# VR Robot

# Final Proposal

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# DISCLAIMER

# EXECUTIVE SUMMARY

For the Summer 2023 476C session, our team was tasked with developing a VR (virtual reality) Robot out of a previous capstone project called R.U.T. (robot utility tank). The goal was to take the previous project and implement a robotic arm and complete VR controls. A product such as this has many applications. In summary, this project can be used to perform tasks in places where a human could not or should not be present. In order to achieve this, the team was given a $2500 base budget along with a list of measurable requirements to attain. The project was split into 3 areas. Area one requires the team to make improvements to the R.U.T. project. The R.U.T. project fell short of its goals mainly in terms of mobility. The team has addressed these shortcomings alongside other minor concerns. Secondly, the team needed to find a path for implementation of a robotic arm. We had the choice of improving a device on the market or developing one from scratch. Lastly, the implementation of the VR controls will tie the two mechanical components together including complete user control over both. The purpose of this report is to discuss this process in any and all detail of our first semester's development and progress.

The design of our VR Robot is as follows:

**RUT Base**

This is the primary robot. The RUT is a unit handed down to our group from a previous capstone. The use of the RUT is primarily for movement and world interaction. This robot is what allows the project to function as a VR project in some regard. By allowing the robot to move within the real world our team is able to attach cameras and use virtual reality headsets to visualize these movements from theoretically anywhere in the world.

**Robotic Arm**

The Robotic arm is a prebuilt one, known as the Braccio++. The arduino based robotic arm is a basic budget arm designed for ease of use. Because of this the group has decided to use the Braccio++ in hopes that we can perfect our control method early on within the project. Additionally to ensure adequate workspace with the arm the links will be redesigned to be longer and stronger if necessary.

**VR Control**

The VR Control of this project is of the utmost importance. That being said, it is also the most difficult part of the project. Currently the cameras aren't “directly” connected to the headset, and are using other platforms to connect to unity. This increases lag, however is a good starting point. On top of this we have gained connection to the Braccio++ in Unity as well. Although it is only through the use of sliders. These basic connections do prove our concept however and currently are satisfactory for the client as well as the professor.

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# 1 BACKGROUND

## *1.1 Introduction*

For the Summer 2023 Session 476C course, group 1 has been tasked with developing a VR (virtual reality) Robot. The goal of this project is to have control of a robot and robotic arm through a VR Headset. Given the world's industries push towards automation, hands off controls, and virtual reality, this project will serve as a platform for all parties involved to get familiar with the technology involved. A robotic device such as this could serve many useful purposes in later development. These include but are not limited to; surgery performed by a doctor who cannot be present, diffusal of an explosive device, planetary exploration, service of machines in hazardous areas, and any other tasks needing human intervention where one cannot be present, or the risk of being present is deemed to have a high risk of injury or fatality.

## *1.2 Project Description*

Following is the original project description provided by the sponsor.

> "Virtual reality (VR) controlled robots are robots that can be controlled remotely by a human with a VR headset. These robots can be used for a variety of Mechanical Engineering applications such as gripping, welding, cutting, and lifting heavy objects while being controlled by a human operator. There are several advantages of using VR-controlled robots. One advantage is that VR-controlled robots can be used to perform tasks that are dangerous for humans. Another advantage is that VR-controlled robots can be used to perform tasks that are difficult for humans. For example, VR-controlled robots can be used to perform tasks in manufacturing that require precision and accuracy. Additionally, VR-controlled robots can be used to perform tasks in healthcare that require a high level of accuracy.
>
> VR-controlled robots have many applications, including in manufacturing, healthcare, and education. For example, Covariant.AI uses VR, artificial intelligence, and various deep learning techniques to teach robots to perform certain tasks.
>
> This project will be built on the existing capstone project which was finished in 2022 at the Mechanical Engineering Department. A full metal frame housing the electrical components as well as a track system that was made in-house was designed. This robot can carry a load of 200 lbs. and 2 mph.
>
> The goal of this capstone project is to add a VR-controlled arm to the robot. This arm will be controlled with a VR Meta Quest 2 headset and mimics the movements of the individual hand. Here is a schematic of the remotely controlled arm using a VR.
>
> The capstone team, in collaboration with the client, will decide on the tasks to be performed by the Robot. The components needed for a VR-controlled robot can vary depending on the type of robot and its intended use. For example, a VR-controlled robot designed to take the place of humans in emergency situations would require different components than a VR-controlled robot designed for manufacturing. Some components that may be needed for a VR-controlled robot include sensors, cameras, and actuators. The robotic arms are controlled by Raspberry Pis, which are running web-based servers designed to accept input from the VR controllers. This input is translated into movements for the robotic arm."

# 2 REQUIREMENTS

In this chapter the reader will find five main aspects of the requirements provided by the client. First of all the customer requirements and their weights  will be discussed showing the completion/progress of each one. The engineering requirements will also be studied in this chapter followed by the functional decomposition and house of quality. Finally this chapter will conclude with an overview of the standard, codes, and regulations specific to this project. It is important to understand that all the information provided in this chapter is accurate to the current stage of the project. Much of this information will divert from the information stated in this chapter as the project keeps developing.

## *2.1 Customer Requirements (CRs)*

Table 1 discusses the customer requirements, their weights, and a brief justification of the weight. Weights are on a scale of 1-5. Similarly table 2 shows a summary of all customer requirements and adds to the percentage met to the current date.

| **Customer Requirements** | **Weight** | **Justification** |
|---|---|---|
| Cost within Budget | 4 | Budget is limited and crucial for project completion. |
| Durable and Robust | 3 | Cannot afford to replace components. |
| Reliable Design | 3 | Given the product's application, it is crucial for it to perform at all times without failure. |
| Safe to Operate | 4 | It cannot pose a risk to the operator or any persons near/involved. |
| Move in 3D | 1 | Low weighting due to the nature of the robot already moving in 3D. |
| Large Work Space | 2 | Tools and the robotic arm can always be implemented in the future, our focus will be more on developing a functional device. |
| Uniform Continuous Force Capacity | 2 | Fine tuning of movements and force applications can be accounted for at a later date. |
| High Mechanical Stiffness | 2 | It is important that our robotic arm does not break however focusing too much on this requirement could push the group to go out of the budget. |
| Low-Latency Communications | 3 | It is important that the robot responds fast to the user's input. |
| High Resolution Sensing | 4 | High resolution sensing is crucial to making movements to the arm that correspond with the user's input. |
| Fast Update Rate | 3 | A fast update rate will allow the user to have no delay in seeing what the robot is doing through the headset. |

Table 1: Customer Requirements

| | Customer's Requirements | Status | | Percentage met |
|---|---|---|---|---|
| 1 | **Improve RUT's drivability** | 75% | *Most subsystems work separately, need to be assembled together.* | 0.75 |
| 2 | **Design robotic arm** | 85% | *All parts are done, need to do testing.* | 0.85 |
| 3 | **Control 1 & 2 via VR-Headset** | 60% | *Major breakthrough with connection between arduino and unity.* | 0.6 |
| 4 | **Assemble together sections 1-3** | 0% | *All subsystems still under research and development.* | 0 |
| 5 | **Keep the budget under $2500** | 100 % | *According to the BOM purchases are still under $2500* | 1 |
| | | | Overall percentage met: | 64% |

Table 2: Customer Requirements-Overall percentage met

Where:

Green = Progress is in between 80% and 100%

Yellow = Progress is in between 50% and 80%

Red = Progress is between 0% and 50%

## 2.2 Engineering Requirements (ERs)

The written scope for this project did not include any engineering requirements, however, the team has made a list of engineering requirements that need to be met in order to successfully complete the customer requirements mentioned above. There are more requirements that the team will need to consider as the project progresses, these new requirements will be discussed in its due time. In the following table the ER's are listed along with the target and justification.

| **Engineering Requirement** | **Target Value** | **Justification** |
|---|---|---|
| Decreased Turn Time | 10 (Seconds) | Inorder for the robot to maneuver in a difficult location in a timely manner. |
| Increased Torque Advantage | 5< (Newtons) | This value is given in the customer requirements and will be critical to perform minimum functions such as gripping. |
| Low Program Speed | 0.5 (Seconds) | Any program will have to update in less than 0.5 seconds in order to minimize delay of response. |
| Low Latency | 50> (milliseconds) | A user's input needs to be delivered to the robot and visual confirmation needs to be received in less than 50 milliseconds in order to reduce misinputs. |
| Increased Arm Length | 0.5 (meters) | The arm needs to be at least 0.5 meters long in order to achieve the required workspace radius. |
| High Network Speed | 30 (Megabits/second) | A high network speed is crucial for all wireless systems to communicate reliably. |
| High Material Strength | 55 (GPa) | A high material strength will be necessary to reduce frequency of yielded components especially during the product's potential application. |

Table 3: Engineering Requirements

Green: Means that the team has been able to fully fulfill this requirement.

Yellow: Means that the team has not fulfilled this requirement but has proof that will be able to fulfill it .

Red: Means that the team has not yet been able to determine how exactly to fulfill this requirement.

## 2.3 Functional Decomposition

The main function of this project is to allow controlling the robot tank with arm under a first person view of VR. The VR should provide the user a free view on the robot chassis then enable control based on that view.

The function of the project is decomposed into Camera, Control Board and Robotic Arm. Camera is used to allow the user to have a view around the robot and create a valid vision space. Control Board is to activate the movement combining RUT and robotic arm then enable solo operation. Robotic Arm is the core of the replacement operation of users, it is used to grab items and hold it for transfer. The purpose and relationship of these functions will be illustrated in the following sessions.

### 2.3.1 Black Box Model

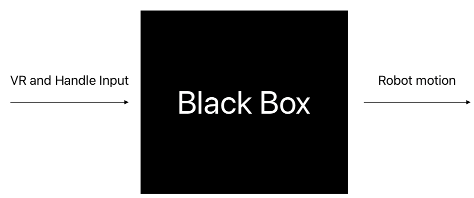


Figure 1: Black Box Model

This is the Black Box Diagram of the project. The input is the operation command of VR and handle, it is a signal input, it is operated at the will of the user. The output is the robot motion, it is a signal and energy output, which needs to have the ability to grab items, and transfer it through a distance on the ground. The camera function does not show up for it forms a loop inside of the black box to help the user identify the position of item and RUT and find a way to transfer it.

The final purpose of the project is to have the robot tank with arm grab items and transfer it in the way the user wants to through VR control. The Black Box model illustrated the necessary input and output. It clarified the final purpose and necessary operation mode, so the function model and designs are to activate this operation.

### 2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

The work progress is based on a dual-centered system. The PC serves as an user portal and the control board serves as a robot portal. The PC allows the combination of viewing and controlling for the user, we use a software as a middleman(currently it is Unity), it receives the view space from a camera and sends it to VR thus forming a free view for the user. Also the portal collects input from the VR handle, processes it to a valid operation command  then transfers it to the control board. The control board receives the command and applies it on RUT and arm.

This diagram provides a vision of how each function connected physically and functionally. It indicates the necessary hardware connection method and programming. The PC needs to have a remote connection to the camera and control board transferring massive data from camera and minor data and command to the control board. Programming is necessary on PC to process the input from the VR handle and make it into a first stage signal then send to the control board. The signal received on the control board needs to be transferred into a valid operation command applying one robotic arm and RUT.

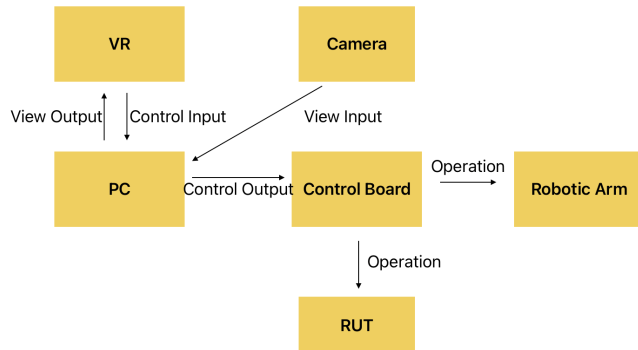


Figure 2: Work-Process Diagram

## 2.4 House of Quality (HoQ)

The House of Quality serves to relate the customer requirements, engineering requirements, and provide a benchmark of the current products. In the top section, the interaction between engineering requirements is shown using + or - to show a positive or negative correlation. Technical requirements are listed in the lower section along with their absolute and relative technical importance values. These values will assist the group by showing the most important areas of the project to focus on from most to least important. **See Appendix B for a larger view of the table.**

**System QFD** | **Project:** VR Robot | **Date:** 07-06-23

| | Decreased Turn Time | Increased Torque Advangtage | Low Program Speed | Low Latency | Increase Robotic Arm Length | High Network Speed |
|---|---|---|---|---|---|---|
| Decreased Turn Time | | | | | | |
| Increased Torque Advangtage | + | | | | | |
| Low Program Speed | | | | | | |
| Low Latency | | | - | | | |
| Increase Robotic Arm Length | | - | | | | |
| High Network Speed | | | - | - | | |
| High Material Strength | | | | | + | |

| Legend | |
|---|---|
| A | CALIBER Mk3 EOD |
| B | Andros F6 |
| C | Wheelbarrow MK9 |

| | | Technical Requirements | | | | | | | Customer Opinion Survey | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Customer Needs | Customer Weights (1-5) | Decreased Turn Time | Increased Torque Advangtage | Low Program Speed | Low Latency | Increase Robotic Arm Length | High Network Speed | High Material Strength | 1 *Poor* | 2 | 3 *Acceptable* | 4 | 5 *Excellent* |
| Cost Within Budget | 4 | | 6 | 4 | 8 | 4 | 6 | 4 | ABC | | | | |
| Durable and Robust Design | 3 | 4 | 6 | | | | | 4 | | | | | ABC |
| Reliable Design | 3 | 6 | 6 | 4 | | | 4 | 6 | | | | | ABC |
| Safe to Operate | 4 | | | 6 | | | | 4 | | | BC | | |
| Move in 3D | 1 | 5 | 1 | | | | | | | | | | ABC |
| Large Work Space | 2 | 3 | | | | 9 | | | | | | | ABC |
| Uniform Continuous Force Capacity | 2 | | 5 | 2 | | | | | | | | | ABC |
| High Mechanical Stiffness | 2 | | 3 | | | | | 3 | | | | | ABC |
| High Resolution Sensing | 4 | | | | 6 | | 8 | | | A | | | BC |
| Low-Latency Communications | 3 | | | 3 | 7 | | 8 | | | | AB | C | |
| Fast Update Rate | 3 | | | 8 | 5 | | 8 | | | | A | BC | |
| Technical Requirement Units | | Seconds | Newtons | Seconds | ms | m | Mb | GPa | | | | | |
| Technical Requirement Targets | | 10 | 5< | 0.5 | 50 | 0.5 | 30 | 55 | | | | | |
| Absolute Technical Importance | | 41 | 69 | 89 | 92 | 30 | 116 | 68 | | | | | |
| Relative Technical Importance | | 6 | 4 | 3 | 2 | 7 | 1 | 5 | | | | | |

Table 4: House of Quality

## 2.5 Standards, Codes, and Regulations

In order to be competitive in the market the project has to meet certain rules and regulations that adhere to ISO and ANSI regulations. Achieving the following standards and codes listed below will help the team design and build the project up to code. There are many codes and standards that have been taken into consideration that are not in the table below, this is because they have been followed and met by external entities like the manufacturer of a certain product that the tem purchased, previous capstone team, welding gear used for the project, machinery used to put together the project, etc.

| Standard Number or Code | Title of Standard | How it applies to Project |
|---|---|---|
| AISI S240 | North American Standard for Cold-Formed Steel Structural Framing | Helps in the design of how the device with interface with the user in a safe manner. |
| AWS B2.1/B2.1M:2021 | Standard Welding Procedure Specifications (SWPS) | Provides practices under ANSI regulations that will prevent any failure due to poor welding practices. |
| ISO 15072:2012 | Hexagon Bolts With Flange With Metric Fine Pitch Thread - Small Series - Product Grade A | Provides reliability to all the parts that will be held by nuts and bolts. This will help choose the nuts and bolts appropriate for the project. |
| ISO/TC 270 | Plastics and rubber machines | Provides insight when seeking to purchase the right PLA for 3D printing. |
| IEC 60034-1 +A1 and A2 | Electric Motor Standards as Defined By the IEC and the Harmonized European Standard | Rotating electric motors. Part 1: Rating and design |
| IEC 60034-6 | Electric Motor Standards as Defined By the IEC and the Harmonized European Standard | Rotating electric motors. Part 6: Cooling (IC code) |
| IEC 60034-14 | Electric Motor Standards as Defined By the IEC and the Harmonized European Standard | Rotating electric motors. Part 14: Mechanic vibration for machines with drive shaft heights of 56mm or more. Measuring, estimate and vibration limits |
| IEC 60072-1 | Electric Motor Standards as Defined By the IEC and the Harmonized European Standard | Dimensions and output power for rotating electric motors. Part 1: Frame size 56 to 400 and flange size 55 to 1080. |
| ISO/TR 19247 | Camera Testing Guidelines | Guidelines for reliable testing of digital still cameras describes best practices for performing tests of digital cameras, including test criteria, conditions, protocols and documentation, as well as the training of personnel for reliable testing. |

Table 5: Standards of Practice as Applied to this Project

As a conclusion for this chapter, the team has successfully managed to work towards meeting all the customer's and engineering requirements. The current state of the project is at 64 percent. This number shows that the team has had a great head start given that the team has only worked on the project for about 7 weeks. Some testing has been done mostly regarding the RUT part, more testing is foreseen but it will have to be done during the fall semester.

So far the team has been leaning more on "proof of concept" rather than on "Theory" since the team believes that the time can be used more efficiently if the concept is proven and then the theory is applied to that concept. An example of this is the traction issue that the track has, a couple of parts have been designed and 3D printed to see if they can fix the traction issue. Once the parts were attached to the wheel and proved that the concept actually works then the team is going to go ahead and design a similar part that will perform the same job but that will actually meet the standards and codes.

Things to look forward in the next semester regarding the engineering and client requirements are, but not limited to:

- Prove that all the subparts of the system meet all the standards and codes
- Adjust any requirements that fall outside of the codes and standard
- Create a list with new requirements as they come up
- Fix any issues with current requirements
- Meet regularly with David Willy to ensure that all the client requirements are being met
- Reach out to field experts for input and feedback
- Adjust BOM as needed
- Order new parts as needed
- Increase budget if necessary

# 3 Testing Procedures (TPs)

To meet the CRs and ERs, 6 tests are designed to verify and help improve the project in multiple aspects regarding HoQ. The tests are labeled from basic to advanced in function. Contents below provides details of tests planned for this project, including objective, resource required and schedule.

## *3.1 Testing Procedure 1: On-Cable Software Test*

This is a basic test. The purpose of the test is to build and verify the accessibility of software functions of arm,camera and RUT regardless of wireless connection. The test is helpful in meeting all ERs except remote control. This will be one the first tests that are scheduled and many of the other tests are based on this.

### 3.1.1 Testing Procedure 1: Objective

This test is to verify the activation of software functions. Cable is used to connect the arduino board or RUT control board to the computer. Arm is tested for reaction when controller inputs, one person is required to watch the movement of arm along with controller, check if all coded functions work, including rotating, grabings, forward, backward, lift, fall and wrist rotation, and find out the error in movement. Camera is tested for the existence of the view in Unity, the view should change with the movement of the camera and be visible in VR mode. RUT is connected to the computer as well, it will be tested if it reacts the same way as VR controller inputs. This individual test is particular because it starts almost all the other tests, it is necessary to check the activation of coded functions before assembling, also it is going to address the errors on the coding side if the system does not work properly.

### 3.1.2 Testing Procedure 1: Resources Required

The necessary items of this test are RUT, camera, arm and board, computer, cable, one operator and the workshop. Also, an inspector is optional to watch the movement of the arm and RUT. Computers with Unity is the basic hardware, RUT, camera and arm are used for testing functions of software. The workshop has enough space to test the RUT, dorms have enough space for testing arm and camera.

### 3.1.3 Testing Procedure 1: Schedule

The test is scheduled around the beginning of September. It is expected to take almost a month to complete and it is expected to be done at the end of Sept. To ensure the other test started on time, this test should be completed in the early stage.

## *3.2 Testing Procedure 2: Robotic Arm Load Test*

This is a basic test, the purpose is to find out the maximum and recommended weight of the lifted object. The test should be done before test 5.

### 3.2.1 Testing Procedure 2: Objective

In this test, the arm will lift a weighted item under serial input of Unity starting from horizontal to vertical, all sections of the arm should be straight. The weighted items will be hung under the end of the arm. To change the weight of an item, a bottle with water will be put on a scale, addition and reduction of water can change the weight. The weight will be added by 50g starting from 50g, if it cannot lift for the first time, reduce 25g then add 12.5g if lifted up or reduce 12.5g if not, then is the end of the test. The weight of the last lifted item*0.95 is the maximum weight. The recommended weight is 0.5*maximum weight. The error boundary is 0.125N and the target is 5N of maximum weight lifted. This test directly affects the CR of maximum weight lifted.

### 3.2.2 Testing Procedure 2: Resources Required

Resources required for this test are a computer, controller, arm, 2 bottles, water, scale and a person. Space is not required in the list for it is not requiring a large space. A bottle with water is the lifted item that is easy to change in weight. Water is conveyed between 2 bottles. Computer is used for having an input of lifting. A minimum of one person is required for this test but 2 or more persons are recommended for one person to control the arm, the other one to refill the water and hang it on.

### 3.2.3 Testing Procedure 2: Schedule

This test is scheduled after test 1, around the beginning of October. It will not take a long time after the completion of test 1, but the result leads to whether we have to change the motor. So actually, this test happens once test 1 is done. Also, test 5 and 6 are built on the outcome of this.

## *3.3 Testing Procedure 3: RUT Mobility Test*

This is a basic test, it is designed to check the mobility of RUT after improvement. It can keep the control of the original way so no tests are required before this.

### 3.3.1 Testing Procedure 3: Objective

To test the mobility, a person needs to run RUT in a circuit shaped like '8' of 15 laps in the workshop. After finishing the laps, sprocket and track needs to be checked for any problems or defects. RUT needs to be able to run smoothly in the circuit. The test is recommended to be done multiple times for testing durability but it is not specified in CRs and ERs. The result affects the mobility aspect of this project.

### 3.3.2 Testing Procedure 3: Resources Required

Resource required for this test is controller, RUT, a large space and a minimum of one person. The workshop has enough space for this test. A VR controller is not necessary and the origin controller is enough. One person is sufficient to complete the entire test.

### 3.3.3 Testing Procedure 3: Schedule

This test is scheduled in September, completed by the other subgroup apart from the controlling side. The outcome might result in changes in the designs of suspension and sprocket of RUT. Test 5 is built on this so it should be done along with test 1.

## *3.4 Testing Procedure 4: Remote Connection Stability and Latency Test*

This is an intermediate test, the purpose is to judge the reliability of remote connection functions. The test is designed to help meet the requirement of low latency remote control. The test is scheduled after test 1.

### 3.4.1 Testing Procedure 4: Objective

Robotic arm, camera and RUT will be tested in this test. To do the test of latency, we need to send some data from the computer to the target function model under the supervision of a latency monitor. Also, the arm will be running for ten minutes to convey an object of the recommended weight from a place to another then back. If no crashes or obvious decreasement in performance are detected, the system can be seen as stable. After the test, export the latency data as a curve of time, find out the maximum and average value. Repeat the same step on camera and RUT, but for testing camera, play another video on another screen in front of the camera and see if there is error. For RUT, do the same test using VR remote control and repeat the steps of test 3.

### 3.4.2 Testing Procedure 4: Resources Required

The resources required by this test are camera, RUT, robotic arm, computer, mobile phone, latency monitor software, large space and an object for lifting. Mobile phones are used to play video and test the stability of cameras. Only the RUT test requires a large space. A minimum of 1 person is required for this test but it is recommended to have 2 or more.

### 3.4.3 Testing Procedure 4: Schedule

This test is scheduled after test 1,2 and 3. The scheduled time is around the middle or end of October, before November. The test takes about 2 hours but if there are any changes resulting from the test, the purchase and delivery might take a week. Test 5 is dependent on this so the test is necessary to conduct right after the prerequisite. The potential changes resulting from the test is the change of remote connection hardware.

## *3.5 Testing Procedure 5: Overall Stability and Latency Test*

This is an advanced test, it is the combination of the previous tests with finalization. Assembling is required for this test. This test is focusing on the final function of the project, once this test is done, it marks the completion of the project in the view of meeting CRs and ERs.

### 3.5.1 Testing Procedure 5: Objective

This test is to find out the stability and latency of control of the final robot. The robot needs to carry an object of recommended weight and carry it to another edge of the room then carry back, repeat. In general, it is the combination of the steps of test 1, 3, 4. Latency monitor is used to record data when operating. The biggest difference from the previous test is the power supply is the battery, so we need to make sure the functions work well in association with the battery power instead of plug. The major expectation of the outcome is the functionality when associating all functions, also finding out some defects when assembling.

### 3.5.2 Testing Procedure 5: Resources Required

The resources required for this test are RUT assembly, computer, latency monitor, weighted object and a large space. RUT should be completely assembled. A minimum of 2 persons are required for this test, one controls the robot using VR, the other one records latency data and performance of the robot.

### 3.5.3 Testing Procedure 5: Schedule

This test is scheduled around the beginning of November after assembling. All the previous tests should be completed by then. The result of this test might lead to some modifications on the assemblement. The test takes about 3 hours if there is no error.

# 4 Risk Analysis and Mitigation

In order to ensure success of the VR Robot, an understanding of any and all potential risks needs to be evaluated by the team. An FMEA (Failure Mode and Effects Analysis) was created. This tool will allow us to understand all risks and their ranking through a calculated risk priority number. The top ten critical failures will be analyzed in section 4.1 and the full FMEA can be found in Appendix B.

| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Potential Causes and Mechanisms of Failure | RPN | Recommended Action |
|---|---|---|---|---|---|
| 1. Frame | Cracking | Mobility loss + further damage | Crashing | 50 | Periodic visual checks |
| 1. Battery | Dying | Power loss | Failure to charge | 125 | Charge after use |
| 1. Motor Controller | Shorting out | Power loss | Water | 50 | Ensure enclosure is sealed |
| 1. Power Switch | Wearing | Power loss | Overuse | 40 | Replace periodically |
| 1. Lid Attatchment | Bolts Sticking | Inability to access internals | Overuse | 280 | Upgrade hardware |
| 1. Electronics Housing | Leaking | Electronic Failure | Water | 18 | Ensure enclosure is sealed |
| 1. Motor Mounts | Yielding | Loss of mobility | Torque | 18 | Periodic visual checks |
| 1. Frame | Bending | Reduction of monility | Crashing | 9 | Periodic visual checks |
| 1. Wheel Shaft Mounts | Yiedling | Loss of mobility | Crashing | 24 | Use of stronger materials |
| 2. Track | Snapping | Mobility loss | Over tension | 40 | Periodic visual checks |
| 2. Drive Wheel | Slipping | Mobility loss | Not enough tension | 504 | Use of stronger materials |
| 2. Driven Wheel | Cracking | Mobility loss | Crashing | 24 | Use of stronger materials |
| 2. Drive Wheel Shaft | Twisting | Mobility loss | Torque | 6 | Use of stronger materials |
| 2. Driven Wheel Shaft | Bending | Mobility loss | Crashing | 6 | Use of stronger materials |
| 2. Roller Bracket | Yielding | Mobility loss | Crashing | 45 | Use of stronger materials |
| 2. Roller Wheel | Cracking | Mobility loss | Crashing | 24 | Use of stronger materials |
| 2. Roller Mount | Yielding | Mobility loss | Crashing | 36 | Use of stronger materials |
| 2. Tensioner | Yielding | Mobility loss | Over tension | 36 | Use of stronger materials |
| 2. Tensioner Mount | Yielding | Mobility loss | Over tension | 210 | Use of stronger materials |
| 3. Servo Gear | Stripping | Loss of arm controll | High payload | 315 | Use of stronger materials |
| 3. Servo Motor | Overloading | Loss of arm controll | High payload | 630 | Use of stronger materials |
| 3. Servo Mount | Yielding | Loss of arm controll | High payload | 24 | Use of stronger materials |
| 3. Arm Link | Yielding | Loss of arm controll | High payload | 280 | Use of stronger materials |
| 3. Arm Mount | Yielding | Loss of arm controll | High payload | 60 | Use of stronger materials |
| 3. Arm Hand | Yielding | Loss of arm controll | High payload | 60 | Use of stronger materials |
| 3. Arm Wiring | Wearing | Loss of arm controll | Wear from repeated motions | 6 | Secure wires |
| 3. Arduino | Shorting out | Loss of arm controll | Water or high heat | 8 | Ensure enclosure is sealed |
| 3. Servo Wires | Wearing | Loss of arm controll | Wear from repeated motions | 6 | Secure wires |
| 3. Arm Base Plate | Yielding | Loss of arm controll | High payload | 70 | Use of stronger materials |
| 4. Arduino | Shorting out | Loss of arm controll | Water or high heat | 8 | Ensure enclosure is sealed |
| 4. Arduino | Failing | Loss of connection | Electronic failure | 48 | Find maximum range |
| 4. VR | Failing | Loss of connection | Electronic failure | 420 | Find maximum range |
| 4. Unity | Failing | Loss of connection | Electronic failure | 378 | Find maximum range |
| 4. Camera | Failing | Loss of connection | Electronic failure | 336 | Find maximum range |
| 4. Camera Mount | Yielding | Loss of view | Crashing | 18 | Use of stronger materials |
| 4. Unity Code | Breaking | Loss of control | Code bugs | 448 | Code refinement |
| 4. Controller | Disconnection | Loss of control | Electronic failure | 120 | Find maximum range |
| 4. Controller Connection | Failing | Loss of control | Electronic failure | 200 | Find maximum range |
| 4. Camera Body | Yiedling | Loss of view | Crashing | 20 | Use of stronger materials |

Table 6: Shortened FMEA

## *4.1 Critical Failures*

### 4.1.1 Potential Critical Failure 1: Servo Motors Overloading

Having the servo motors overloading entails requiring a force that is too high for that servo motor to be able to handle. This type of failure is mainly caused by trying to pick up an object too heavy and not having enough torque to pick up that item. This can cause problems with the servo motor breaking or simply just not being able to pick up an object. To keep this failure from occurring the team plans to either find a limit that can be coded into the program to keep it from overloading or keep track and safely gauge the amount the arm can safely lift with a healthy factor of safety.

### 4.1.2 Potential Critical Failure 2: Wheel Slip

Wheel slip refers to mainly the driven wheel of the tank track system, it is when the wheel loses traction with the track or the teeth skip along the track and causes the robot to either stop moving completely or with limited mobility. This failure can mainly be caused by a poorly tensioned track, a bad design of wheel, or misaligned teeth. This failure has the effect of limiting the mobility of the entire robot and depending on the severity could cause there to be no mobility. The only true way to mitigate this failure is to properly design a wheel with teeth to grip into the teeth that are on the track and to have an active tensioning system to always ensure adequate tension on the track..

### 4.1.3 Potential Critical Failure 3: Unity Code Errors

Building what is essentially a whole game inside Unity entails a lot of coding and bug testing and that comes with it a ton of potential errors that could easily break and stop working or potentially cause an error that gives off the wrong signal and breaks something on the robot. The main issue with this failure is that sometimes it is almost impossible to detect before it happens since there is a ton of coding and can easily be caused by a missing symbol, letter, or a whole line of code which can all be super easily looked over during coding. A coding failure in Unity can easily cause a misinput which could cause a simple wrong movement or in worst case a signal that could break something around the robot or break something in the robot itself. This failure is one of the more difficult to mitigate since the team can do as much code checking as possible but always miss something small.

### 4.1.4 Potential Critical Failure 4: VR connection Failure

This would be a problem between either the VR headset and the connection to the computer. One of the main occurrences that can be expected to cause this failure is just going out of the connection range between the headset and computer or could be caused by a hardware malfunction. Having the VR headset would be a very obvious failure with an immediate inability to view or control anything on the robot and would most likely cause the VR headset to go into a black screen. Depending on the severity there is a possibility of still being able to control the robot just without the use of VR. The biggest way to ensure this failure does not occur is to ensure the user is within range to either the computer or a receiver connected to the computer and to have high quality connections if the option is available.

### 4.1.5 Potential Critical Failure 5: Unity Connection Failure

A failure involving a Unity connection failure would be if any of the parts of unity fails to connect and causes a problem. This failure can be caused by a multitude of reasons whether it be internet connection, an issue in the coding that causes everything to disconnect, or unity failing to detect a connection. Having unity disconnect can potentially be catastrophic since most if not all of the controls and data goes through unity before going to VR or robot causing a complete inability to do anything.

### 4.1.6 Potential Critical Failure 6: Camera Connection Failure

A camera connection failure is where the camera for whatever reason stops sending video data to the computer. The cause of this failure can be caused by issues such as wires disconnecting, video data getting corrupted while being sent to Unity, or the robot being out of range of the receiver for the computer. This would cause an issue where there is no video feed to be able to see where the robot is at and potentially cause a problem with getting out of an area. The solution is to ensure a strong connection between the camera and computer, the video data getting corrupted does not really have a solution since that can happen for almost no reason at all.

### 4.1.7 Potential Critical Failure 7: Servo Gear Stripping

This failure is where the small gears inside of the servos get the teeth broken off during use. The causes for this failure can be over stressing the small teeth, or can simply be from fatigue of using them frequently. Having the small teeth get stripped off would mainly cause issues where the arm is inaccurate in its location and if severe enough could cause immobility of the arm. The solution is to regularly check the gears inside the servo motors for any signs of damage, replacing the gears with stronger material, or getting stronger motors if the cause is overloading.

### 4.1.8 Potential Critical Failure 8: Arm Link Yielding

Having the arm links yielding would be referring to the failure of either the mid section of link, or the connection between servos and the arm. This failure could be caused in a multitude of ways if the links are 3D printed like they are currently, the link failure can be from the material used, poor printing quality, small defects while printing, or wet filament. The links failing would have an obvious effect on the ability to use the arm and depending on severity can cause the rest of the arm to fall and potentially get run over by the robot during movement causing more issues. The main solution is to ensure high quality links are created, add additional support inside links to ensure stiffness, or make the links beefier.

### 4.1.9 Potential Critical Failure 9: RUT Top Bolts Stripping

This failure refers to the bolts or connection method to keep the top plate mounted to the robot getting stuck or stripped. The cause of this can only be a couple reasons including over torquing the bolt causing either the bolt or nut to be stripped and stuck or cross threaded. This can have the potential of not being able to perform maintenance on the robot and can waste a ton of time to get the bolts off the robot and potentially the nuts as well depending on if those are welded directly to the underside of the plate. This can be prevented by ensuring proper threading or using a torque wrench to ensure that the bolt is not being over torqued.

### 4.1.10 Potential Critical Failure 10: Tensioner Mount Yielding

This refers to the tensioner that would tension the non driven shaft holding the wheels that have the tank tracks rolling around it. This failure can be caused by the spring snapping or coming out of place and can also be caused by the shaft coming out of the mount causing improper tensioning. Having the tensioner fail would cause a huge issue with the mobility of the robot as it can cause the wheels to slip, the track to completely fall off the wheels, or teeth skipping. The solution for this failure is to ensure rigidity of the tensioner system and ensure the springs dont get dislocated on bumps.

## *4.2 Risks and Trade-offs Analysis*

With these failures most of them work with one another in where if one is mitigated it can help with mitigating another, and not many failures where one issue being fixed hinders another issue getting fixed. For example, getting the tensioner system working perfectly would help mitigate the issue of wheel slip massively, or keeping the servo motors from overloading could help mitigate the chance of gears stripping inside of the servos. Another example is with the connection system to connect everything wirelessly, if a high quality connection device is implemented there should be a low chance of having connection issues between parts. In every case regarding the potential failures, fixing one of them or at the very least mitigating their impact if they can not be completely resolved would only end up making a better end product.

# 5 DESIGN SELECTED – First Semester

Listed below is the description following team 1's decision of our first semester "Final Design". Within section 5.1 will be an in-depth description of the final design, engineering calculations completed, 3D models, etc. Within section 5.2 the reader will encounter the future plan of our design.This future plan includes not only the schedule, but also the bill of materials and a detailed explanation of how the schedule is to be followed.

## *5.1 Design Description*

The design of the project is Singular Arm with 3D Camera and Supporting 2D Cameras. Having a singular arm that has a 3D camera with 2D cameras is a great option as it helps mitigate a key issue with having only 2D cameras of which is depth perception. The 3D camera would help in showing the distance between the arm and the object that is being grabbed. With the 3D camera pointing towards the arm and its workspace it can also help with environments that have no light source as the 3D camera has no need for light. It also has the benefit of using the 2D cameras as a way to move around the robot and workspace if there is light.

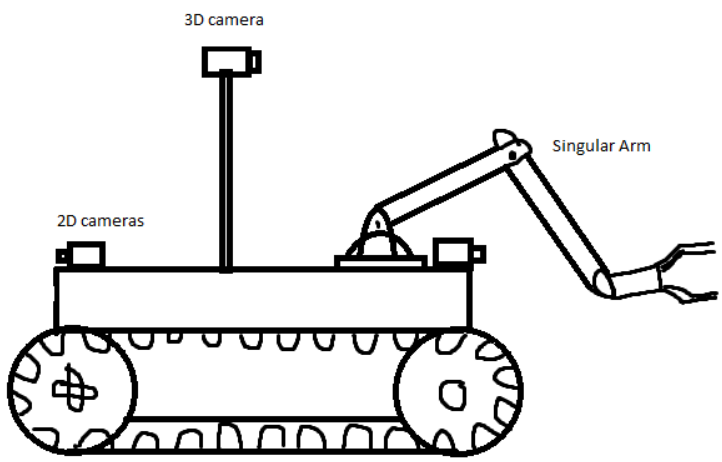


Figure 3: Project Design

### 5.1.1 RUT

RUT comes from a previous capstone project, it uses track for the moving system and is remote controlled by an individual controller. The tank is made of steel and it contains a large space aside from the battery.

Since the preliminary report the RUT has changed quite a bit. The team has moved forward with the design of multiple upgrades for the Robot Utility Tank. Two primary designs are the Roller Bracket and the Traction Wedges.

We add traction wedges on one side of the sprocket and it works well in the test. The original design of RUT had issues in that they glued the sprocket to the bearing, the sprocket fell off due to the reactant force and we might have to redesign the attachment.

According to the suggestions from David Willy, we better redesign the entire sprocket instead of adding wedges directly on one side. The wedge addon design we made now is to test the accessibility of such a way of tracking, and it proves that this kind of design is acceptable in the future.

Also, we designed the tensioner of the track to increase the track tension. It will be added on the sides of the tank body and support the entire tank.

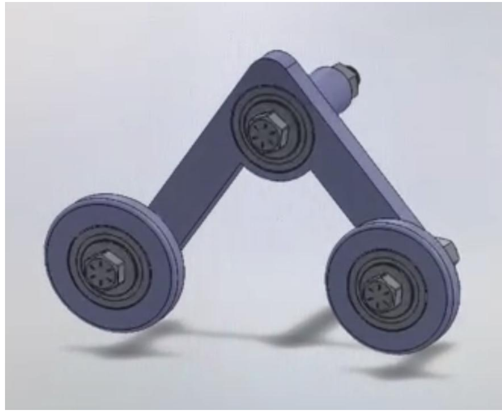

Figure 4: Tensioner CAD model

The figure above is the conceptional tensioner we designed, it is going to test the accessibility of this kind of suspension. We printed an prototype and it is shown in the following figure:

Figure 5: Tensioner Prototype

The conceptual prototype needs to be redesigned for lacking strength. It is used to orientate the proper position for installing tensioners.

In conclusion, we are adding tensioner and redesigning sprockets using the wedge concept to improve mobility.

### 5.1.2 VR Control

Within VR Control lies many small pieces of hardware all working together in order to achieve one goal. Our team's goal was to gain connection to a camera through our main hub Unity. Unity is a game creation software that our team is using to send signals to 1) the VR Headset 2) the Arduino Board 3) the Camera, and 4) the RUT. By doing so we can create a loop connecting all parts of our project together within one software. The VR Control portion specifically is through the use of an Oculus Quest 2.

Figure 6: Oculus Quest 2

This headset will not only control the RUT but also the Robotic Arm. This control connection will be achieved through scripting done in Unity.

Control of the robotic arm is made up of the Unity part and Arduino part. An initializing code needs to be run in arduino first, then it is accessible to build connection from Arduino to Unity.

```
 pinMode(12,OUTPUT);
   digitalWrite(12,HIGH);

 base.attach(11);
 shoulder.attach(10);
 elbow.attach(9);
 wrist_rot.attach(6);
 wrist_ver.attach(5);
 gripper.attach(3);// put your setup code here, to run once:
gripper.write(73);
 shoulder.write(90);
 elbow.write(85);
 wrist_ver.write(90);
 wrist_rot.write(90);
 base.write(0);
```

Figure 7: Initializing Code in Arduino

After initializing Arduino, we use a Unity plugin called Uduino to build a serial portal from Unity to Arduino for Unity does not support Serial.IO.Portal library. Then in Unity, we can access arm using the following C# codes.

```
using UnityEngine;
using System.Collections;
using Uduino;

public class Servo : MonoBehaviour
{
    public int servoPin = 9;
    [Range(15, 165)]
    public int servoAngle = 90;
    private int prevServoAngle = 90;

    void Start()
    {
        UduinoManager.Instance.pinMode(servoPin, PinMode.Servo);
    }

    void Update()
    {
        if (servoAngle != prevServoAngle) // Condition to not send data each frame
        {
            UduinoManager.Instance.analogWrite(servoPin, servoAngle);
            prevServoAngle = servoAngle;
        }
    }
}

```

Figure 8: Unity Codes Accessing Arduino

After we build the serial connection, we need to find the input code from the VR controller and link them together, then it makes the control from the VR controller to the robotic arm.

### 5.1.3 Robotic Arm

Robotic Arm is one of the most important target functions of the project, it is used for grabbing and lifting items. Currently, we keep the Singular Arm design with Braccio++ and we elongated the arm by 3D printing 2 sections in the middle.

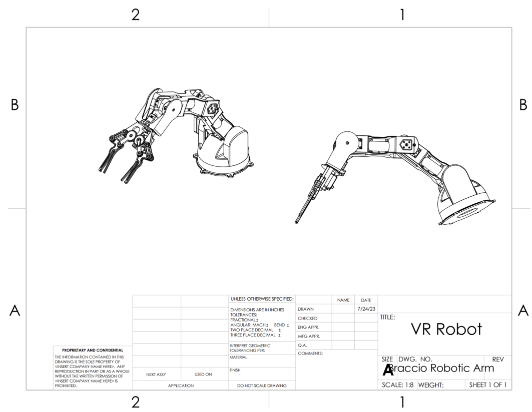


Figure 9: Braccio++ Arm

The picture above is the original 3D model of the arm provided by the company. It is designed to have a degree of freedom of 6. Base chassis is rotating in the horizontal plane, 3 sections making the majority of the arm serving the function of elongating and lifting. According to the Guide of the arm[7], the wrist can twist 90 degrees in both directions. The base is rotatable in 90 degrees in both directions so that is 180 degrees in total.

The arm has a control board fitting the connection to Arduino, power supply one the arm board is necessary when operating.

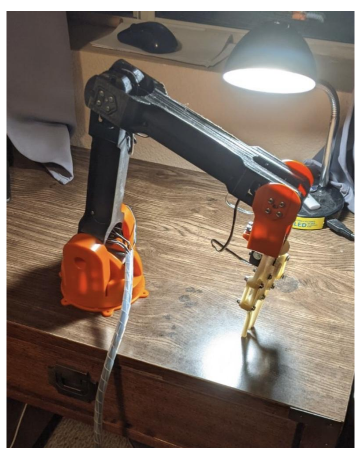

Figure 10: Elongated Arm

The picture above is the elongated arm using 3D printing. We extended the section in the original CAD file then replaced the parts.

For the calculation of maximum net lifting force under the circumstance of maximum range, we have a result of 0.353kg by calculating. The process is provided below:

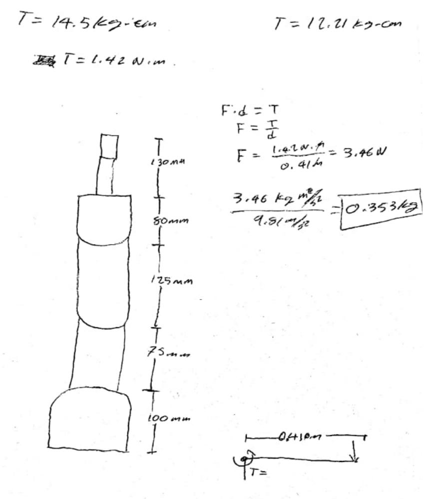


Figure 11: Force Calculation

From the calculation, the supporting force is not enough, we are planning to change the motor in the basis to increase lifting force.

## *5.2 Implementation Plan*

Team 1 plans on implementing our design through a series of proof-of-concept videos as well as a possible prototype. Our team in particular has a lot of subsystems within this project and as such we believe that proving each subsystem works is the key first step to the final product. In order to do so the team has decided to move forward in making proof-of-concept videos. Each of these videos will be directed by the head of each subsection, which goes as follows: **Eric -** VR Control, **Levi -** RUT, **Sam/Tyler/Zijian** - Robotic Arm. Listed below is the full Bill of Materials as well as the future Schedule team 1 has created based on our needs.

| VR Robot Arm | August | September | | | | October | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Week | Week | Week | Week | Week | Week | Week | Week | Week |
| Task | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| *Research Arm Connection* | | | | | | | | | |
| *Research Greater Camera Connection* | | | | | | | | | |
| *Buy Cameras* | | | | | | | | | |
| *Buy Better Servos (IF NECESSARY)* | | | | | | | | | |
| *Print RUT Upgrades* | | | | | | | | | |
| *Get RUT Upgrades Machined* | | | | | | | | | |
| *Test* | | | | | | | | | |

Table 7: Future Schedule 1/2

| November | | | | December | | |
|---|---|---|---|---|---|---|
| Week | Week | Week | Week | Week | Week | Week |
| 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

Table 8: Future Schedule 2/2

| BOM Level | P/N | Part Name | Description | Qty | UOM | Price | Exporter | Purchased Y/N |
|---|---|---|---|---|---|---|---|---|
| 1 | T05000 | Tinkerkit Braccio Robot | A fully operational robotic arm, of which the team has had practice using thanks to generous loaners from the school. | 1 | Each | $100.99 | Arrow | Yes |
| 1 | **899-00182-02** | Oculus Quest 2 | Fully immersive VR headset and controllers. Built for ease of use, and wifi connection friendly. | 1 | Each | $299.99 | Meta Quest | Yes |
| ~~1~~ | ~~OS30A~~ | ~~YDLIDAR 3D Depth Camera~~ | ~~3D camera used to impliment 3D tracking into the Unity game (for VR integration).~~ | ~~1~~ | ~~Each~~ | ~~$139.00~~ | ~~YDLIDAR~~ | No |
| ~~1~~ | ~~TB-3DCAM-8060-USB~~ | ~~Terabee 3Dcam 80x60~~ | ~~3D Camera capable of streaming depth and video footage. This camera is also compatible with direct python interaction, and pre existing softwares for ease of use.~~ | ~~1~~ | ~~Each~~ | ~~$250.00~~ | ~~Terabee~~ | No |
| ~~2~~ | ~~SC15184~~ | ~~Raspberry Pi 4~~ | ~~Small, single board computer designed as a means to connect everything together.~~ | ~~1~~ | ~~Each~~ | ~~$69.90~~ | ~~Amazon~~ | No |
| 2 | M-C2Y-DS13 | Matterhack Pro Series PLA Filament | 1kg Spool of Matterhackers PRO series PLA filament for 3D printing at home. | 1 | Each | $46.67 | Matterhackers | Yes |
| 2 | ABX00021 | Arduino | Small, single board based computer used specifically with the control method of the robot | 1 | Each | $59.94 | Arduino | Yes |
| 3 | N/A | Track Wedge | A wedge 3D printerd with the goal to reduce the reliance on friction between the wheels and the track and to rely more on stress between the track and wheels | 8 | Each | Free | Personal | 3D Printed |
| 3 | N/A | Track Tensioner | A tensioner designed for the RUT with the goal to tension the track, preventing bottomoing out and other issues | 2 | Each | Free | Personal | 3D Printed |

Table 9: Bill of Materials

# 6 CONCLUSIONS

In conclusion the team was able to complete the project to a 64 percent mark. The team was tasked to create an utility robot enabled by a robotic arm that is controlled by VR via wirelessly. Many of the subsystems have been designed and tested as shown in the customer requirements chapter. The team is still researching and developing a system of cameras that will be able to connect to Unity and via wirelessly control the RUT and the arm. Since the camera/VR section was not able to be completed the team will set aside some time next semester to work on the final stages of camera selection. Most of the sub parts of the project need to be assembled together, this is why the team will focus on doing the final assemblies in the fall

Things to look forward to next semester: assemble all parts together including the camera, new machined wheels with traction upgrades, track tensioners, arm connector, and electronic box with an upgrade from previous electronic box.

Once all the items above are assembled the team should be in good shape to present the final and improved project to the faculty. It is important to notice that even at the end of the fall semester there will be some requirements that will not be able to be met due to the restricted budget.

# 7 REFERENCES

[1]"Arduino Coding Reference", https://www.arduino.cc/reference/en/
[2]"Unity Manual", https://docs.unity3d.com/Manual/index.html
[3]"RUT Project", https://ceias.nau.edu/capstone/projects/ME/2022/22Spr01_RobotRE/
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[5]"Camera Measurement Standards," www.imaging.org. https://www.imaging.org/IST/IST/Standards/Camera_Measurement_Standards.aspx#19247 (accessed Jul. 30, 2023).
[6]"Standard Welding Procedure Specifications (SWPS) : Resources : Standards : American Welding Society," www.aws.org. https://www.aws.org/standards/page/standard-welding-procedure-specifications-swps (accessed Jul. 30, 2023).
[7]"Getting Started with the TinkerKit Braccio Robot", https://docs.arduino.cc/retired/getting-started-guides/Braccio
[8] VR Headset https://www.nytimes.com/wirecutter/reviews/best-standalone-vr-headset/

# 8 APPENDICES

## 8.1 Appendix A: FMEA

Product Name: VR Robot

Development Team

Page No. 1 of 1

FMEA Number 1

Date 7/25/23

Subsytems: RUT (1), Track(2), Arm(3), VR System(4)

| Subsystem and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Severity (S) | Potential Causes and Mechanisms of Failure | Occurance (O) | Current Design Controls Test | Detection (D) | RPN | Recommended Action |
|---|---|---|---|---|---|---|---|---|---|
| 1. Frame | Cracking | Mobility loss + further damage | 5 | Crashing | 1 | User training | 10 | 50 | Periodic visual checks |
| 1. Battery | Dying | Power loss | 5 | Failure to charge | 5 | Battery charge | 5 | 125 | Charge after use |
| 1. Motor Controller | Shorting out | Power loss | 5 | Water | 1 | Housing seal | 10 | 50 | Ensure enclosure is sealed |
| 1. Power Switch | Wearing | Power loss | 4 | Overuse | 1 | User feel | 10 | 40 | Replace periodically |
| 1. Lid Attatchment | Bolts Sticking | Inability to access internals | 7 | Overuse | 4 | User training | 10 | 280 | Upgrade hardware |
| 1. Electronics Housing | Leaking | Electronic Failure | 6 | Water | 1 | Seal check | 3 | 18 | Ensure enclosure is sealed |
| 1. Motor Mounts | Yielding | Loss of mobility | 3 | Torque | 2 | Visual Check | 3 | 18 | Periodic visual checks |
| 1. Frame | Bending | Reduction of monility | 3 | Crashing | 1 | Visual Check | 3 | 9 | Periodic visual checks |
| 1. Wheel Shaft Mounts | Yiedling | Loss of mobility | 4 | Crashing | 2 | Visual Check | 3 | 24 | Use of stronger materials |
| 2. Track | Snapping | Mobility loss | 5 | Over tension | 1 | Stretch check | 8 | 40 | Periodic visual checks |
| 2. Drive Wheel | Slipping | Mobility loss | 8 | Not enough tension | 7 | Tension value | 9 | 504 | Use of stronger materials |
| 2. Driven Wheel | Cracking | Mobility loss | 2 | Crashing | 3 | User training | 4 | 24 | Use of stronger materials |
| 2. Drive Wheel Shaft | Twisting | Mobility loss | 3 | Torque | 1 | Visual Check | 2 | 6 | Use of stronger materials |
| 2. Driven Wheel Shaft | Bending | Mobility loss | 3 | Crashing | 1 | Visual Check | 2 | 6 | Use of stronger materials |
| 2. Roller Bracket | Yielding | Mobility loss | 3 | Crashing | 3 | Visual Check | 5 | 45 | Use of stronger materials |
| 2. Roller Wheel | Cracking | Mobility loss | 3 | Crashing | 2 | Visual Check | 4 | 24 | Use of stronger materials |
| 2. Roller Mount | Yielding | Mobility loss | 3 | Crashing | 3 | Visual Check | 4 | 36 | Use of stronger materials |
| 2. Tensioner | Yielding | Mobility loss | 4 | Over tension | 3 | Visual Check | 3 | 36 | Use of stronger materials |
| 2. Tensioner Mount | Yielding | Mobility loss | 7 | Over tension | 3 | Visual Check | 10 | 210 | Use of stronger materials |
| 3. Servo Gear | Stripping | Loss of arm controll | 7 | High payload | 5 | Max force | 9 | 315 | Use of stronger materials |
| 3. Servo Motor | Overloading | Loss of arm controll | 9 | High payload | 7 | Max force | 10 | 630 | Use of stronger materials |
| 3. Servo Mount | Yielding | Loss of arm controll | 4 | High payload | 1 | Max force | 6 | 24 | Use of stronger materials |
| 3. Arm Link | Yielding | Loss of arm controll | 7 | High payload | 5 | Max force | 8 | 280 | Use of stronger materials |
| 3. Arm Mount | Yielding | Loss of arm controll | 5 | High payload | 2 | Max force | 6 | 60 | Use of stronger materials |
| 3. Arm Hand | Yielding | Loss of arm controll | 5 | High payload | 2 | Max force | 6 | 60 | Use of stronger materials |
| 3. Arm Wiring | Wearing | Loss of arm controll | 3 | Wear from repeated motions | 1 | Fatigue test | 2 | 6 | Secure wires |
| 3. Arduino | Shorting out | Loss of arm controll | 4 | Water or high heat | 1 | Seal check | 2 | 8 | Ensure enclosure is sealed |
| 3. Servo Wires | Wearing | Loss of arm controll | 3 | Wear from repeated motions | 1 | Fatigue test | 2 | 6 | Secure wires |
| 3. Arm Base Plate | Yielding | Loss of arm controll | 5 | High payload | 2 | Visual Check | 7 | 70 | Use of stronger materials |
| 4. Arduino | Shorting out | Loss of arm controll | 4 | Water or high heat | 1 | Seal check | 2 | 8 | Ensure enclosure is sealed |
| 4. Arduino | Failing | Loss of connection | 3 | Electronic failure | 4 | Connection tes | 4 | 48 | Find maximum range |
| 4. VR | Failing | Loss of connection | 7 | Electronic failure | 6 | Connection tes | 10 | 420 | Find maximum range |
| 4. Unity | Failing | Loss of connection | 7 | Electronic failure | 6 | Connection tes | 9 | 378 | Find maximum range |
| 4. Camera | Failing | Loss of connection | 7 | Electronic failure | 6 | Connection tes | 8 | 336 | Find maximum range |
| 4. Camera Mount | Yielding | Loss of view | 2 | Crashing | 1 | User training | 9 | 18 | Use of stronger materials |
| 4. Unity Code | Breaking | Loss of control | 8 | Code bugs | 8 | Code test | 7 | 448 | Code refinement |
| 4. Controller | Disconnection | Loss of control | 3 | Electronic failure | 4 | Connection tes | 10 | 120 | Find maximum range |
| 4. Controller Connectio | Failing | Loss of control | 5 | Electronic failure | 4 | Connection tes | 10 | 200 | Find maximum range |
| 4. Camera Body | Yiedling | Loss of view | 2 | Crashing | 1 | User training | 10 | 20 | Use of stronger materials |

Table 1 FMEA

| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Potential Causes and Mechanisms of Failure | RPN | Recommended Action |
|---|---|---|---|---|---|
| 1. Frame | Cracking | Mobility loss + further damage | Crashing | 50 | Periodic visual checks |
| 1. Battery | Dying | Power loss | Failure to charge | 125 | Charge after use |
| 1. Motor Controller | Shorting out | Power loss | Water | 50 | Ensure enclosure is sealed |
| 1. Power Switch | Wearing | Power loss | Overuse | 40 | Replace periodically |
| 1. Lid Attatchment | Bolts Sticking | Inability to access internals | Overuse | 280 | Upgrade hardware |
| 1. Electronics Housing | Leaking | Electronic Failure | Water | 18 | Ensure enclosure is sealed |
| 1. Motor Mounts | Yielding | Loss of mobility | Torque | 18 | Periodic visual checks |
| 1. Frame | Bending | Reduction of monility | Crashing | 9 | Periodic visual checks |
| 1. Wheel Shaft Mounts | Yiedling | Loss of mobility | Crashing | 24 | Use of stronger materials |
| 2. Track | Snapping | Mobility loss | Over tension | 40 | Periodic visual checks |
| 2. Drive Wheel | Slipping | Mobility loss | Not enough tension | 504 | Use of stronger materials |
| 2. Driven Wheel | Cracking | Mobility loss | Crashing | 24 | Use of stronger materials |
| 2. Drive Wheel Shaft | Twisting | Mobility loss | Torque | 6 | Use of stronger materials |
| 2. Driven Wheel Shaft | Bending | Mobility loss | Crashing | 6 | Use of stronger materials |
| 2. Roller Bracket | Yielding | Mobility loss | Crashing | 45 | Use of stronger materials |
| 2. Roller Wheel | Cracking | Mobility loss | Crashing | 24 | Use of stronger materials |
| 2. Roller Mount | Yielding | Mobility loss | Crashing | 36 | Use of stronger materials |
| 2. Tensioner | Yielding | Mobility loss | Over tension | 36 | Use of stronger materials |
| 2. Tensioner Mount | Yielding | Mobility loss | Over tension | 210 | Use of stronger materials |
| 3. Servo Gear | Stripping | Loss of arm controll | High payload | 315 | Use of stronger materials |
| 3. Servo Motor | Overloading | Loss of arm controll | High payload | 630 | Use of stronger materials |
| 3. Servo Mount | Yielding | Loss of arm controll | High payload | 24 | Use of stronger materials |
| 3. Arm Link | Yielding | Loss of arm controll | High payload | 280 | Use of stronger materials |
| 3. Arm Mount | Yielding | Loss of arm controll | High payload | 60 | Use of stronger materials |
| 3. Arm Hand | Yielding | Loss of arm controll | High payload | 60 | Use of stronger materials |
| 3. Arm Wiring | Wearing | Loss of arm controll | Wear from repeated motions | 6 | Secure wires |
| 3. Arduino | Shorting out | Loss of arm controll | Water or high heat | 8 | Ensure enclosure is sealed |
| 3. Servo Wires | Wearing | Loss of arm controll | Wear from repeated motions | 6 | Secure wires |
| 3. Arm Base Plate | Yielding | Loss of arm controll | High payload | 70 | Use of stronger materials |
| 4. Arduino | Shorting out | Loss of arm controll | Water or high heat | 8 | Ensure enclosure is sealed |
| 4. Arduino | Failing | Loss of connection | Electronic failure | 48 | Find maximum range |
| 4. VR | Failing | Loss of connection | Electronic failure | 420 | Find maximum range |
| 4. Unity | Failing | Loss of connection | Electronic failure | 378 | Find maximum range |
| 4. Camera | Failing | Loss of connection | Electronic failure | 336 | Find maximum range |
| 4. Camera Mount | Yielding | Loss of view | Crashing | 18 | Use of stronger materials |
| 4. Unity Code | Breaking | Loss of control | Code bugs | 448 | Code refinement |
| 4. Controller | Disconnection | Loss of control | Electronic failure | 120 | Find maximum range |
| 4. Controller Connection | Failing | Loss of control | Electronic failure | 200 | Find maximum range |
| 4. Camera Body | Yiedling | Loss of view | Crashing | 20 | Use of stronger materials |

Table 2 Shortened FMEA

## 8.2 Appendix B: House of Quality

**System QFD**

**Project:** VR Robot
**Date:** 07-06-23

| | Decreased Turn Time | Increased Torque Advangtage | Low Program Speed | Low Latency | Increase Robotic Arm Length | High Network Speed | High Material Strength |
|---|---|---|---|---|---|---|---|
| Decreased Turn Time | | | | | | | |
| Increased Torque Advangtage | + | | | | | | |
| Low Program Speed | | | | | | | |
| Low Latency | | | - | | | | |
| Increase Robotic Arm Length | | - | | | | | |
| High Network Speed | | | - | - | | | |
| High Material Strength | | | | | + | | |

Legend
A CALIBER Mk3 EOD
B Andros F6
C Wheelbarrow MK9

| Customer Needs | Customer Weights (1-5) | Decreased Turn Time | Increased Torque Advangtage | Low Program Speed | Low Latency | Increase Robotic Arm Length | High Network Speed | High Material Strength | 1 Poor | 2 | 3 Acceptable | 4 | 5 Excellent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cost Within Budget | 4 | | 6 | 4 | 8 | 4 | 6 | 4 | ABC | | | | |
| Durable and Robust Design | 3 | 4 | 6 | | | | | 4 | | | | | ABC |
| Reliable Design | 3 | 6 | 6 | 4 | | | 4 | 6 | | | | | ABC |
| Safe to Operate | 4 | | | 6 | | | | 4 | | | BC | | |
| Move in 3D | 1 | 5 | 1 | | | | | | | | | | ABC |
| Large Work Space | 2 | 3 | | | | 9 | | | | | | | ABC |
| Uniform Continuous Force Capacity | 2 | | 5 | 2 | | | | | | | | | ABC |
| High Mechanical Stiffness | 2 | | 3 | | | | | 3 | | | | | ABC |
| High Resolution Sensing | 4 | | | | 6 | | 8 | | | A | | | BC |
| Low-Latency Communications | 3 | | | 3 | 7 | | 8 | | | | AB | C | |
| Fast Update Rate | 3 | | | 8 | 5 | | 8 | | | | A | BC | |
| **Technical Requirement Units** | | Seconds | Newtons | Seconds | ms | m | Mb | GPa | | | | | |
| **Technical Requirement Targets** | | 10 | 5< | 0.5 | 50 | 0.5 | 30 | 55 | | | | | |
| **Absolute Technical Importance** | | 41 | 69 | 89 | 92 | 30 | 116 | 68 | | | | | |
| **Relative Technical Importance** | | 6 | 4 | 3 | 2 | 7 | 1 | 5 | | | | | |

Table 3: House of Quality