani	Not started		10/1/2024
		Edit the document	Aliya	Not started		10/1/2024
		Submit the document	Cade	Not started		10/1/2024
	Functional Decomposition		-	Completed	10/4/2024	10/4/2024
		Utilize the knowledge of engineering needs and previous work to create new sub-systems or modify existing ones	Kemani	Completed		10/3/2024

		For each sub-system, determine lower-level functions	Jacob	Completed		10/3/2024
		Organize a graphic detailing the hierarchal structure of the sub-systems and functions	Aaron	Completed		10/3/2024
		List each function and determine its physical importance to each sub-system	Cade	Completed		10/3/2024
		Based on function/system relationships, determine the most important system and function(s)	Cade	Completed		10/3/2024
		Write the document	Aaron	Completed		10/4/2024
		Edit the document	Kemani	Completed		10/4/2024
		Submit the document	Aliya	Completed		10/4/2024
VDR2			-	Not started	11/12/2024	

	Targets and Metrics		-	Completed	10/18/2024	10/18/2024
		List all determined functions	Jacob	Completed		10/15/2024
		Assign a measurable metric/target to each function	Kemani	Completed		10/18/2024
		Determine specific values and units when possible	Cade	Completed		10/18/2024
		Research and identify testing methodology	Aliya	Completed		10/18/2024
		Research and identify measuring equipment and tools	Kemani	Completed		10/18/2024
		Write the document	Cade	Completed		10/18/2024
		Edit the document	Aaron	Complete		10/18/2024
		Submit the document	Aaron	Completed		10/18/2024
	Concept Generation		-	Not started	10/25/2024	

		Divide concept generation amongst team members	Aaron	Not started		
		Conduct research on any sponsor-specified technology and products from adjacent markets	Kemani	Not started		
		Brainstorm concepts using various methods of formation	Aliya	Not started		
		Create preliminary sketches and diagrams to visualize different concepts	Aaron	Not started		
		Organize concepts by varying fidelity	Cade	Not started		
		Discuss and improve high and medium fidelity concepts	Jacob	Not started		
		Write the document	Kemani	Not started		
		Edit the document	Aliya	Not started		

		Submit the document	Cade	Not started		
	Concept Selection		-	Not started	11/1/2024	
		From engineering needs, create a list of overarching customer requirements	Jacob	Not started		
		Perform binary piecewise comparison on the list to determine the heaviest weighted requirements	Aaron	Not started		
		Create a House of Quality ranking targets/metrics by their ability to meet customer requirements	Aaron	Not started		
		Eliminate unnecessary targets/metrics	Cade	Not started		
		Perform research on competing products or previous iterations for benchmarking	Aliya	Not started		

		Create a Pugh containing concepts to each other and ~~possible benchmark~~benchmark	Aaron	Not started		
		Eliminate poor-performing concepts	Kemani	Not started		
		Using an analytical hierarchy process, compare each final target/metric against each other to determine its weighting	Aaron	Not started		
		Check AHP comparison of final target/metrics for consistency	Cade	Not started		
		Using an analytical hierarchy process, compare each final concept against each other for every target/metric	Aaron	Not started		

		Check AHP comparisons of final concepts for consistency	Aliya	Not started		
		From the analytical hierarchy done, create a final rating matrix and calculate alternative values for each concept	Kemani	Not started		
		Write the document	Jacob	Not started		
		Edit the document	Aliya	Not started		
		Submit the document	Kemani	Not started		
	Risk Assessment		-	Not started	11/8/2024	
		Read and discuss safety expectations	Cade	Not started		
		Complete Worksheet 1 and Worksheet 2	Jacob	Not started		
		Receive confirmation and from advisor	Aliya	Not started		
		Submit Worksheet 1 and Worksheet 2	Kemani	Not started		

VDR 3			-	Not started	12/3/2024	
	Bill of Materials		-	Not started	11/15/2024	
		Begin engineering drawings/plans for selected concept	Jacob	Not started		
		Determine desired building material(s)	Cade	Not started		
		Determine required components	Aaron	Not started		
		Research pricing and availability of both material and components	Aliya	Not started		
		Select the best fit material and components based on pricing and availability	Cade	Not started		
		Itemize all material stock and components	Aaron	Not started		
		Write the document	Kemani	Not started		

		Edit the document	Jacob	Not started		
		Submit the document	Aliya	Not started		
	Spring Plan		-	Not started	11/22/2024	
		Create blank timeline	Aliya	Not started		
		Identify and date deliverables	Cade	Not started		
		Speak with sponsor/advisor about additional milestones	Jacob	Not started		
		Begin to identify basic tasks that can help complete deliverables and milestones	Kemani	Not started		
		Write the document	Aaron	Not started		
		Edit the document	Cade	Not started		
		Submit the document	Jacob	Not started		

	Rapid Prototype		-	Not started	12/3/2024	
		Discuss methods for developing a rapid prototype	Aliya	Not started		
		Simplify detailed design for a rapid prototype	Jacob	Not started		
		Select and purchase necessary materials	Cade	Not started		
		Assemble Prototype	Aaron	Not started		
		Create digital rendering of prototype	Kemani	Not started		
	End of Semester Document		-	Not started	12/3/2024	
		Discuss status quo of project	Aliya	Not started		
		Discuss future work from spring plan	Jacob	Not started		
		Discuss and identify problems	Aliya	Not started		
		Write the document	Kemani	Not started		

		Edit the document	Aaron	Not started		
		Submit the document	Cade	Not started		
Poster (not included in VDR3)			-	Not started	12/6/2024	
		Assemble Poster Contents	Aliya	Not started		
		Edit Poster Contents	Cade	Not started		
		Submit Poster Contents	Kemani	Not started		
Embodied Design Rough Plan (Spring 2025)			-	Not started		
	Prototyping		-	Not started		
		Check received shipments for all components/materials	Jacob	Not started		
		Reorder or find alternative	Cade	Not started		

		components/materials if necessary				
		Machine necessary custom parts	Kemani	Not started		
		Assemble the prototype and integrate all components.	Aaron	Not started		
		Perform preliminary tests to verify basic functionality.	Aliya	Not started		
	Testing		-	Not started		
		Create a test plan outlining testing procedures and criteria.	Aliya	Not started		
		Conduct tests according to the plan, including performance, reliability, and safety tests	Kemani	Not started		
		Collect and analyze test data to evaluate the prototype’s performance	Aaron	Not started		
		Identify and document any issues or areas for improvement	Cade	Not started		

		Make necessary adjustments and perform additional tests as required	Jacob	Not started		
	Building		-	Not started		
		Finalize the design based on testing feedback	Aliya	Not started		
		Develop a detailed plan for the final build, including timeline and resource allocation	Jacob	Not started		
		Fabricate or acquire all necessary components for the final build	Cade	Not started		
		Assemble the final product, ensuring all parts are correctly integrated and functional	Aaron	Not started		
		Conduct testing of the completed device to ensure it meets all project requirements	Kemani	Not started		

Appendix C: Target Summary

Table 7: *Target Summary*

Function	Metric	Target
Acquire Path Parameters	Time Delay Between Interface and Motion Systems (sec)	0.5-1 sec
Export Path Parameters		
Interpret Parameters to Nominal Control Data		
Sense Position	Translation Measurement	Error ± 0.05 in
Compare Output to Nominal Control Data	Desired Control Time Constant (sec)	0.5 sec
Calculate Error	Desired Steady State Output Error (in)	± 0.1 in
Calculate Actuation Data	Frequency of New Data Generation (Hz)	100 kHz
Actuate Steering	Maximum Actuation Torque (~~lb~~lb.*ft)	-
	Desired Steering Coefficient of Kinetic Friction	0.215
Display Output	Display Output area (in^2)	8.5 in x11 in

	Desired Completion Time (sec)	60 sec
Withstand Static Load	Total Mass (~~lb~~lb.)	22 ~~lb~~lb.
Withstand Inertial Forces	Ratio of Base Mass to Linkage Mass	2
Withstand Cyclical Stresses	Life Cycle (years)	5 years
House Mechanical Components	Available Volume (in^3)	32 in x 28 in x 55 in
House Electrical Components		
Organize Connections		
Facilitate Transportation	Total Mass (~~lb~~lb.)	22 ~~lb~~lb.
Receive Power	Input Voltage (V)	120V AC

Appendix D

Morphological Chart

Function	Display Output	Driving Methods	Controls	Wheel Cylinder Interaction		Carriage Linkage Interaction
Idea 1	Racecar Game	Internal gearset drive	Rotary potentiometer to	Oiled Brass Wheel	Aluminum Cylinder	Inverted crank

			sense position			linkage pin slider
Idea 2	Long Exposure Drawing Guessing Game	Internal endpoint friction contact drive	Linear/string potentiometer using absolute or incremental encoder	Nylon Wheel	PVC Cylinder	Inverted crank linkage slot slider
Idea 3	Carbon Tracing Paper Drawing Guessing Game	Internal total lengthwise friction contact drive	Accelerometer to sense position	Polyurethane Wheel	Steel Cylinder	Dual belt Linkage system
Idea 4	Egg Balance Run	Internal self-intersecting belt drive	Inertial Measurement Unit (IMU) to sense position	Polypropylene Wheel	Carbon Fiber Cylinder	Quick-Swap Linkage Modules
Idea 5	Projectile Trajectory Game	External gearset drive	Joystick controller input	Natural Rubber Wheel	Powder Coated Aluminum Cylinder	Adjustable Carriage Angle
Idea 6	Waveform Interaction Study	External endpoint friction contact drive	Touch screen input	Toy Car Wheel	Aluminum Cylinder with Skateboard Grip Tape	Pivoting Linkage Arm
Idea 7	Roller Coaster	External central point friction	XBOX/Play Station	Wooden Wheel	Wooden cylinder	High-Precision Gear Linkage

	Potential Energy Study	contact drive	controller input			
Idea 8	Gridded Paper Curve Plotting	External total lengthwise friction contact drive	Servo potentiometer	Cardboard Wheel	Matted Cylinder	
Idea 9	Open a Box	Distance tensioned belt drive	Voice recognition input	Velcro wheel	Cardboard Cylinder	Shock-Absorbing Linkage
Idea 10	Open and Close a Door	Externally tensioned belt drive	Lead and screw linear actuator	Foam Wheel		Telescopic Linkage
Idea 11	Toss a Student a Ball	Motor driven pin coupled direct drive	Rack and pinion linear actuator			Magnetic Carriage Connection
Idea 12	Throw a Piece of Paper into a Trashcan	Motor driven clamp coupled direct drive	DC/AC Motor(s) rotary actuator			Tension-Controlled Linkage
Idea 13	Sweep the Floor	Motor driven weld coupled direct drive	Stepper motor(s) rotary actuator			Quick-Swap Linkage Modules
Idea 14	Laser Display	Hand cranked pin coupled direct drive	Servo Motor(s) rotary actuator			

Idea 15	Flip a Table	Hand cranked clamp coupled direct drive	Draw pad interaction interface			
Idea 16	Kick a Soccer Ball	Hand cranked weld coupled direct drive	Rotary Encoder			
Idea 17	Change the AC Temperature		Mobile App interface			
Idea 18	Open and close a laptop		Simple button input			
Idea 19	Paint a Portrait		Optical sensor(s)			
Idea 20	Tik tac toe		Proximity sensor(s)			
Idea 21			Keyboard and Mouse Data Input			
Idea 22			PID Controller			

Concept Idea	Concept Description
Morphological Idea	
1	The concept features a Racecar Game with Internal Gearset Drive, controlled by a Rotary Potentiometer. It has Oiled Brass Wheel interaction and uses an Inverted Crank Linkage Pin Slider for carriage linkage.
2	This concept includes a Long Exposure Drawing Guessing Game with Internal Endpoint Friction Contact Drive. It uses a Linear/String Potentiometer for control, Nylon Wheel interaction, and an Adjustable Carriage Angle.
3	A Projectile Trajectory Game driven by an External Gearset Drive, controlled by a Joystick Controller Input. The concept features Natural Rubber Wheel and Inverted Crank Linkage Slot Slider for interaction
4	The concept involves an Egg Balance Run using Internal Self-Intersecting Belt Drive, with IMU to sense position. The wheel-cylinder interaction is through Polypropylene Wheel, and the linkage uses Quick-Swap Linkage Modules.

5	This concept includes Waveform Interaction Study with External Endpoint Friction Contact Drive, controlled by Touch Screen Input. It features Toy Car Wheel and Pivoting Linkage Arm for carriage linkage.
6	A Carbon Tracing Paper Drawing Guessing Game that uses a Motor Driven Pin Coupled Direct Drive. It is controlled by Voice Recognition Input and uses Wooden Wheel for wheel interaction, along with Shock-Absorbing Linkage.
7	This concept uses Gridded Paper Curve Plotting with Distance Tensioned Belt Drive, and it is controlled by a Lead and Screw Linear Actuator. It features a Foam Wheel for wheel interaction, with a Telescopic Linkage.
8	Featuring Laser Display with a Hand Cranked Weld Coupled Direct Drive, controlled by a Rack and Pinion Linear Actuator. The wheel interaction involves a Velcro Wheel, and it uses Magnetic Carriage Connection.
9	The concept is Flip a Table, driven by Hand Cranked Clamp Coupled Direct Drive, and controlled using Optical Sensor(s). It features Cardboard Wheel interaction and a Tension-Controlled Linkage.

10	Involves Kick a Soccer Ball using Motor Driven Pin Coupled Direct Drive, with control through Proximity Sensor(s). The concept uses Wooden Wheel and Magnetic Carriage Connection for linkage.
11	The concept is about Change the AC Temperature using a Motor Driven Pin Coupled Direct Drive, controlled by a Mobile App Interface. It features Natural Rubber Wheel interaction and Quick-Swap Linkage Modules.
12	Open and close a laptop concept using Externally Tensioned Belt Drive, controlled by Simple Button Input. It features Foam Wheel interaction and uses a Telescopic Linkage.
13	Paint a Portrait concept using Hand Cranked Clamp Coupled Direct Drive, controlled by Optical Sensor(s). The concept features Cardboard Wheel interaction with Magnetic Carriage Connection.
14	The concept is Tic Tac Toe, driven by Hand Cranked Weld Coupled Direct Drive, and controlled by Proximity Sensor(s). It has a Wooden Wheel and uses Shock-Absorbing Linkage.
15	Racecar Game driven by External Gearset Drive and controlled using a Joystick Controller Input. It features a Nylon Wheel and Inverted Crank Linkage Slot Slider.

16	The concept is a Long Exposure Drawing Guessing Game with Internal Gearset Drive, controlled by a Rotary Potentiometer. It features Oiled Brass Wheel interaction and Adjustable Carriage Angle.
17	Egg Balance Run using Internal Self-Intersecting Belt Drive, controlled with an IMU to sense position. The wheel interaction is via Polypropylene Wheel and Pivoting Linkage Arm.
18	The concept is Carbon Tracing Paper Drawing Guessing Game with Motor Driven Pin Coupled Direct Drive, controlled by a Lead and Screw Linear Actuator. It features Velcro Wheel and Tension-Controlled Linkage.
19	Flip a Table driven by Distance Tensioned Belt Drive and controlled using Voice Recognition Input. It features a Foam Wheel and Telescopic Linkage.
20	Waveform Interaction Study using External Endpoint Friction Contact Drive, controlled by Touch Screen Input. The concept has a Toy Car Wheel and Quick-Swap Linkage Modules.
21	Laser Display with Hand Cranked Weld Coupled Direct Drive, controlled by a Rack and Pinion Linear Actuator. It features Velcro Wheel interaction and Magnetic Carriage Connection.

22	The concept is Kick a Soccer Ball with Hand Cranked Clamp Coupled Direct Drive, controlled by Proximity Sensor(s). It features Cardboard Wheel interaction and Tension-Controlled Linkage.
23	Change the AC Temperature concept with Externally Tensioned Belt Drive, controlled by Mobile App Interface. It uses Wooden Wheel and Shock-Absorbing Linkage.
24	Projectile Trajectory Game with External Gearset Drive, controlled by a Joystick Controller Input. The wheel interaction is with Natural Rubber Wheel, and Adjustable Carriage Angle is used for linkage.
25	The concept is Racecar Game with Internal Gearset Drive, controlled using a Rotary Potentiometer. It features Nylon Wheel interaction with Inverted Crank Linkage Pin Slider.
26	Gridded Paper Curve Plotting concept with Motor Driven Pin Coupled Direct Drive, controlled by Voice Recognition Input. It uses Cardboard Wheel and Magnetic Carriage Connection.
27	Flip a Table driven by Hand Cranked Clamp Coupled Direct Drive, with control through a Lead and Screw Linear Actuator. It features Foam Wheel and Telescopic Linkage.

28	Egg Balance Run driven by Internal Self-Intersecting Belt Drive, controlled by an IMU to sense position. It features Toy Car Wheel interaction and Quick-Swap Linkage Modules.
29	The concept is Long Exposure Drawing Guessing Game with Internal Gearset Drive, controlled by Linear/String Potentiometer using Encoder. It features an Oiled Brass Wheel and an Adjustable Carriage Angle.
30	Paint a Portrait driven by Externally Tensioned Belt Drive, controlled using Optical Sensor(s). It uses a Wooden Wheel and Shock-Absorbing Linkage.
31	Laser Display using Hand Cranked Clamp Coupled Direct Drive, controlled by Proximity Sensor(s). It features Velcro Wheel and Magnetic Carriage Connection.
32	Racecar Game driven by External Gearset Drive, with Joystick Controller Input for control. The wheel interaction is through Natural Rubber Wheel and uses Inverted Crank Linkage Pin Slider for linkage.
33	Waveform Interaction Study using External Endpoint Friction Contact Drive, controlled by Touch Screen Input. It features Nylon Wheel and Pivoting Linkage Arm.

34	Long Exposure Drawing Guessing Game driven by Internal Endpoint Friction Contact Drive, controlled by a Rotary Potentiometer. It uses an Oiled Brass Wheel and an Inverted Crank Linkage Slot Slider for linkage.
35	Gridded Paper Curve Plotting driven by Motor Driven Pin Coupled Direct Drive, with control through Voice Recognition Input. The wheel interaction is with Wooden Wheel and uses Shock-Absorbing Linkage.
36	Kick a Soccer Ball using Motor Driven Pin Coupled Direct Drive, controlled by a Lead and Screw Linear Actuator. It features Foam Wheel and Tension-Controlled Linkage.
37	Egg Balance Run driven by Internal Self-Intersecting Belt Drive, controlled by an IMU to sense position. It has a Polypropylene Wheel and uses Quick-Swap Linkage Modules.
38	Carbon Tracing Paper Drawing Guessing Game driven by Hand Cranked Weld Coupled Direct Drive, controlled by a Rack and Pinion Linear Actuator. It uses Velcro Wheel and Telescopic Linkage.
39	Change the AC Temperature driven by Distance Tensioned Belt Drive, with control via Mobile App Interface. It features Cardboard Wheel and Magnetic Carriage Connection.

40	Paint a Portrait using Externally Tensioned Belt Drive, controlled by Optical Sensor(s). It has a Toy Car Wheel and Adjustable Carriage Angle.
41	Simulate the optimal path on a racecar course, sensing distance by string potentiometers. The device is driven by a belt drive with and external tensioner and the CVT frictional interaction is between a polyurethane wheel on a steel cylinder and the linkage-carriage interaction by an inverted crank-slider pin connection
42	Using a laser and photosensitive paper to play ~~a long exposure~~a prolonged exposure drawing guessing game, using a simple button input. The device is driven by an internal endpoint friction contact drive and the CVT frictional interaction is between a polyurethane wheel on a PVC cylinder and the linkage-carriage interaction by a pivoting link connection.
43	Doing a roller coaster potential energy study using rotary potentiometers to sense position. The device is driven by an external total lengthwise friction drive and the CVT frictional interaction is between a nylon wheel on a PVC cylinder and the linkage-carriage interaction by a high position gear linkage connection.

44	Drawing a plot on gridded paper using a haptic drawing pad interaction interface. The device is driven by a concentric-axes,clamp-coupled direct drive and the CVT frictional interaction is between a polypropylene wheel on a powder coated aluminum cylinder and the linkage-carriage interaction by a magnetic carriage connection
45	This device would provide a game to teach projectile motion. Movement is driven by a pivoting linkage arm. The arm is driven by nylon wheels steered on an aluminum cylinder driven with an external endpoint friction contact drive~~.~~. Steering can be done by ~~servos~~servos, and sensing can be done by rotary encoders. This could be controlled by a PID controller. A keyboard can be used to input parameters.
46	This device would provide a game to teach about wave properties and their effect on interference. Movement is driven by a pivoting linkage arm. The arm is driven by nylon wheels steered on an aluminum cylinder driven with an external endpoint friction contact drive~~.~~. Steering can be done by ~~servos~~servos, and sensing can be done by rotary encoders. This could be controlled by a PID controller. A keyboard can be used to input parameters.

SCAMPER	
47	Combine (Concept 2): Add a sensor-controlled lighting system to the Long Exposure Drawing Game to simulate changes in ambient conditions for more immersive game dynamics.
48	Adapt (Concept 2): Modify the Long Exposure Drawing Game by adding a color-changing LED for creative tracing feedback.
49	Modify (Concept 4): Increase wheel friction on the Egg Balance Run for greater stability, adjusting the difficulty of maintaining balance.
50	Put to Another Use (Concept 1): Adapt the Racecar Game to include trajectory prediction by adjusting angles, demonstrating physics concepts.
51	Eliminate (Concept 5): Remove one wheel in the Waveform Interaction Study to show the effect of imbalanced forces on movement.
52	Reverse (Concept 4): Design the Egg Balance Run to flip the cylinder’s rotation direction randomly, adding a reaction-time component to the learning experience.
53	Substitute (Concept 3): Use a haptic feedback joystick instead of a traditional one for the Projectile Trajectory Game, enhancing control sensitivity.

54	Combine (Concepts 10 and 9): Merge Kick a Soccer Ball and Flip a Table into a single concept, using multiple pivoting linkages for compound movements.
55	Adapt (Concept 13): Include a pressure sensor in the Paint a Portrait concept to simulate brush strokes, offering different resistance for artistic control.
56	Modify (Concept 6): Add a feedback delay to the Carbon Tracing Game, creating a lag effect that challenges players' timing skills.
57	Put to Another Use (Concept 7): Adapt the Gridded Paper Plotting concept into an educational tool for plotting real-world data in high school physics.
58	Eliminate (Concept 12): Simplify the Open and Close a ~~Laptop~~laptop mechanism by using a single continuous drive system instead of multiple belts.
59	Reverse (Concept 11): Reverse the gear motion in Change the AC Temperature to visualize cooling and heating cycles alternately.
60	Substitute (Concept 43): Replace the standard potentiometer in the Roller Coaster Energy Study with a tension-sensing potentiometer to enhance simulation.

61	Combine (Concept 15): Integrate voice commands in the Racecar Game to adjust speed, allowing hands-free control for quick adjustments.
62	Adapt (Concept 17): Adapt the Egg Balance Run to include a second cylinder, demonstrating two-axis balance control for increased difficulty.
63	Modify (Concept 20): Use a rubber-coated cylinder in the Waveform Study to adjust grip dynamics, influencing frequency results in the wave interaction.
64	Put to Another Use (Concept 8): Repurpose the Laser Display as a blueprint sketching tool, where students input coordinates to draw technical diagrams.
65	Eliminate (Concept 14): Remove proximity sensors in Tic Tac Toe and use a visual tracking camera instead for improved real-time response.
66	Reverse (Concept 3): Reverse the controller input in the Projectile Trajectory Game so angle adjustments are inverted, adding complexity to trajectory prediction.

67	Substitute (Concept 12): Replace the Foam Wheel in Open and Close a laptop with a rubberized wheel for smoother, quieter operation.
68	Combine (Concept 7): Add a second cylinder in the Gridded Paper Curve Plotting for ~~dual-axis~~dual axis plotting, expanding educational possibilities for geometry.
69	Substitute (Concept 16): Use a proximity sensor instead of a rotary potentiometer in the Long Exposure Drawing Game to adjust speed based on the user's hand position, improving user interaction time.
70	Adapt (Concept 5): Include a second adjustable pivot in the Waveform Interaction Study to demonstrate phase shift concepts in wave interference.
71	Replace (Concept 35): the Rotary Potentiometer with a Voice Recognition Input to provide hands-free control and make the user interaction more intuitive.
72	Modify (Concept 1): Add a real-time timer display to the Racecar Game to show lap times, meeting the metric of tracking time for user engagement.

73	Eliminate (Concept 10): Remove the magnetic carriage in Kick a Soccer Ball to use a simple pin linkage, reducing complexity while retaining basic movement functionality.
74	Reverse (Concept 6): Reverse the drive direction in the Carbon Tracing Game periodically, teaching students about friction and inertia as they respond to changes in direction.
75	Substitute (Concept 8): Use a motor-driven clamp instead of a hand crank for the Laser Display, increasing precision for controlled movements.
76	Substitute (Concept 21): Use a laser pointer with adjustable focus instead of a stationary laser in the Laser Display, allowing users to see how different focal lengths affect clarity.
77	Adapt (Concept 15): Include a vibration motor in the Racecar Game to simulate engine feedback, enhancing the sensory experience for users.
78	Eliminate (Concept 12): Remove the telescopic linkage in Open and Close a ~~Laptop~~laptop, simplifying it to a basic pivot system, reducing overall weight and supporting the portability metric.

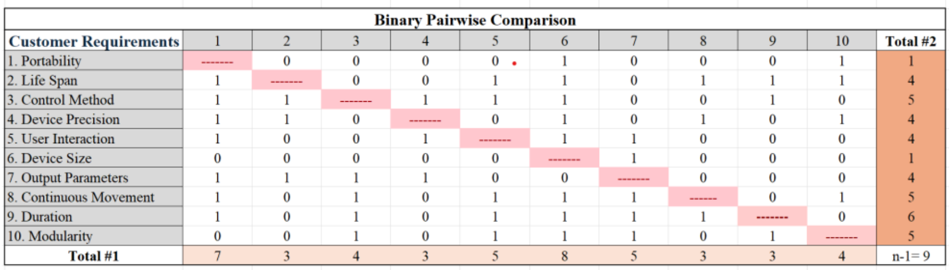
79	Put to Another Use (Concept 37): Use the Egg Balance Run mechanism for a different challenge, such as balancing a weighted ball instead of an egg, to increase difficulty and variability.
80	Modify (Concept 15): Add a spring-loaded mechanism to the Racecar Game's linkage that adjusts wheel contact pressure on the rotating cylinder based on speed.
81	Combine (Concept 23): Integrate a thermal sensor in the Change the AC Temperature game to display real-time temperature feedback on the interface, enhancing user interactivity.
82	Adapt (Concept 11): Use a programmable app interface to control a wider range of temperatures in Change the AC Temperature, demonstrating environmental effects and supporting usability metrics.
83	Adapt (Concept 41): Introduce a variable tension adjustment on the rotating cylinder's belt drive, allowing students to manually increase or decrease tension to see how it impacts speed and torque transfer in the CVT
84	Adapt (Concept 33): Adapt Waveform Interaction Study with a phase-tracking LED that shows frequency changes in real-time, supporting targets related to interaction speed.

85	Eliminate (Concept 44): Remove the magnetic carriage in Drawing Plot on Gridded Paper, simplifying linkage and improving transportability.
86	Eliminate (Concept 24): Remove joystick control from Projectile Trajectory Game and replace with buttons for a more accessible control scheme.
87	Substitute (Concept 36): Replace the foam wheel in Kick a Soccer Ball with a more durable rubber wheel for improved accuracy and wear resistance.
88	Combine (Concept 46): Combine the Waveform Interaction Study with a drawing feature, allowing students to visualize combined waveforms on a graph.
89	Combine (Concept 7): Integrate an automatic feedback system that adjusts the wheel position on the rotating cylinder based on load, simulating real-world CVT response to varying forces.
90	Substitute (Concept 17): Replace the standard belt drive in the Egg Balance Run with a flexible, elastic drive belt that stretches under load.
Biomimicry	

91	Human Arm/Elbow: Flexing and rotating the arm creates controlled reciprocating movement.
92	Crab Legs: Jointed legs oscillate in a multi-directional, reciprocating fashion
93	Human Jaw: Hinged Motion for chewing combines rotation and sliding movements
94	Bat Echolocation: Bats use sound waves to detect their position relative to objects, inspiring ultrasonic sensors
95	Spider Web Vibration: Spiders sense web vibrations for positioning, inspiring vibration-based position sensors
96	Ant Navigation: Ants use polarized light for orientation, inspiring polarized light sensors for precise positioning.
97	Whiskers in Mammals: Animals use whiskers to detect nearby objects, inspiring tactile proximity sensors.
98	Insect Compound Eyes: Insects detect motion changes for positioning, inspiring optical sensors.
99	Gecko Foot Pads: Geckos sense surface grip for positioning, inspiring tactile feedback sensors.
100	Human Proprioception: Muscle and joint sensors sense body position, inspiring ~~strain~~strain, or tension sensors.

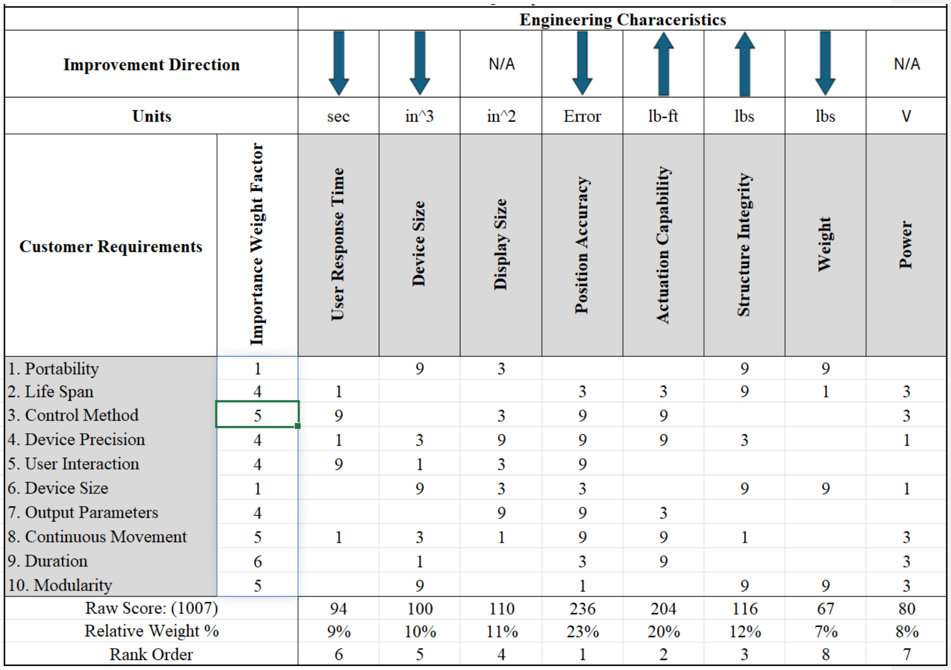
Appendix E

Table 8: *Binary Pairwise Comparison*



Binary Pairwise Comparison											
Customer Requirements	1	2	3	4	5	6	7	8	9	10	**Total #2**
1. Portability	-------	0	0	0	0	1	0	0	0	1	1
2. Life Span	1	-------	0	0	1	1	0	1	1	1	4
3. Control Method	1	1	-------	1	1	1	0	0	1	0	5
4. Device Precision	1	1	0	-------	0	1	0	1	0	1	4
5. User Interaction	1	0	0	1	-------	1	1	0	0	0	4
6. Device Size	0	0	0	0	0	-------	1	0	0	0	1
7. Output Parameters	1	1	1	1	0	0	-------	0	0	0	4
8. Continuous Movement	1	0	1	0	1	1	1	------	0	1	5
9. Duration	1	0	1	0	1	1	1	1	-------	0	6
10. Modularity	0	0	1	0	1	1	1	0	1	-------	5
Total #1	7	3	4	3	5	8	5	3	3	4	n-1= 9

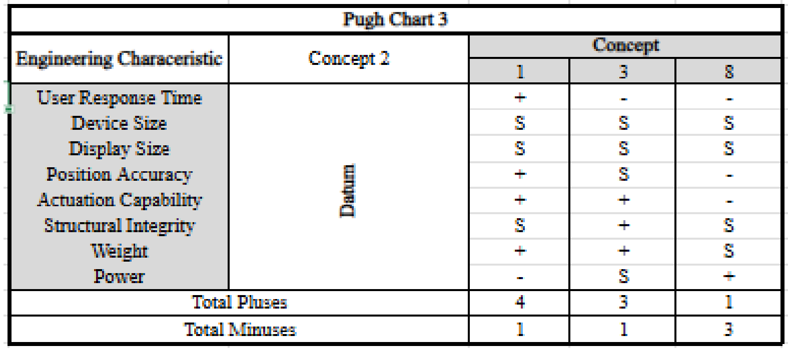
Table 9: *House of Quality*



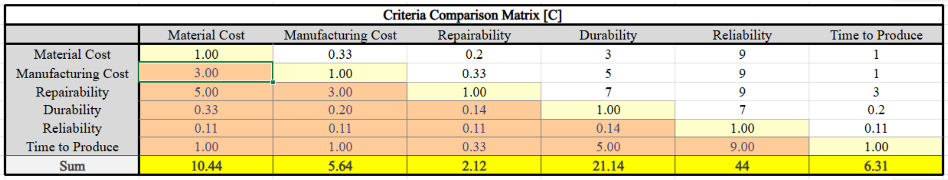
		Engineering Characteristics							
Improvement Direction		↓	↓	N/A	↓	↑	↑	↓	N/A
Units		sec	in^3	in^2	Error	lb-ft	lbs	lbs	V
Customer Requirements	**Importance Weight Factor**	**User Response Time**	**Device Size**	**Display Size**	**Position Accuracy**	**Actuation Capability**	**Structure Integrity**	**Weight**	**Power**
1. Portability	1		9	3			9	9	
2. Life Span	4	1			3	3	9	1	3
3. Control Method	5	9		3	9	9			3
4. Device Precision	4	1	3	9	9	9	3		1
5. User Interaction	4	9	1	3	9				
6. Device Size	1		9	3	3		9	9	1
7. Output Parameters	4			9	9	3			
8. Continuous Movement	5	1	3	1	9	9	1		3
9. Duration	6		1		3	9			3
10. Modularity	5		9		1		9	9	3
Raw Score: (1007)		94	100	110	236	204	116	67	80
Relative Weight %		9%	10%	11%	23%	20%	12%	7%	8%
Rank Order		6	5	4	1	2	3	8	7

Pugh Chart 1									
Engineering Characeristic	2024 REU Large-scale CVT Device	**Concept**							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
User Response Time	**Datum**	+	+	+	-	+	+	+	+
Device Size		+	+	+	+	+	+	+	+
Display Size		-	+	-	-	-	+	-	+
Position Accuracy		+	+	+	+	+	-	+	-
Actuation Capability		+	-	+	S	S	-	+	-
Structural Integrity		S	+	+	S	-	-	+	S
Weight		-	-	-	S	-	-	-	S
Power		-	-	S	S	-	-	S	S
Total Pluses		4	5	5	2	3	3	5	3
Total Minuses		3	3	2	2	4	5	2	2

Pugh Chart 2						
Engineering Characeristic	Concept 4	**Concept**				
		1	**2**	**3**	**7**	**8**
User Response Time	**Datum**	+	+	+	-	+
Device Size		S	S	S	S	S
Display Size		+	S	-	S	-
Position Accuracy		S	-	+	-	-
Actuation Capability		S	-	+	-	-
Structural Integrity		+	+	S	+	+
Weight		-	+	-	+	+
Power		+	-	S	-	+
Total Pluses		4	3	3	2	4
Total Minuses		1	3	2	4	3



Pugh Chart 3				
Engineering Characeristic	Concept 2	**Concept**		
		1	3	8
User Response Time	**Datum**	+	-	-
Device Size		S	S	S
Display Size		S	S	S
Position Accuracy		+	S	-
Actuation Capability		+	+	-
Structural Integrity		S	+	S
Weight		+	+	S
Power		-	S	+
Total Pluses		4	3	1
Total Minuses		1	1	3



Criteria Comparison Matrix [C]						
	Material Cost	Manufacturing Cost	Repairability	Durability	Reliability	Time to Produce
Material Cost	1.00	0.33	0.2	3	9	1
Manufacturing Cost	3.00	1.00	0.33	5	9	1
Repairability	5.00	3.00	1.00	7	9	3
Durability	0.33	0.20	0.14	1.00	7	0.2
Reliability	0.11	0.11	0.11	0.14	1.00	0.11
Time to Produce	1.00	1.00	0.33	5.00	9.00	1.00
Sum	10.44	5.64	2.12	21.14	44	6.31

Normalized Criteria Comparison Matrix [NormC]							
	Material Cost	Manufacturing Cost	Repairability	Durability	Reliability	Time to Produce	{W}
Material Cost	0.096	0.059	0.094	0.142	0.205	0.158	0.126
Manufacturing Cost	0.287	0.177	0.156	0.237	0.205	0.158	0.203
Repairability	0.479	0.532	0.472	0.331	0.205	0.475	0.416
Durability	0.032	0.035	0.067	0.047	0.159	0.032	0.062
Reliability	0.011	0.02	0.052	0.007	0.023	0.017	0.022
Time to Produce	0.096	0.177	0.157	0.237	0.205	0.158	0.172
Sum	**1**	**1**	**1**	**1**	**1**	**1**	**1**

Consistency Check		
{Ws}=[C]{W} Weighted Sum Vectors	{W} Criteria Weights	Cons={Ws}./{W} Consistency Vectors
0.832	0.126	6.603
1.398	0.203	6.887
2.803	0.416	6.738
0.392	0.062	6.323
0.133	0.022	6.045
1.148	0.172	6.674
	Average Cons (λ)	**6.55**

Final Rating Matrix			
	Concept 2	Concept 1	Concept 3
Material Cost	0.6	0.2	0.2
Manufacturing Cost	0.6	0.2	0.2
Repairability	0.429	0.143	0.429
Durability	0.429	0.429	0.143
Reliability	0.6	0.2	0.2
Time to Produce	0.429	0.143	0.429

Alternative Value Matrix	
	Alt. Value
Concept 2	0.489
Concept 1	0.181
Concept 3	0.331
Sum	**1**

References

OpenAI. (2024). *ChatGPT* (May 2024 Version) [Large language model]. https://chat.openai.com/chat

Moebs, W., Ling, S. J., & Sanny, J. (2016). 6.2 Friction. In *University Physics Volume I*. OpenStax. https://openstax.org/books/university-physics-volume-1/pages/6-2-friction

Ordonez, C. (2024). Mobile Robotics: Sensors. Tallahassee; FAMU-FSU College of Engineering.

SE1 compact string pot • incremental encoder - te connectivity. (n.d.).

https://www.te.com/commerce/DocumentDelivery/DDEController?Action=showdoc&DocId=Data+SheetSE1ApdfEnglishENG_DS_SE1_A.pdfCAT-CAPS0071