

# **Remote, Underground Powervault Inspection Robot**

ECE 4011 Senior Design Project

Team P.V.I.R.

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## **Executive Summary**

P.V.I.R is a remotely operated, recon robot that uses non-destructive testing methods (NDT) to retrieve information from powervaults. P.V.I.R will consist of a water-tight aluminum body for movement, a mechanical arm for positioning the camera and other sensors, a sensor package to retrieve information in the powervault, and a user interface for interacting with the robot. The robot must be able to read gauges in a poorly lit environment, and relay information to a remote server. The base of the robot has been built by a previous mechanical team. This project will focus on designing and implementing the sensor package, the control system, and the data collection and display system of the robot. A mechanical arm will support the camera and other sensors.

P.V.I.R is designed to be used to gather information in situations where powervaults are not safe for humans to enter. The pilot of the P.V.I.R can inspect the powervault without putting themselves in a dangerous situation. The P.V.I.R has visual sensing capability for reading gauges in the powervault, audio sensing to record high voltage, electrical discharge, gas sensors to test air quality, and an RGB-D sensor to map the terrain of the powervault. The P.V.I.R will be controlled remotely by a user interface program that runs on a computer or tablet. The program will also organize and record the information received.

The total price of all the components used in design are approximated to be around \$755. Some of the sensors and microcontrollers used in this project are legacy parts and are do not contribute to the actual cost of development. The cost of parts for the robot is around \$420 with room left over for shipping cost and tax. P.V.I.R will be sold for \$1750.

# **Powervault Inspection Robot**

## **1. Introduction**

Team P.V.I.R is designing a power vault inspection robot. The team is requesting \$500 from Georgia Institute of Technology - College of Electrical and Computer Engineering. The \$500 will be used to develop a sensor package, a control GUI, and a mechanical arm to be used by a vault inspection team.

### **1.1 Objective**

The objective of P.V.I.R is to evaluate the environment of a transformer vault. This will reduce the risk that workers have to take while doing routine inspections. P.V.I.R is a durable and easy to control, mobile, recon robot that gathers information specific to power vaults. It will retrieve and display visual data, infrared data, data concerning air quality, and spatial mapping. The main body of the powervault inspection robot was designed by a previous team. This project will focus on designing and building the sensor package, the software package and the mechanical arm that supports the sensor package.

### **1.2 Motivation**

The motivation behind P.V.I.R consists of a need to speed up the downtime of the power grid due to repairs and to minimize the likelihood of injuries for utility workers in a dangerous environment. An inspection robot will cut down the number of workers hurt while on the job. In 2016, the number of fatalities on the job was 5,190 people [1]. This is an average of about 14 people a day. Inspection robots will help utility workers understand and troubleshoot problems in a safer and more efficient manner. Previous senior design teams and the EPRI have designed and tested robot vehicles that navigate in underground vaults [2]. Underground inspection robot designers are aware that the end users are utility workers with prior experience performing vault

inspections and scheduled maintenance routines. Both of these procedures require different types of information that will be expected from the robot. The improvements offered by our design include a more efficient and convenient means of communication from the user to the robot, as well as, a more enjoyable user interface by including a VR headset and a tablet.

### **1.3 Background**

Previous groups have completed a few tasks related to our project. More than one form of mobile robot can survey a powervault, ranging from watertight treaded vehicles to aerial drones. Each of these iterations were tested and some were equipped with control systems and sensor packages. This provided the group with the option of either building a robot from scratch or starting with a pre-existing robot as a base, which is an essential building block. The pre-existing robot bodies were intended to be waterproof, dust resistant, and durable on uneven terrains. The current tasks of the group are based on a continued design problem to create a suitable, tele-operated, mobile robot to survey power vaults of varying sizes and conditions. These conditions include but are not limited to varying vault dimensions, gas content, standing water levels, and varying locations of instrument gauges in the vault. A starting point already exists regarding the project, but the team will be focused on developing the sensor package, setting up an efficient control system, developing a servo arm. The servo arm can adjust the height for the camera to read the gauges accurately. A novel concept unique to our design is incorporating a virtual reality headset to enable a real-time viewing mode for the user. The final design solution is imagined to be a two person system with one operator and one observer, since most power vault inspections are typically two person endeavors due to safety regulations.

## 2. Project Description and Goals

The team will be prototyping a sensor package, software package and a mechanical arm. The sensor package will contain an IR camera, gas, temperature, humidity, and air quality sensors. A camera will be anchored on a mechanical arm which will be able to move vertically and rotate 360°. A microphone will be used to pick up possible corona in the transformer vault. All of the sensor data will be displayed on a control GUI that the team is also developing. This GUI will be displayable on a tablet or laptop. The GUI will display all important information desired by the utility workers operating P.V.I.R to optimize the power vault procedure efficiency by providing quick access to data for educated decisions and improvised actions.

The goals for the project are as follows:

- Create an efficient sensor setup to take necessary readings in the power vault.
- Build a motor powered arm that is attached to the top of the robot, which allows the sensor setup to be raised and lowered to the required height.
- Program a control system that manages the motor speed and maneuverability in an easily understood and secure manner that functions through a user interface an operator can interact with on a PC.
- Integrate a virtual reality experience that runs in real time to provide the observer up to date visual feeds of the robot's point of view.

The total estimated cost for this project is around \$264,000. This accounts for the cost of labor of five engineers working on average of eight hours a week each for 16 weeks, the costs of the hardware purchased, and the cost of the website creation. This is interpreted as if these are research and development engineers since the solution would implemented many times over by

the company. The main audience for this design solution would be utility companies such as Georgia Power.

### 3. Technical Specifications

Table 1. Mechanical Arm Specifications

Mechanical Arm Specs	
<u>Feature</u>	<u>Specification</u>
Height	Variable height from 1 - 6 feet
Degrees of Freedom	2 degrees of rotation
Size	Fits in a 1.5 Meter Diameter Manhole
Weight	Dependent on Material

Table 2. Sensor Package Specifications

Sensor Package Specs	
<u>Feature</u>	<u>Specification</u>
Video	Can Stream Video to GUI
Gas Sensor	Check Air Quality
IR Thermal Camera	Record Thermal Images

Table 3. SLAM Specifications

SLAM Specs	
<u>Feature</u>	<u>Specification</u>
Real-Time	Generates Real-Time 3D Map

Table 4. GUI Specifications.

GUI Specs	
<u>Feature</u>	<u>Specification</u>
Mobile	Able to be Used on Mobile Platforms
Control Capabilities	Able to Remotely Control the Robot
Logging	Able to Log Information
Data Streaming	Real-Time Data Streaming

## 4. Design Approach and Details

### 4.1 Design Approach

The GUI design has a number of avenues that can be pursued. The GUI will have a video display window surrounded by cards that display the sensor information. Data can be logged over time and saved for future viewing. The main programming scripts considered are Python, C# or Matlab's App Designer. Each option has pros and cons that are worth exploring. C# and App Designer have an easy to use, drag and drop builder that will make organizing the GUI easier. Kivy is a Python library that naturally runs multiple functions in parallel and compartmentalizes each section of the GUI. Kivy also can be exported as an android or IOS app, making this option compatible with mobile phones and tablets. This is very important to the desired use of the GUI because tablets and phones are more user friendly for field application due to their portability. Python also has a large volume of libraries that can be used alongside kivy to make the overall program more versatile and dynamic. Matlab's App Designer has better capacity for graphing charts in 2D and 3D.



The critical path of the GUI design is the communication design. Each of the programming scripts mentioned above are built to make the graphical portion of design easier. The difficulty comes from the organization and prioritization of data being sent to the main program. The program will utilize TCP/IP to send and receive information securely. The GUI design described above allows for the information to be processed and organized by the Raspberry Pi before sending to the GUI. In order to reduce the difficulty of this task, smaller, less complicated, tasks are prototyped to prove a method. These methods will be used to code the final program. This will reduce the amount of time spent on debugging the full program. All options have similar capabilities when it comes to the layout of the program.

Figures 1, 2, 3, and 4 below shows the current layout concepts of the GUI. Figures 1, and 2 are implemented in the Python language. Figure 1 shows a login page. This will be used to add a layer of security to the controls of the robot.

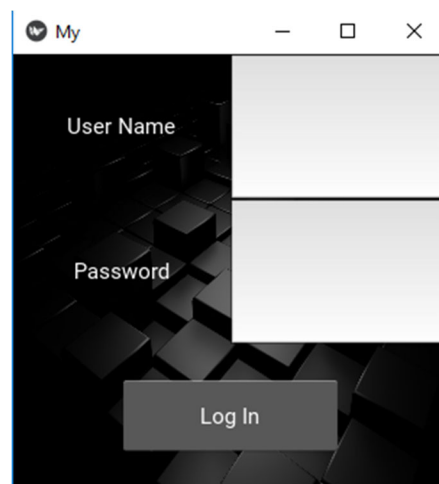


Figure 1. Login page of GUI.

Figure 2 shows the main page which will be displayed following the login page. The main page will mostly consist of the video feed from the robot. On the peripherals of the main page are live values from P.V.I.R's sensors. Each page will have access to a side menu that will

be used to navigate between pages. Figure 3 shows how the navigation tab will look over the current page. This has not yet been built in the prototype.

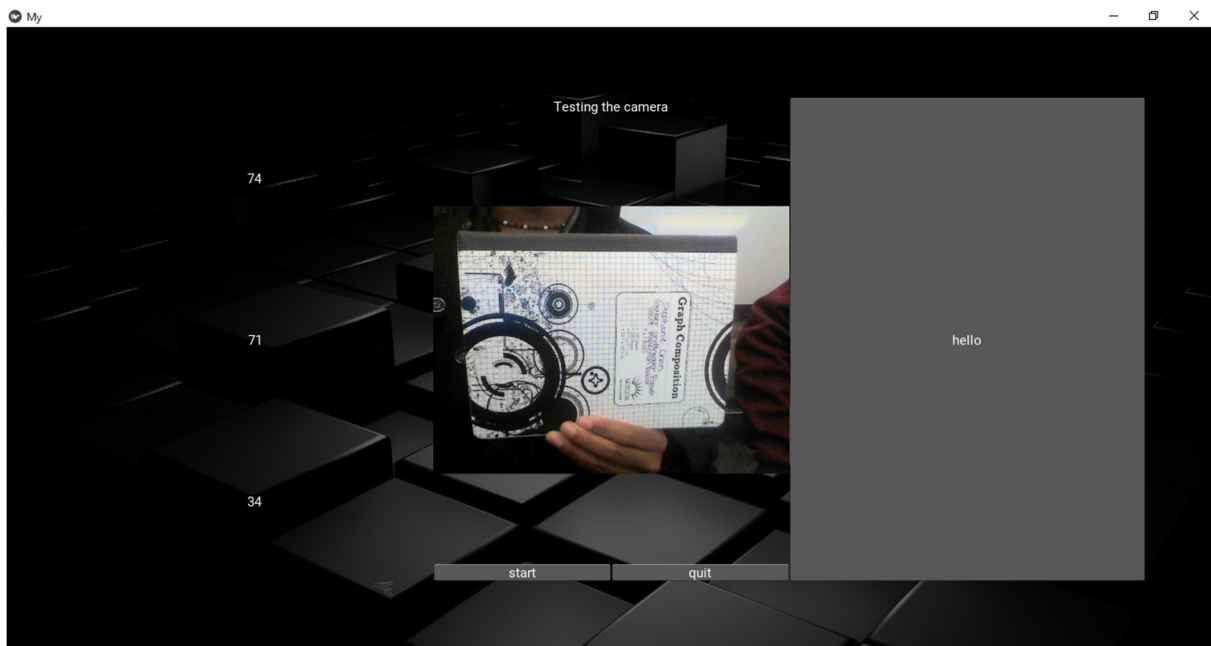


Figure 2. Main Page of GUI.

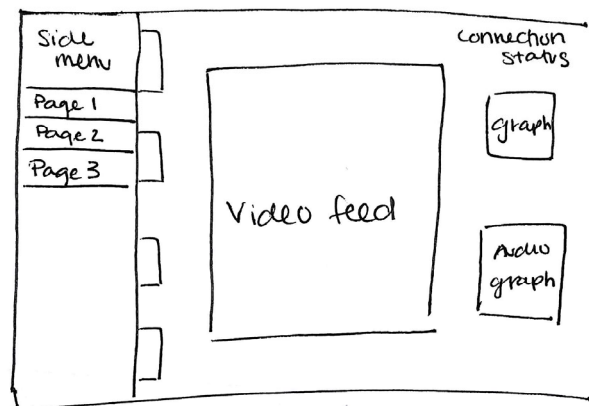


Figure 3. Main page of GUI with side menu displayed.

Lastly, Figure 4 shows an additional page that will allow the user to view time plots of sensor data in more detail. This has not been prototyped in Python yet.

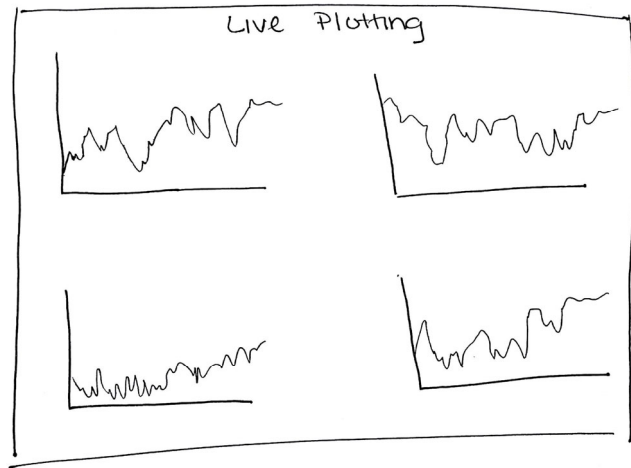


Figure 4. Additional live plotting page of GUI.

The team is considering the use of T-slots for the mechanical arm on which the camera and sensor package will be mounted. A rough design sketch of this setup is shown in Figure 5. A CAD drawing for this has been started. The mechanical arm will consist of two t-slot bars mounted on a platform with a servo attached at the base to rotate the arm 360°. The camera and sensor package will be attached on a platform between the two bars. Servos will be attached on the sides of the platform so the user has the ability to tilt the camera up and down. A scissor lift design also is being taken into consideration because a condensed lift will be more stable while the robot is in motion.

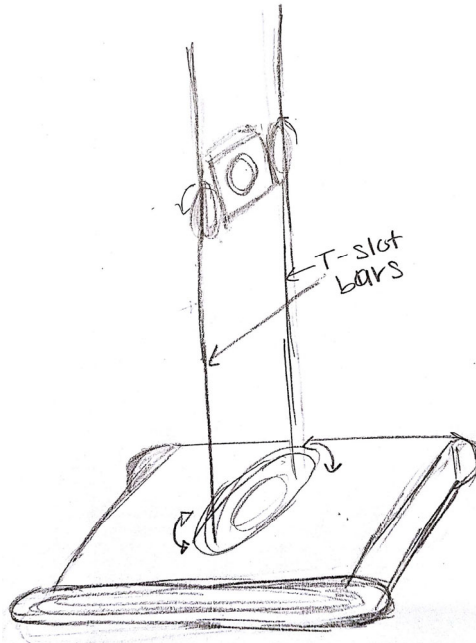


Figure 5. Design sketch showing mechanical arm connection and servos using t-slots.

When designing the hardware set up of the robot, the team created 4 iterations of a connection diagram. The team will be taking the approach that utilizes both the Arduino and Raspberry Pi along with the VR headset and sensor package mentioned prior as shown in Figure 6. The iterations that are not used are shown and discussed in section 4.3 of this project proposal. A few things are being tested to verify the feasibility of our design: OpenCV use on a Raspberry Pi, camera type selection for the use of OpenCV with Raspberry Pi, and interfacing a microcontroller that uses C++ to operate with the Raspberry Pi. These have yielded the following outcomes. Using OpenCV on a Raspberry Pi is possible, but requires a large amount of space on the microSD that serves as the boot disk for the microcontroller, thus requiring the user to adjust the partition and remove many large libraries that will be unnecessary in the project. Webcam integration with a Raspberry Pi via USB hub is possible, but the stream rate has an extreme amount of latency and would cause the system to be slightly behind for the observer versus the remote operator. A Pi camera functions better, but when dealing with the conditions in the vault

the Pi camera does not have a very large chance of surviving without a protective casing, thus a GoPro has been considered. This may cause the original problem to reoccur due to the GoPro not being designed for a Raspberry Pi. Interfacing the Raspberry Pi with a microcontroller that runs C++ is definitely possible already via a serial connection using a master slave connection. There are a lot of pre-existing examples. The aspects of the project left to verify are the interfacing the Tango Tablet with the Raspberry Pi, integrating the VR apparatus with the Raspberry Pi and threading all of these processes together so the design parts can operate in parallel.

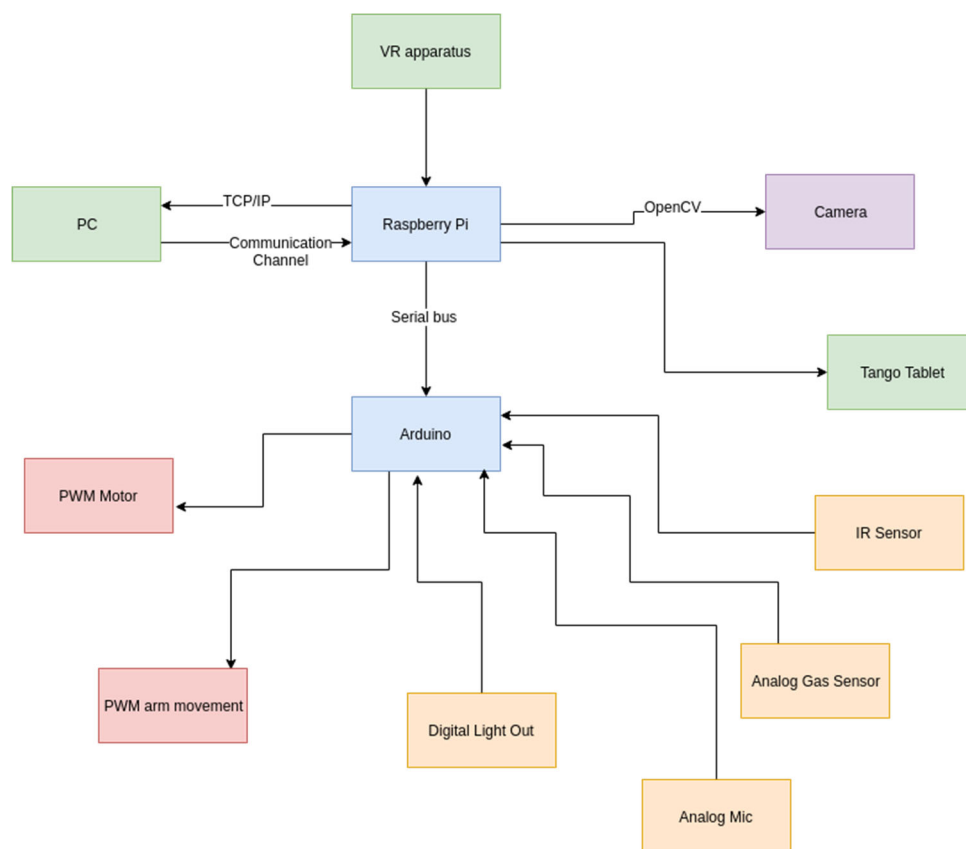


Figure 6. Hardware setup for the proposed design solution.

## **4.2 Codes and Standards**

### **1. Ethernet: IEEE 802.3**

- a. This standard ensures that the ethernet ports for the robot's microprocessor and the machine the application is running on are compatible [3]. This includes TCP/IP protocols.
- b. It also standardizes the speed of communication between the devices [3].

### **2. Wireless: IEEE 802.11**

- a. This standard ensures wireless local area network (WLAN) communication between separate systems are compatible [4].

### **3. Serial Bus Communication: RS-232, RS-422 and RS-485**

- a. RS-232 is the oldest and most widely used serial communication protocol and is used in most laptop serial interfaces. RS-232 was developed in 1962 [5].
- b. RS-422 and RS-485 are newer and faster communication protocols [5].

### **4. I<sup>2</sup>C Protocol**

- a. This standard ensures a specific serial bus master slave protocols works between devices [6].
  - i. This makes it easier to send complex information between multiple processors by putting one in charge of the others while only using 2 wires [6].

### **5. USB 1.1 2.0, 3.0/3.1**

- a. USB 1.1 was the first edition of the USB standard, developed in 1988. Since then, the standard has been upgraded to 2.0 and 3.0/3.1 which have faster speeds [7].
- b. This allows for universal ports that enable communication.

### 4.3 Constraints, Alternatives, and Tradeoffs

Three alternative designs that had varying interactions between microcontrollers, sensors, and the user were considered and pros and cons were compared. One of the designs ruled out has every device and every I/O of the system had to go through a single Raspberry Pi as shown in Figure 7. While the exclusion of the Arduino microcontroller implied one less communication platform to worry about, there were a few trade-offs. Major trade-offs with this approach were that Python was the main programming language, which not many of us are familiar with. Only one device controlling all aspects of the robot increases the concern for scheduling parallel work. Furthermore, an ADC would have been necessary to receive input from the analog sensors.

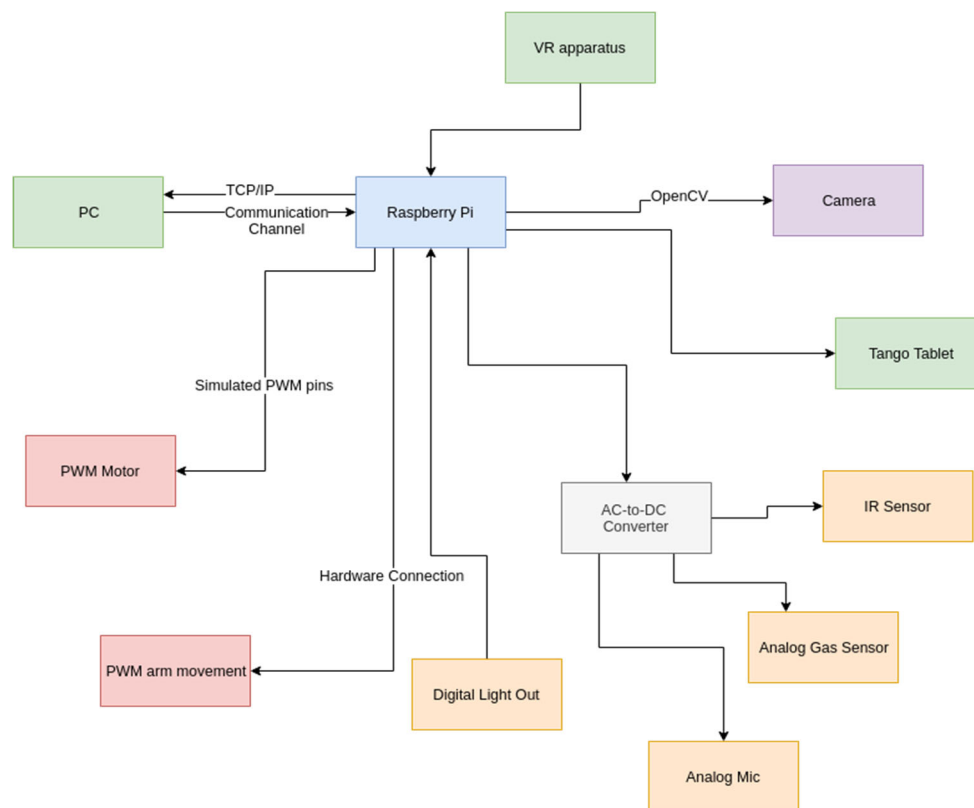


Figure 7. Second iteration showing all connections going through a single Pi.

Another design iteration not selected utilizes both the Raspberry Pi and the Arduino like the chosen iteration in section 4.1 of the project proposal. In this iteration, the VR headset was

not included. This iteration is shown in Figure 8. It should be noted that the VR headset will require more labor as another device and user interface will need to be designed and coded. This will result in a higher overall cost. The trade-off from the exclusion of the VR headset was the novelty brought by the virtual experience from the VR headset.

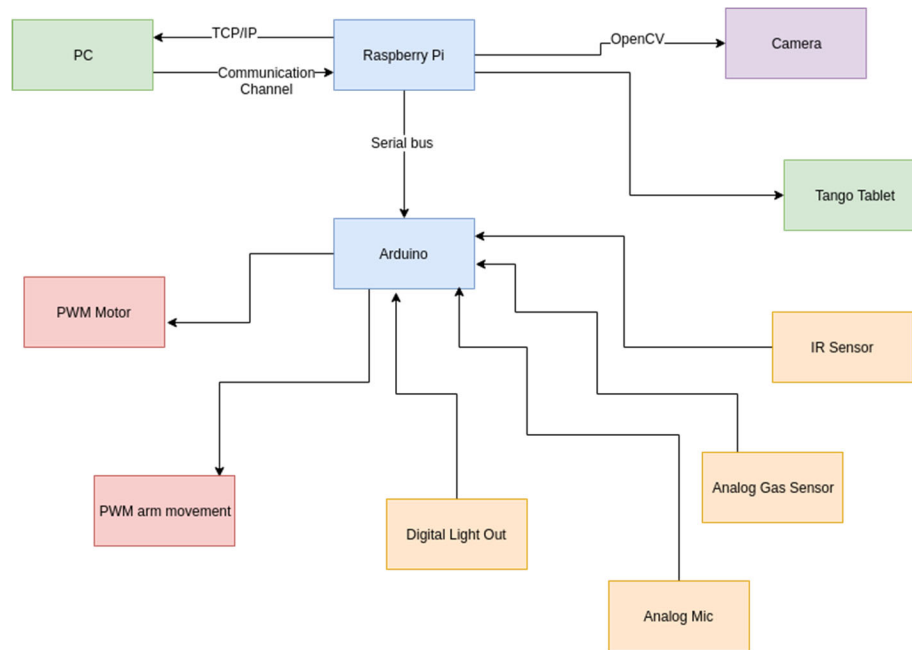


Figure 8. Third iteration showing all connections going using a Pi and Arduino without VR.

The last design iteration not selected has a single Raspberry Pi controlling every aspect of the project much like the iteration shown above in Figure 7. The difference is that the VR headset is not included in this design shown in Figure 9. Once again, the major trade-off from this approach is a high dependability on the Raspberry Pi.



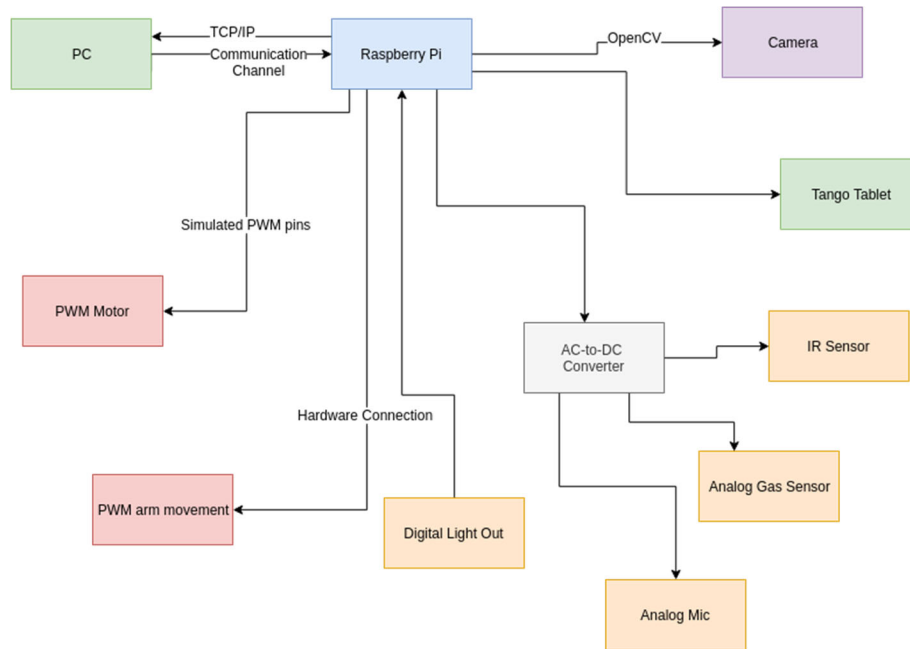


Figure 9. Second iteration showing all connections going through a single Pi without VR.

Constraints limiting the design options and the overall robot performance were the robot size cannot exceed the size of the manhole. The limited budget to purchase parts limiting our freedom to buy higher quality parts with perhaps better performance, which also limits our ability to buy extra accessories for the robot. The robot needs to be flexible and intuitive for the user which implies that the user interface needs to be accessible without a steep learning curve for non-technical utility workers. Robustness, waterproof capabilities, and wireless communication through walls were other major constraints taken into consideration primarily due to obstacles on the ground and the hazardous environment P.V.I.R. will be exposed to. These constraints were driving motives to lower the robot at the manhole and use an antenna as a means of wireless communication between the robot and the manhole location.

## **5. Schedule, Tasks, and Milestones**

We've begun the CAD design of the robot and the different software components and it will be modified until the end of the semester, and resume next semester when the actual implementation starts in January 2019. Appendix A contains the Gantt chart with an estimated timeline of project milestones. The Gantt chart lists break down of the milestones including the designing, planning, building and testing of the mechanical arm, sensor package, and user interface. The Gantt chart shows the start time, end time, and duration of all of the tasks.

Appendix B includes a PERT chart that identifies the critical path. The tasks included in the critical path are associated with the development and testing of the software needed for the amplifier. The tasks that include software are more at risk because the team's skill set is more competent in hardware compared to software and will require more time. Appendix C contains a table that lists the tasks that are to be completed and serves as a key for the PERT chart in Appendix B.

## **6. Project Demonstration**

Our Senior Design Expo will be demonstrated using a two-part approach. The first part will be to test P.V.I.R. at Bunker-Henry Transformer Vault under field conditions where practical variables will be assessed. The different tests will be video-recorded and will be available as a visual proof at our final Design Expo. The next part of the demonstration will be to test the robot the day of the Expo and have it perform specific tasks to test the user interface and the different design requirements.

## **7. Marketing and Cost Analysis**

### **7.1 Marketing Analysis**

Robots and drones are becoming a more popular option for industrial inspection [8]. Regular inspection is important to maintain equipment and worker safety. Many robots today can inspect pipeline, buildings, equipment, and more. Because of modern day technology inspection robots are faster and more efficient than the average utility worker. They are safer because the utility worker will no longer have to go into a power vault or other potentially dangerous environments. AETOS, GE Inspection Robotics, and Honeybee Robotics are in the top companies in the inspection robot market [9]. Currently AETOS has a wide range of unmanned land inspection robots. Their robots are equipped with different types of sensors and imaging technology that can inspect for corrosion, cracks, defects and other damages [10]. The AETOS robot uses nondestructive testing (NDT) methods and can be configured to conduct different types of land based inspections, specifically for oil and gas, petrochemical, and infrastructure. Like the AETOS robot, P.V.I.R also utilizes many different sensors and imaging systems for inspection. The AETOS website does not list the different sensor capabilities but P.V.I.R uses gas sensors, infrared array sensors, sound sensors, a camera and a RGB-D camera for inspection. P.V.I.R also uses NDT methods to inspect the power vault. Unlike the AETOS land robot, P.V.I.R is not unmanned and is instead controlled using a gaming system controller. This allows the utility worker to have full control over what they want to see in the power vault and where they want to drive it. Additionally, while the AETOS land robot can be configured for different types of inspections, the P.V.I.R is designed specifically for the utility workers to inspect the power vaults that they are working in and to ensure that they are in a safe work environment.

## 7.2 Cost Analysis

The P.V.I.R is made up of three parts, a robot base, a mechanical arm, and a sensor package. For the purposes of this project, the cost of the robot base development is not accounted for because the base was developed by a previous team. The needed components for the development of the mechanical arm and sensor package is shown in Table 5. The prices for the microcontrollers, webcam, tango tablet, and microphone are estimated prices as these part will be procured from Dr. Mick West Robotics Laboratory. The total cost column in Table 5 show the cost to the P.V.I.R team without having to purchase the obtained items.

Table 5. Individual Component Cost

Type	Item	Qty	Unit Price	Total Cost
Microcontroller	Raspberry Pi 3	2	\$35.75	\$0.00
Microcontroller	Arduino Uno	2	\$16.90	\$0.00
Sensor	Arduino Gas Sensor	1	\$8.50	\$8.50
Sensor	Adafruit HTU21D-F Temperature & Humidity Sensor Breakout Board	1	\$14.95	\$14.95
Sensor	Adafruit SGP30 Air Quality Sensor Breakout - VOC and eCO2	1	\$19.95	\$19.95
Video	Logitech Webcam 920c	1	\$44.95	\$0.00
Video	Tango Tablet	1	\$180.00	\$0.00
Video	ADAFRUIT AMG8833 IR THERMAL CAMERA	1	\$39.95	\$39.95
Video	Google Daydream View - VR Headset (Slate)	1	\$41.00	\$41.00
Audio	AMP Microphone Audio Evaluation Board	1	\$6.95	\$0.00
Comms	200ft Ethernet cord	1	\$15.95	\$15.95
Comms	Hawking Hi-Gain Wireless-AC Network Upgrade - Wireless Access Point	1	\$39.99	\$39.99
Light Source	Chromo Inc Macro Ring 48 LED Power Light	1	\$29.98	\$29.98
Power Source	Duracell Ultra 12V 1.3AH AGM SLA Battery with F1 Terminal	2	\$21.99	\$43.98
Motors	Greartisan DC 12V 120RPM Gear Motor High Torque Electric Micro Speed Reduction Geared Motor Eccentric Output Shaft 37mm Diameter Gearbox	2	\$14.99	\$29.98
Servo Motors	Parallax Inc 900-00008	3	\$13.99	\$41.97
Testing	Jumper Wires Male to Male, Solderless Breadboard and Arduino	1	\$7.89	\$7.89
Testing	Breadboard Solderless - 3 ct 400 Pin with 4 Power Rails for Arduino and Pi	1	\$7.99	\$7.99
Mechanical Arm	T-Slots Bars 500mm 4pc set	2	\$29.99	\$59.98
Mechanical Arm	T-Slots nuts and connectors 4pc set	2	\$7.99	\$15.98
<b>Total Estimated Price</b>			<b>\$755.24</b>	
<b>Total Cost</b>				<b>\$418.04</b>

The total cost of labor shown in Table 6 was determined with an assumed salary of \$60,000 per engineer. This gives an average of \$28.85 per hour. Assuming an engineer is working the typical 40 hour work week for 12 weeks, the total number of hours worked will be 480 hours. This gives a total cost of labor to be \$13,848.00.

Table 6. Total Labor Hours and Cost per Engineer

Project Areas	Labor Hours	Labor Cost
<b>Project Design</b>		
Hardware Design	20	\$577.00
Software Design	80	\$2,308.00
Mechanical Arm Design	15	\$432.75
<b>Build and Testing</b>		
Debugging	60	\$1,731.00
Mechanical Arm Build	20	\$577.00
Control System Build	10	\$288.50
Testing	90	\$2,596.50
Robot Assembly	30	\$865.50
<b>Demo Preparation</b>		
Presentation	3	\$86.55
Reports and Proposal	10	\$288.50
Website	40	\$1,154.00
<b>Weekly Group Meetings and Lab time</b>	102	\$2,942.70
<b>Total Labor Cost</b>	480	<b>\$13,848.00</b>

The development cost shown in Table 7 is calculated using 30% of the total labor cost as the fringe benefit and 120% of materials and labor as the overhead. The total development cost comes out to be \$264,449.73.

Table 7. Development Cost

	Cost
<b>Parts</b>	\$418.04
<b>Labor</b>	\$69,240.00
Fringe Benfits	\$20,772.00
Subtotal	\$90,430.04
Overhead %	\$83,589.65
<b>Total</b>	<b>\$264,449.73</b>

Over a 5-year period, there will be 4,950 units produced and sold. This number is chosen because there are about 3,300 power utility companies in the United States [11] and it is assumed that the average number robots per company is 1.5. The components that make up the sensor package and mechanical arm can be bought in bulk for a discounted price of \$400 per unit. The manufacturing employees will be paid \$15 an hour to assemble the robot. The engineers responsible for testing the robot will be paid \$28 an hour. The sales expense will make up 10%

of the final selling price of \$1,750. This selling price is competitive with other inspection robots on market currently. SuperDroid Robots have an inspection robot with the cost of \$1,836 [12]. As shown in Table 8, the estimated profit per unit is \$295.56. This is calculated with fringe benefits being 30% of labor and overhead being 120% of labor, materials, and fringe benefits. The estimated amortized development cost is \$25. Over a 5-year period, the total profit will be \$1,463,022.00.

Table 8. Selling Price and Profit per unit with 5-year profit for 4950 units

	Cost
<b>Parts Cost</b>	<b>\$400.00</b>
<b>Assembly Labor</b>	<b>\$60.00</b>
<b>Testing Labor</b>	<b>\$14.00</b>
<b>Total Labor</b>	<b>\$74.00</b>
Fringe Benefits, % of Labor	\$22.20
Subtotal	\$570.20
Overhead, % of Material, Labor, & Fringe Benefits	\$684.24
Subtotal, Input Costs	\$1,254.44
Sales Expense	\$175.00
Amortized Development Costs	\$25.00
Subtotal, All Costs	\$1,454.44
Profit	\$295.56
<b>Selling Price</b>	<b>\$1,750.00</b>
<b>5-Year Profit</b>	<b>\$1,463,022.00</b>

## 8. Current Status

The various parts and components for the project have been determined and listed in a bill of materials. We have decided on a set-up for the two microcontrollers and the peripheral connections. Task A, as listed in Appendix C, the design and development of the GUI, has begun. Currently, the GUI shows a working login page and can access the camera and display a live camera feed. Task B, scrapping previous robots, is 100% complete. Additionally, the mechanical arm CAD design has started. The remaining tasks from Appendix C has not been started at this time.

## 9. References

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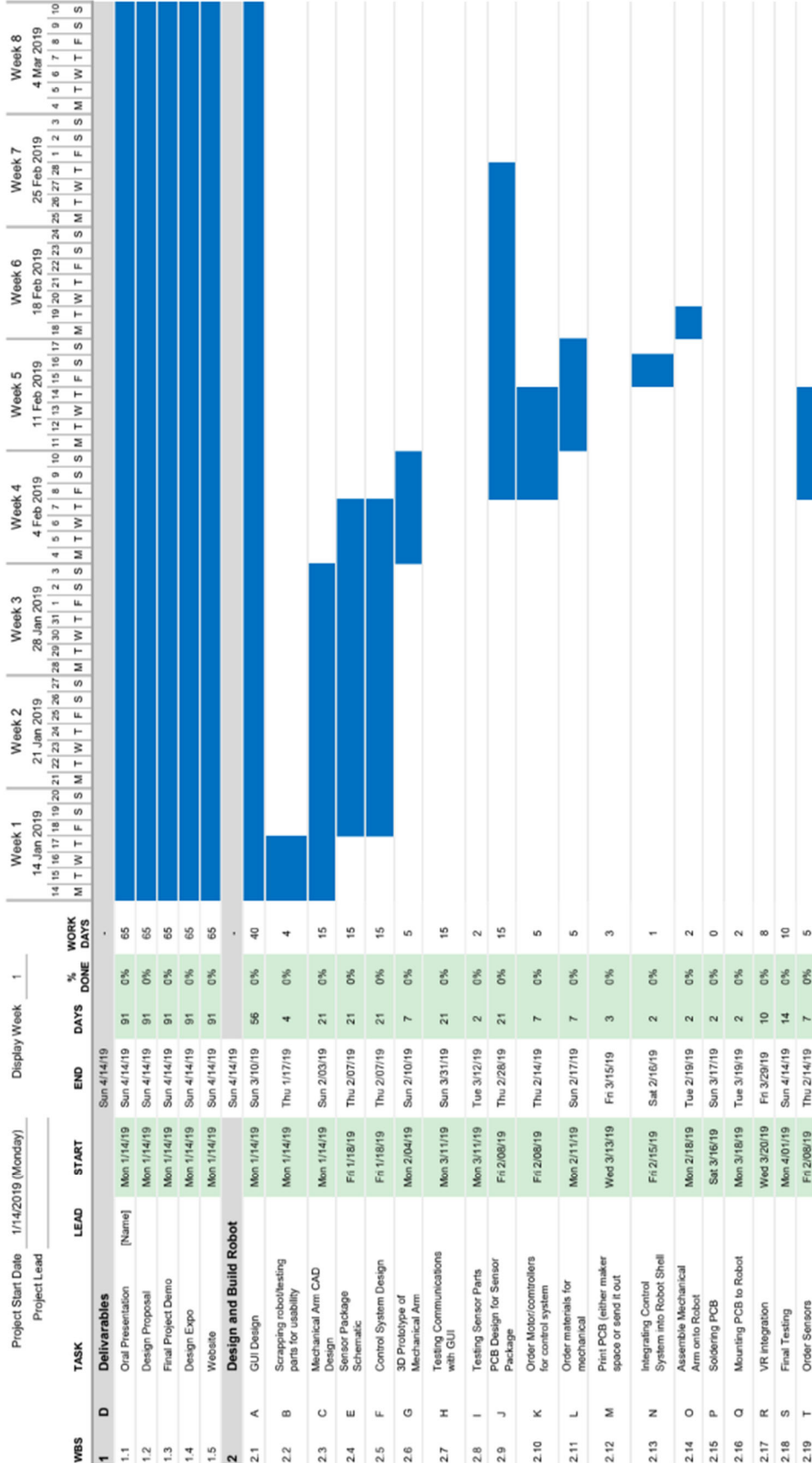
## **Appendix A - Project Gantt Chart**

See next page for project Gantt Chart

# Underground Power Vault Robot Project Schedule

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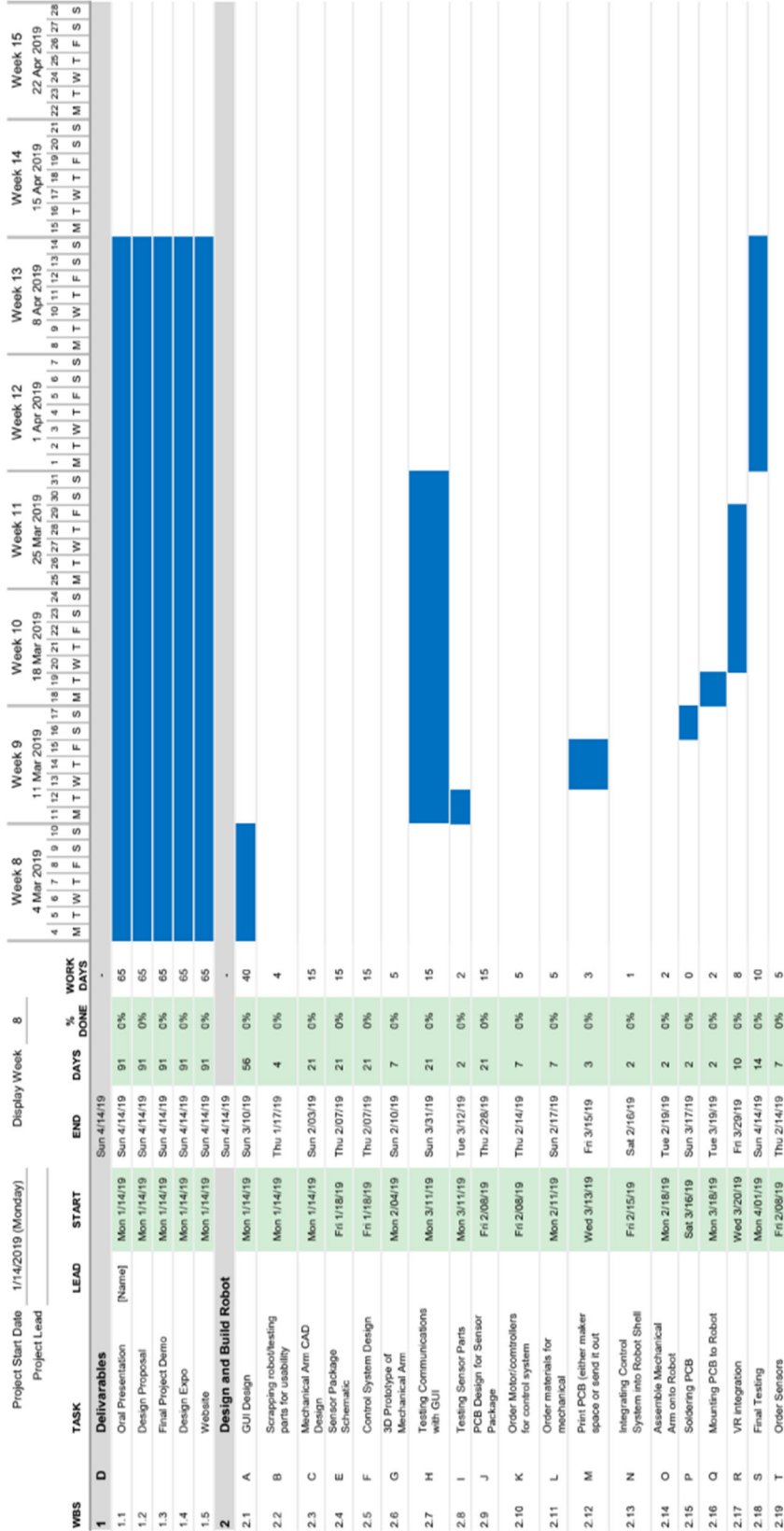
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# Underground Power Vault Robot Project Schedule

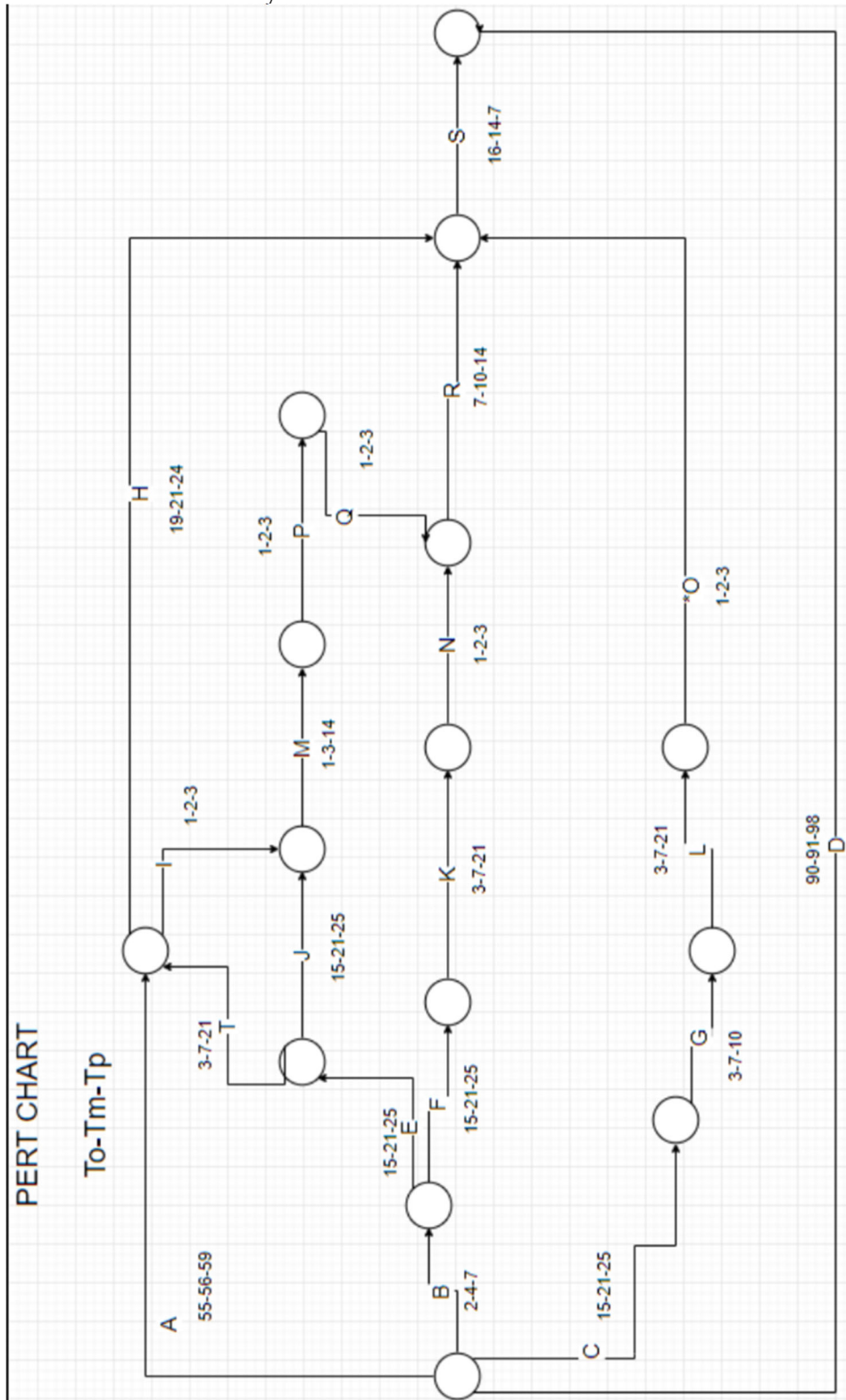
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## Appendix B - Project PERT Chart

See appendix C for Task List / Key



## Appendix C - Task List

Letter	Task Description
A	GUI Design
B	Scrapping robot/testing parts for usability
C	Mechanical Arm CAD design
D	DELIVERABLES
E	Sensor Package Schematic
F	Control system design
G	3D prototype of mechanical arm
H	Testing communications with GUI
I	Testing sensor parts
J	PCB design for sensor package
K	Order motors/controllers for control system
L	Order materials for mechanical arm
M	Print PCB (either maker space or send it out)
N	Integrating control system into robot shell
O	Assemble mechanical arm onto robot
P	Soldering PCB
Q	Mounting PCB to robot
R	VR integration
S	Final Testing
T	Order sensors

Deliverables include Oral Presentation, Final Design Proposal, Final Project Demo, and Design Expo