ECE 4950: Closed-Loop Motor Control, Life-Cycle Analysis, and Risk Assessment
AATOF

Nicholas Dreitzler, Eric Prioleau, Mark Pham, Hunter Reaux, and Ethan Severance
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Executive Summary:

The purpose of this project was to develop an intermediary robotic device to serve as a proof of concept for the proposed solution. Towards this end, the students worked to develop a thorough list of customer requirements, the specific engineering requirements derived from these, and the tests of the system that enable the proposed system to be verified as satisfactory. For this system, the electromagnet will not be implemented, but rather the customer requests a simple “clock arm” which will be used to make sure that the student’s algorithm for identifying the centroid of the colored sticker specified via the user interface will function correctly. This removes the need to finalize the electromagnet and game board design while still allowing the motor control and the student’s identification algorithm to be tested. The functionality of this system via Hardware-in-the-Loop procedures was explored, and the systems implemented in hardware, software, and simulation programs are described herein, as well as the tests performed on and with these systems. A safety analysis and Design Failure Mode and Effect Analysis was also performed to ensure that the design is safe, and to check for weak points in the system and the effects of a component or system failure. To emphasize the environmental concerns that must be considered in all design projects, a life cycle analysis of the outer cladding for the packaging container for the shipment of the completed robots was performed in order to determine the appropriate material for covering the steel frame of the shipping box between the options provided to the students. This enabled the students to observe the estimated life cycle impact of the material on the environment, as well as the cost to the company when purchasing the materials to make the containers. As a final concern, the students were required to determine appropriate Continuing Education opportunities for the organization defined in the previous project, so that the qualifications of the manager and the employees alike may continue to be enhanced during their tenure on the project. The cost to the firm is quantified, and the expected benefit of such education is described.

Engineering Requirements for the Motor Control subsystem

Table 1: Mapping Customer Requirements to Engineering Requirements

Engineering Requirements for Motor Control System		
Customer Requirements	Engineering Requirements	Test Methodology
Autonomous System	Able to complete tasks with no human interaction	Run task to completion without interacting with device
Inexpensive	< \$100	Total cost to build product is less than \$100
	< 1 hour setup time	Time setup of device
Robust	The system should still operate correctly after multiple operations	The system should be able to perform the same operation several times in a row.
Fast	Rotation speed at least 4 rads/s	Rotate device and measure speed in rads/s
Efficient	The motor should rotate to the closest chocen sticker.	Observe system movement and judge if they ar optimal
	Uses less than 100 Wh	Measure power draw of system
Safe	No hazards exist that are frequent, probable, occasional or remote with a severity rating of critical or catastrophic	Keep detailed records of any potential hazard and how severe these hazards are.
User-friendly	Simple input format for the user	A user with no prior knowledge of the system is able to operate it.
Efficient Closed-loop motor control	Maximum overshoot of reference point tracking < 5°	Start motor at 0° and then set reference point at 180°, measure maximum overshoot
	Rise time < 0.5 seconds	Start motor at 0° and then set reference point at 180°, measure rise time
	Settling time < 1 seconds	Start motor at 0° and then set reference point at 180°, absolute error stays below 0.5% after 1 second
Smooth motion	Motor makes no abnormal jumps	Verify that no jumps occur during operation

Overview of Hardware-in-the-Loop:

Hardware-in-the-Loop (HIL) simulates hardware in the control loop so that prototypes are not needed to test the controller design. HIL simulations can be used to test the performance of the controller, in real time, with realistic stimuli. A full simulation of the control system would run on a working prototype of the system. This requires for there to be a working prototype that exists before testing of the control system can begin. Thus, there is a delay in the design of the controller as it must wait for the prototype to be ready before testing can begin. During this testing, if the controller fails it could potentially damage the prototype; which would cost both time and money to replace. HIL can be used to alleviate both of these problems. Since HIL simulations do not require a working prototype, performing HIL simulations is a key part of the design process as it allows for rigorous testing of the controller before, or in parallel of, the making of said controller. Importantly, full simulations must still be performed as the controller must still be able to function when used on the actual system but, HIL simulations can drastically reduce the number of these tests that must be performed.

Document Hardware:

The camera that was used for this project was the Docooler USB 2.0 HD Camera. This camera's specifications include a resolution of 640 x 480 and a frame rate of 30 frames per second. The camera provides a decent number of photos and videos that allow the group to be able to analyze both the location and color of the stickers of the test game board file printed on a 8.5 x 11 inch piece of white paper.

This camera is not an appropriate sensor for this project; its resolution is too low and it handles noise quite poorly. Both of these problems create a situation where the system fails if the lighting is not sufficient. This means that an LED light must be used to illuminate the game board during the scanning process. This requirement adds another element to the system that can possibly fail/need to be replaced. The use of the LED could be avoided if the camera was either of higher quality or a different identifying system was used.

A motor driver was used to act as an interface between the Arduino and the motor. This was done because the Arduino does not output enough current to adequately drive the motor. The motor driver has its own power supply, so it is able to provide the high current needed to drive the motor.

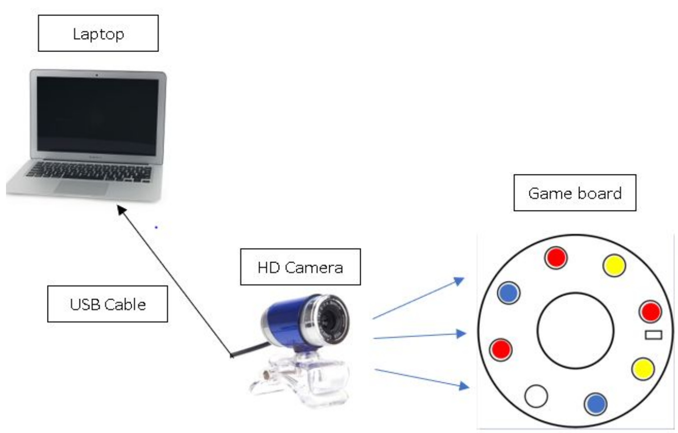


Figure 1: Camera and Laptop Setup

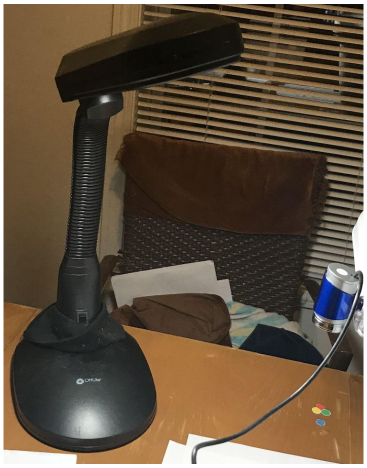


Figure 2: LED Light

Hardware:

Lenovo Y700 Laptop
USB Cable
Docooler USB 2.0 HD Camera
LED Light
Tohoku motor
Motor driver

Document Software:

The software of this project starts by setting up the camera to be able to take pictures within the program. The webcamlist function was used to sync the camera with the Matlab code. Specifically, webcam_list[2] was used since the Docooler HD camera is the second camera on the list (with number one being the default laptop camera). A camera preview is also included to ensure that the first snapshot is taken correctly. The first snapshot taken will be the background image and the second snapshot will be the game board with the colored stickers. Using Run and Advance in Matlab, the program will wait in between snapshot 1 and 2 until the user clicks Run and Advance again. This allows the user as much time as necessary to prepare the pictures to be taken. Once both snapshots are taken Image Processing begins. After image processing the user is able to select either red, blue, yellow, or green and the motor will rotate so that the pointer is pointed at the centroid of the closest washer of the chosen color. Simulink was used to drive this rotation as well as controlling it. In order to do both, a closed-loop control system was used.

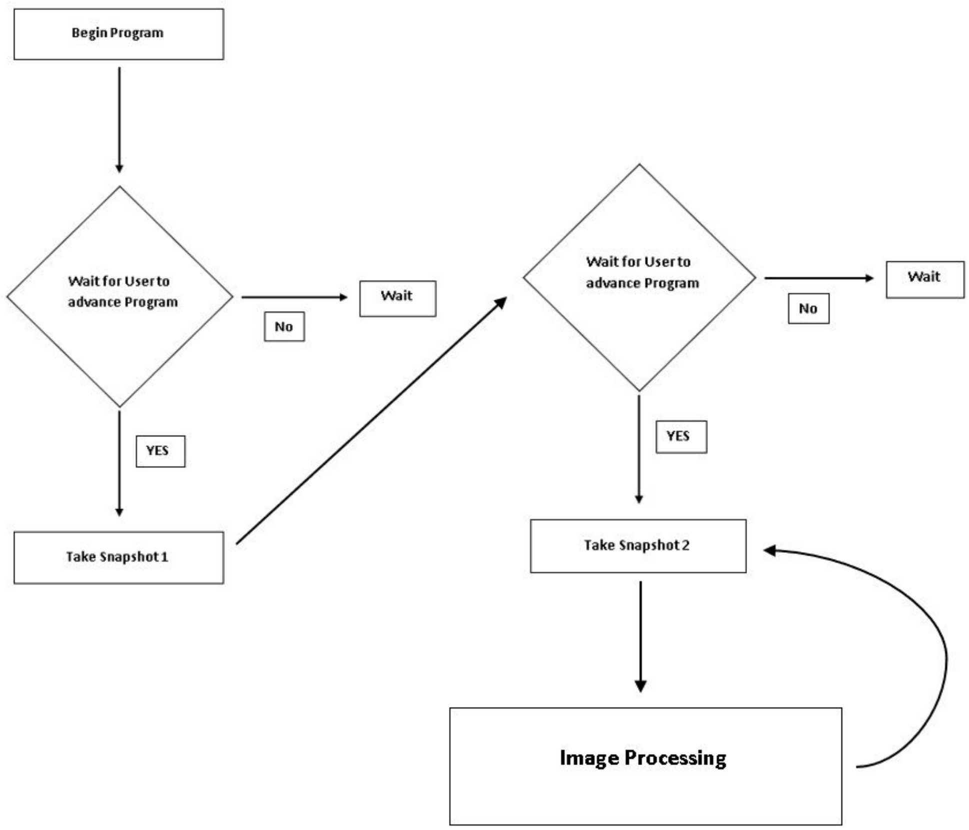


Figure 3: General Algorithm Flowchart

Closed loop control:

Reference point tracking was designed where the motor's angle was the reference point being tracked. The error signal is defined as the difference between the reference point and the current angle of the motor. This signal is then sent to a PID controller with predetermined gains, and the output of the controller is then sent to a subsystem designed to rotate the motor. The current angle of the motor is then measured and fed back into the system to create the closed loop control. This system can be seen in figure 4.

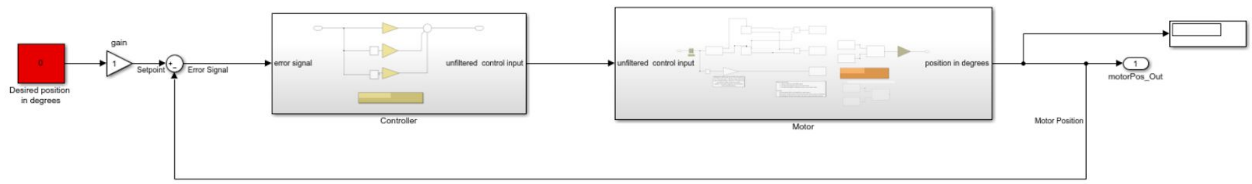


Figure 4: Closed loop control

Data Structure:

The data structure requirements are shown in figure 5:

- Color and location of each identified colored stickers.
- Location (pixel coordinates) of the centroid of each identified colored sticker.
- Images used for analysis. Since you are using background subtraction to process your image data, the following figures should be saved:
    - Original (background) image.
    - Current image.
    - Difference image.
    - Difference image after noise removal with detected foreground objects only.
    - Additional outputs from image processing steps used

Figure 5: Data Structure Requirements

The data structure created for this project is named gamestate and contains the following information:

gamestate. loc	(x,y) pixel location of every colored sticker centroid
gamestate.angle	Angle in degrees of every colored sticker
gamestate.color	Color of every sticker
gamestate.back_Orig	Background Image (game board without stickers)
gamestate.current	Original Image (game board with stickers)
gamestate.diff	Background Subtraction Image
gamestate.diffrem	Binary Background Subtraction Image

Using the regionprops function with the final Binary image, we are able to obtain a large amount of useful data; specifically the location of the every centroid in the Binary Image (of every colored sticker) These values are stored into our structure in gamestate.loc. The angle calculations follow a -180 degrees to +180 degrees standard measuring from right to left.

These angles were determined using a mathematical computation between the vector of the current centroid location to the center point and the horizontal axis through the center. Finding the colors of the stickers was also something that had to be calculated. Although red, green, and blue were easy to compute, yellow took a relatively close amount of red and green. Our group decided to use a ratio of 0.90/1.10. This means that red and green must be within 10% of each other for the color yellow. It should be noted that currently the color is determined by the pixel at the centroid location. While this works for colored stickers, when using a washer with a hollowed middle, how our group calculates color will have to be altered. Visual representation can be seen in the figure 7.

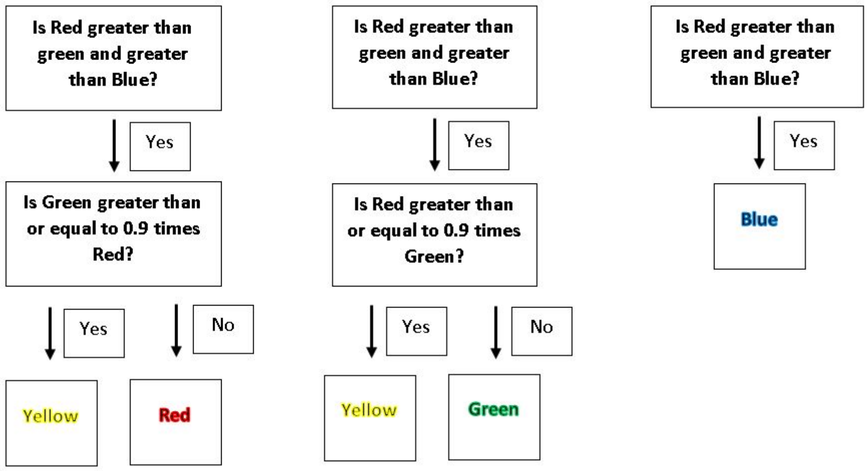


Figure 7: Color State Diagram

With the structure filled with the necessary information for each colored sticker, the centroid locations as well as the center of the picture are put onto the original image.

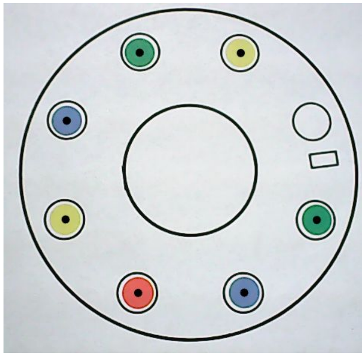


Figure 8: Original Image with Centroid Dots

Once the current gamestate is determined, then the user will be able to select a color washer. Once selected the washer with the smallest angle difference with the current position will be selected and the motor will rotate to that washer. If there is a tie then the washer that is clockwise from the current position will be the one rotated too.

Software:

Matlab R2020a
Matlab Image Processing Toolbox
Simulink 10.2
Matlab Image Acquisition Toolbox
Matlab Support Package for OS Generic Video Interface

Document Motor Experiments:

To provide accurate representation of a working model, three motor experiments were performed and documented. These experiments should provide video evidence of our model pointing to the locations of washers on the game board in various orders and positions. 7 washers were used in the 3 experiments: 3 red washers, 2 yellow washers, and 2 green washers.

Test 1:

The first experiment shows that the model is capable of pointing to every washer found on the board with no regards of color. Beginning at the starting position on the gameboard, the washers were positioned in the order of green, red, blank space, red, yellow, red, green, and yellow respectively. The washers were placed in such a way that no two colors were together while also leaving an opening with no washer within. From the 0th degree, the motor will move the arm in counterclockwise fashion pausing when the arm is pointing towards each individual washer, once all washers have been located, the arm will reset back to the starting position. It should be noted that the motor does not pause at the position without a washer.

Test 2:

The second experiment demonstrates that the model is capable of pointing to every washer of a specific color found on the game board. This works similar to how the first test does, but it utilizes the user interface to specify a specific color of washers to point to. Beginning at the starting position on the game board, the washers were positioned in the order of: green, yellow, red, blank space, yellow, red, green, and red. The color chosen for this particular experiment was red. Once the color was specified using the GUI, the motor was rotated to point towards all three red washers found on the game board before resetting to the starting position.

Test 3:

The third experiment points towards all washers on the game board, grouped by color. The washers were placed in the same position as the second test. The motor the points first towards all red washers, then all green washers, and finally all yellow washers.

PID Controller:

The PID controller controls the impact of error on functionality by using the proportional gain of the past, present, and future. Proportional control amplifies error so that the signal is proportional to the error. Integral control makes the integral of the error proportional to the signal. This also causes the steady state error (SSE) to go to zero. Finally, the derivative control increases the speed of the response and reduces the peak overshoot of the signal.

From the practical motor experiments, our group was able to determine how the gain variables within the simulink model affected the motors response. It was found that the speed the motor rotated increased as the proportional gain increased. Initially, the motor would approximately rotate to the correct position, but would vibrate rather than stopping completely. By increasing the derivative gain with the proportional gain, the vibrations were reduced when moving to the proper position. Manipulating the integral gain also controlled how far the motor would overshoot past the desired angle of the washer.

User Interface:

Before getting to the GUI, the camera must be able to perform background subtraction and then the user must place the washers in whatever order they want. After doing this the GUI will ask the user to select one of four colors. These colors are red, green, yellow, or blue. Once the user selects a color the motor will begin to rotate to the nearest washer of the designated color. Consecutive clicks of the same button will continue to the next washer found of the same color. When no more washers remain of said color, the motor will rotate the arm back to the 0th degree in order to reset for the next test. If no such color is present on the game board then the motor will not move. For the purposes of Project 3, only the Red, Green, and Yellow colors will actively cause the motor to rotate because we were not provided with blue colored washers. Clicking the calculate button instead of a color will cause the motor to rotate and point at every available washer in counter clockwise order. When the last available washer has been reached, the motor will rotate back to the starting position to prepare for the next test. This GUI can be seen in figure 9.

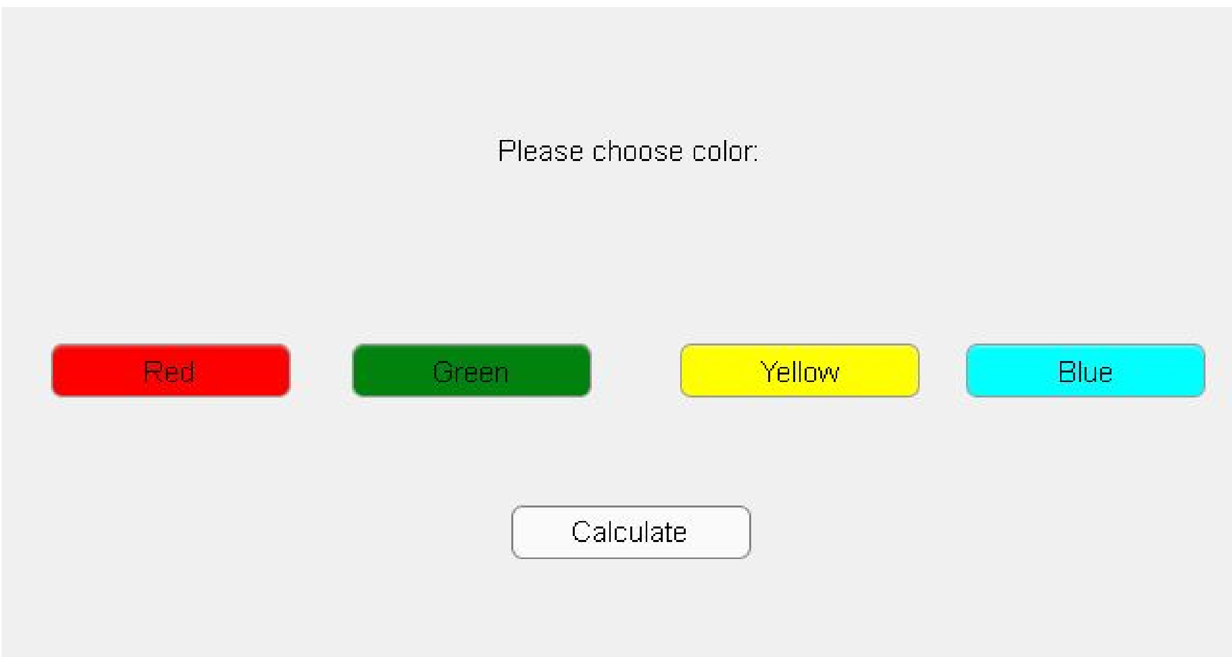
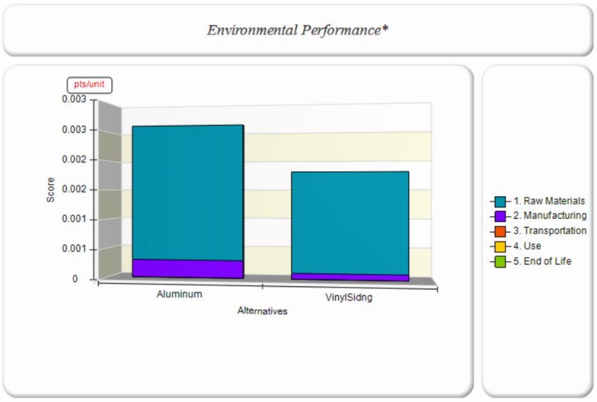


Figure 9: GUI for Motor System

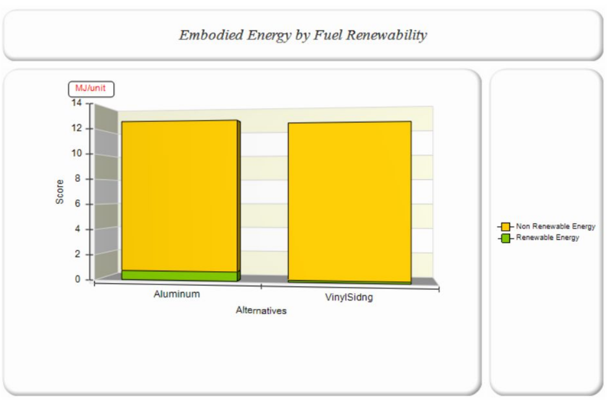
The user is limited to five actions: select one of four colors and a button to start calculations. They only have these actions as they are the only ones that are needed to operate the motor. In addition, they are not given any option to input their own values. This means that they will have a harder time breaking the device. An important option left out is the gains of the PID controller. They are not able to make any changes to these gains because these gains need to be predetermined and not updated during the operation of the device. By removing the ability for users to modify any of the predetermined values in the simulink model, this keeps the motor functioning properly to match what is expected of this assignment. This includes the speed at which the motor rotates to each position reducing error resulting from momentum.

This GUI connects the Camera-As-A-Sensor and the Tohoku motor by giving the user the option to select a color washer that the motor will point to. The GUI will use the washer locations determined by the camera to tell the motor which washer to point to. It does this by updating the block constant at the beginning of the simulink model that controls the motor. After doing this the reference point for the simulink model will be updated and will thus cause the motor to rotate to the chosen washer.

AATOF Engineering
Life Cycle Analysis for Shipping Box Cladding



Graph 1: Environmental Performance **Graph 2**: Global Warming



Graph 3: Embodied Energy by Fuel Renewability **Graph 4**: Economic Performance

Interpretation of results:

As can be seen in the above charts, the vinyl siding presents a much lower environmental impact than aluminum. The only exception being the "Embodied Energy" category, where the two are roughly identical. It is important to recall that in the Building for Environmentally and Economical Sustainability software, the Environmental Performance graph (Graph 1) should be viewed as a penalty score, implying that a lower score, which the vinyl siding has, is better. It can be observed from the results presented in the graph titled Global Warming (Graph 2), neither option enables much use of renewable energy (Graph 3) and both are raw material intensive products to produce. However, the high energy savings obtained from the use of recycled aluminum may serve to provide a different dynamic for this calculation, were this to be taken under consideration. The vinyl is also a cheaper material than the aluminum siding is, so the economic incentive to use the less environmentally impactful material is present as well according to the analysis performed via the BEES software.

While vinyl siding presents a lower total environmental impact than does aluminum siding in the entirety of the BEES assessment provided above, in some areas the differences are more pronounced. Vinyl siding presents a much lower impact on global warming by substantially reducing the CO_2 emissions for comparable quantities of siding material as compared to what is required by aluminum siding. Given that the embedded energy of the two materials is approximately the same, this indicates that the embedded energy of the vinyl siding is due to the polymer makeup of the siding, being derived from oil. Thus, while aluminum siding takes substantially more energy to manufacture than does the vinyl siding, the vinyl siding has a much higher energy content in the material itself. The vast majority of the environmental impact for both materials is due to the raw materials, with the next largest component being from manufacturing. This is due to the extractive nature of producing both the bauxite ore to process into aluminum, and the need for drilling in order to obtain the petroleum to process into vinyl. The future economic costs for both materials are roughly the same; it is in the initial purchase costs where the vinyl siding presents substantial savings when compared to the aluminum siding, which presents substantial benefits to the firm when constructing the shipping container, as the immediate costs are of primary concern in determining affordability.

The steel frame is providing the structure and rigidity of the container, the siding material's ability to resist deformation is of minimal importance. The increased flexibility of the vinyl may contribute to such a package, being of suitable size, performing better in regards to potential puncture or tear resistance. Such a consideration would be of utmost importance were the robots to be shipped via a waterway, especially over the ocean as the effect of seawater on metallic and electronic components would be deleterious. According to the stipulations provided in the assignment document, both materials are suitable, but since vinyl has a smaller environmental impact than does aluminum, in addition to being the cheaper of the two options, AATOF will select vinyl to cover the steel frame used to construct the packing box for the robots, as this is both environmentally and economically more sound than is the aluminum siding.

Continuing Education Considerations

Team Member Activities		
Activity	**Benefit**	**Cost**
International Society of Automation Certified Automation Professional Certification	Every member of the team who will be working on the project directly as their primary role will be certified by an international body to possess the requisite knowledge for controls systems.	$445/exam * 4 persons + $32.50/hr * 8hr/day * 3d * 4 persons = $4900
ICMIMT 2021: 15. International Conference on Mechanical and Intelligent Manufacturing Technologies, New York	Provide an interactive environment to encourage all team members to develop ideas on how to improve system and production.	Travel, $2500 + Registration, $800 + Lodging, $4000 + Missed productivity, ($32.50/hr * 8hr/d *3d*4persons) $3120 = $10,420
Modern Robotics: Mechanics, Planning, and Control Specialization Coursera	Team members will be able to further their knowledge of robotics and control systems.	Online course, free registration, Missed productivity, ($32.50/hr * 8hr/d *5d*4persons) $5200
2021 IEEE 4th International Conference on Soft Robotics (RoboSoft) New Haven, CT	Introduce team members to professionals in the industry, provide exposure to cutting edge robotics designs.	Travel, $2500 + Registration, $1200 + Lodging, $2000 + Missed productivity, ($32.50/hr * 8hr/d *5d*4persons) $3120 = $10,900

Manager Activities		
Activity	**Benefit**	**Cost**
IEEE Controls System Society Membership	Access to IEEExplore library, professional recognition.	$25 for annual membership
Professional Engineering License	Enables project manager to provide PE stamp to project, giving a known, quality baseline for system evaluation.	$375 for exam + time taken for preparation, $32.5/hr * 8hr/d * 2d $520 $895
2021 American Control Conference in New Orleans, Louisiana	Provides opportunities for manager to meet experts in the field and enables new ideas to be developed.	Travel, $1500 + Registration, $600 + Lodging, $1000 + Missed productivity, ($32.50/hr * 8hr/d *3d) $780 = $3880
ICIEB 2021: International Conference on Innovation in Economics and Business Sydney, Australia	Provides manager with relevant training and new ideas to enhance productivity.	Travel, $3500 + Registration, $500 + Lodging, $1500 + Missed productivity, ($32.50/hr * 8hr/d *4d) $1040 = $6540

AATOF Engineering
Safety Analysis for Robot Design

AATOF DFMEA Assessment for Robotic Assembly Component Failures						
Component or Subsystem	**Mode of Failure**	**Symptom**	**Effect**	**Probability (A-E)**	**Severity (I-IV)**	**Risk Index**
Motor	Overheating	System no longer rotates the assembly	Windings and insulation may fail or catch fire	E	I	(I-E)
Lazy Susan	Bearing surfaces seize	Assembly seized and no longer allows rotation	May cause motor to burn out trying to rotate immobile object	D	I	(I-D)
Camera	Internal chip fails	No output to program of game board	Robot is left without the ability to detect the game board	E	III	(III-E)
	Filtering system malfunction	Camera is unable to distinguish between colors	Robot can detect relative light absorption, but not the colors of the washers	E	III	(III-E)
Electromagnet	Wire breaks	System is unable to pick up and rearrange washers	Assembly will not have ability to rearrange washers	D	II	(II-D)
Power Supply	Short Circuit	Outputs connected, excessive current produced	Damage to power supply or motor	C	I	(I-C)
Power supply	Wire insulation failure	Bare conductor exposed to external people and objects	Shock hazard to personnel	B	III	(III-B)
Data transmission	System produces	Robot behaves in	Failure to complete	B	IV	(IV-B)

connection	erroneous signal or had unintended feedback	unexpected and undesirable manner(s)	rearrangement, potential motor overspeed issue			
Electromagnet suspension	Electromagnet is not sufficiently supported or maintained in position	Assembly to support electromagnet drops magnet or magnet is misaligned	Potential damage to gameboard or electromagnet	D	II	(II-D)
Camera suspension	Camera does not point at game board or falls	Camera cannot be focused on game board or falls without outside intervention	Potential damage to camera/ inability of camera to detect game board and washers	C	II	(II-C)

Likelihood/ Impact	Very Probable (A)	Probable (B)	Occasional (C)	Remote (D)	Improbable (E)
Catastrophic (I)			•	•	•
Critical (II)			•	••	
Marginal (III)		•			••
Negligible (IV)		•			

It was determined by the analysis methods outlined above that the primary hazards were to the equipment itself, due to improper handling, and to the user, through shock potential. In order to minimize the potential to damage the equipment needed for this robot to work, the intended design for construction incorporates the use of reinforcing supports and geometrically favorable structures to reduce the possibility of failure. Sufficient fasteners and adhesives were used to further ensure the sound attachment of all base components. While not implemented at this stage due to the requirements of the subproject, the final design incorporates the use of a vertical support for the camera as well as for the electromagnet. A balanced construction is intended to reduce the instability of the robot and its housing once these additional elements are incorporated.

The primary hazard to the user is that of shock due to improper grounding or shorted wires. In order to mitigate these potential concerns all external components of the assembly are made of wood, as wood is an insulator and does not allow for the buildup of charge or the transmission of current. The metallic or electronic components, with which the user may interface, will be grounded and isolated by wood in order to fully mitigate the risk to the user posed by the system.