

Summer Student Program 2023



CMS Inspection Robot

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Project Report

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Table of Contents

Abstract:	3
Acknowledgement:	3
Background:	4
Aims:	5
Overall project design description:	5
Hardware and mechanical design:	6
Mechanical design:	6
3D printing:	6
Chassis Design	7
Electrical and Electronics:	8
Overview:	8
Design and Wiring:	8
Power Issues:	9
Controller:	10
Overview:	10
Arduino:	10
Why an Arduino:	10
Mecanum Wheels:	11
Arduino Codes:	11
Software:	11
Deploying and testing:	12
Results and Conclusion:	13

Table of Figures

Figure 1 Physical Prototype	6
Figure 2 3D printing station	6
Figure 3 SolidWorks Prototype Model	7
Figure 4 Schematic of the upper level of the robot.....	8
Figure 5 Schematic of the lower level of the robot.....	9
Figure 6 Wiring of the robot in real life	9
Figure 7 Flowchart of the Robot Control System.....	10
Figure 8 Web application preview	11
Figure 9 Pictures from the deployment of the robot in the CMS experimental caverns	12

Abstract:

This project focused on the development of a CMS Inspection Robot for the Compact Muon Solenoid (CMS) experimental cavern at the Large Hadron Collider (LHC). The cavern's harsh conditions, including high radiation, strong magnetic fields, and cryogenic gases, make human access restricted during beam operation. To overcome this limitation, the project aimed to design and deploy a surveillance robot capable of conducting visual inspections and maintenance during beam operation. The project aimed to create a foundational platform for future summer student projects, allowing them to continue building upon the existing design.

The prototype robot was designed to be compact, lightweight, and made from non-flammable materials to withstand hostile cavern conditions. It featured mecanum wheels for omnidirectional movement, and the hardware design included components such as Jetson Nano, OAK-D lite camera, Arduino Mega, DC motors, and DC motor drivers. The software/control system was implemented using Arduino interfacing with the hardware, enabling serial communication with the Jetson Nano acting as the main controller programmed with ROS2. The web interface, developed with Flask and React.js, allowed manual robot control via Wi-Fi.

Testing of the prototype robot demonstrated its successful operation in normal conditions. Additionally, a test deployment in the experimental CMS caverns revealed that the robot performed well under the influence of magnetic fields up to 45 mT. However, improvements were suggested for future iterations, including addressing motor-shaft connection issues and implementing a method of measuring speed and localizing the robot using other environmental cues.

Overall, the Summer Student Program achieved a significant milestone in designing and deploying the CMS Inspection Robot, paving the way for further advancements in future student projects. The robot's capabilities in visual inspections and maintenance during beam operation offer potential contributions to the efficient maintenance of the CMS experimental cavern at the LHC.

Acknowledgement:

We would like to thank the CMS EAM team, especially our advisors Mr. Jørgen Pedersen, Mr. Richard Morton, and Mr. Zein Zebib, for guiding us throughout this project. We are especially thankful to IdeaSquare, especially Mr. Markus Nordberg and Ms. Dina Zimmermann for providing us with the space and resources. We are also very grateful to CERN and our sponsors for this opportunity. Finally, we would like to thank Mr. Martin Gastal, Mr. Lars Tore, and Ms. Ana Dordevic for their continuous support throughout this program.

Background:

The CMS (Compact Moun Solenoid) experimental cavern (UXC55) is one of four caverns located at the LHC (Large Hadron Collider). The cavern location is in point 5, at which the collision between particles happens. The cavern also houses one of the most powerful magnets since their experiment aims to have the highest magnetic field in the detectors. As a result, the conditions in the caverns are very hostile and access to the caverns is restricted during beam operation. Mainly, the high amount of radiation produced from particle collision, the strong magnetic field, and the cryogenic gases used for cooling the magnets are the biggest threats and restrictions for human access.

However, maintenance, repairs, and upgrades must be carried out during scheduled access stops, which can be spaced several months apart and typically last only a few days or hours. In case of emergencies or any failures, the LHC would be halted, and data collection is paused for all other experiments. At CERN, unscheduled downtime is strongly avoided, but to avoid any failures, you need to physically monitor everything for any observable potential failures, which is only possible in the small windows of time where the LHC is stopped.

It would be ideal if a robot could be bought and deployed in the caverns for the purpose of doing such visual inspections and maintenance. However, the harsh conditions in the caverns also pose problems for robots, not only humans. The magnetism and radiation doesn't allow us to deploy a robot off the shelf, and building a robot specific for the cavern requirements is necessary. CMS currently aims to design and deploy a surveillance robot that can work during beam operation.

Aims:

This project is a very complex and challenging engineering task that requires a good amount of research, time, testing, design, and . Previous projects have shown that a two-month summer student program will not be enough for major progress in this challenge, so our current aim is to build a good base for future students to continue afterwards. We will try our best to accelerate the progress in the tasks that we were given so that future students can have the room to explore different tasks and improvements to the prototype.

Overall project design description:

This project was a collaboration of two students, Firas Abou Karnib and Aljoharh Alshwaish. To obtain the best results, each person worked on a different aspect of the robot separately and supplemented each other with help and advice. My teammate, Aljoharh, worked on the software and controller side of the robot, where she worked on building a ROS2 controller in the jetson nano, worked on the web interface that controls the robot, and worked on automating the robot. I worked on the hardware and mechanical side of the robot, where I designed and modeled the chassis of the robot, 3D printed and tested the chassis, worked on the wiring of the robot, and studied and researched improvements for the chassis and future suggestions.

I also must note that Aljoharh started on the project 2 weeks after my arrival, meaning she also has 2 extra weeks where she can improve the robot software and automation after I leave. I will be discussing the current state of this robot as of July 28, 2023.

Hardware and mechanical design:

Mechanical design:

- 2.3kg in weight
- 18.1 cm in height (when the antennas are horizontal)
- 22 cm length, 30 cm width (with wheels, it's 20.5 x 18.5 cm without the wheels)
- All the chassis is printed from PLA plastic.



Figure 1 Physical Prototype

3D printing:

The chassis for the robot was 3D printed using Prusa i3 MK3S+ printers in IdeaSquare. These printers provided high-quality prints and were reliable with low rates of errors. However, they had limitations such as a small printer bed and maximum print size, resulting in slower print times. The parts did not require tolerances except for some high-speed printed parts that needed a 0.1 mm estimate. To overcome the size limitations, the large chassis was split into smaller parts for printing using PruseSlicer 2.6.0.

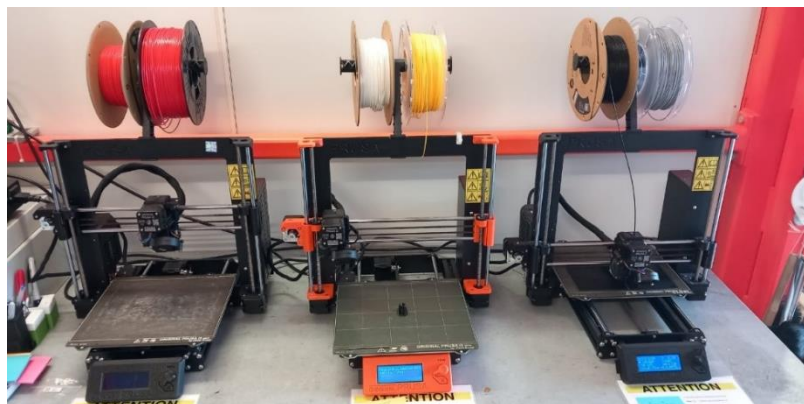


Figure 2 3D printing station

Chassis Design

The mechanical design aimed to create a compact, lightweight, and efficient chassis to house all the robot's circuitry and components. The prototype had to be 3D printed and be less than 20 cm to navigate the CMS caverns. The process was iterative with every iteration being a vast improvement onto the previous design. The design process involved developing motor mounts and wheel couplings to accommodate mecanum wheels. Challenges included ensuring proper support for the wheels and connecting the motor to the wheel shaft effectively. The electrical and electronic components were modeled accurately using online 3D models, though improvements could be made with more time. The chassis design focused on organizing and assembling the components on multiple floors with ventilation for heat dissipation. The final prototype addressed various issues, and parts were 3D printed separately and later glued together to reduce printing times.

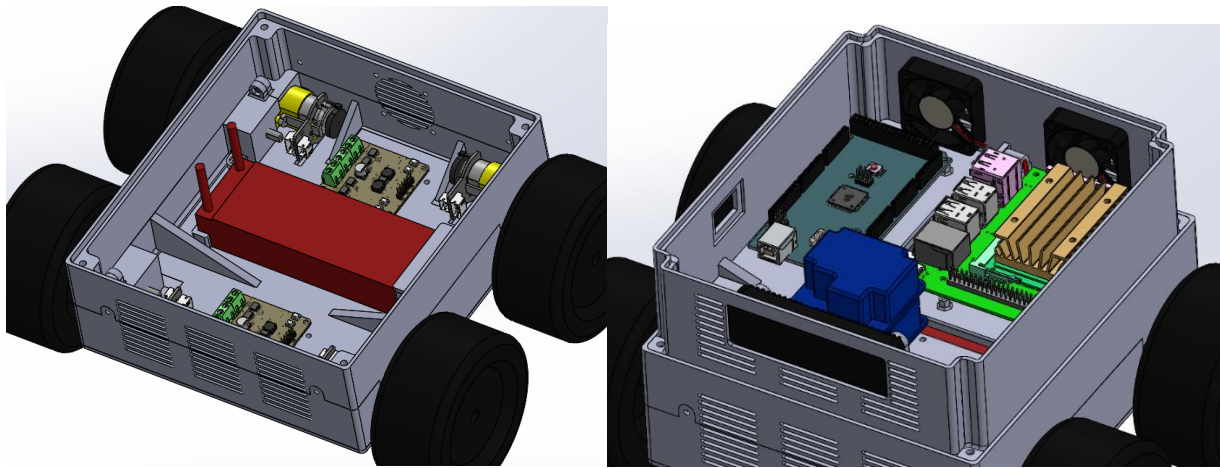


Figure 3 SolidWorks Prototype Model

Electrical and Electronics:

Overview:

- 1-to-2-hour lifespan when fully deployed
- Components:
 - Jetson nano J41 x1
 - OAK-D lite camera x1
 - Arduino Mega 2560 x1
 - DC-DC power module 25W x2 (DFR0205 power module dfrobot)
 - DC motors x 4 (fit0458 motor)
 - Black mecanum wheel 97 mm (x2 left, x2 right)
 - DPST switch x1
 - DC fan (40 x 40 mm 5V) x3
 - DC motor driver (MDD3A) x2
 - 6000 mAh LiPo battery x1

Design and Wiring:

In the hardware design section, we faced challenges due to time constraints, resulting in the use of existing electrical components for the robot prototype instead of ordering better quality components. After successfully 3D printing the chassis, the wiring and assembly of the circuit was . The circuit schematic was made accurately to reflect the real circuit layout, with each level of the chassis represented on separate sheets.

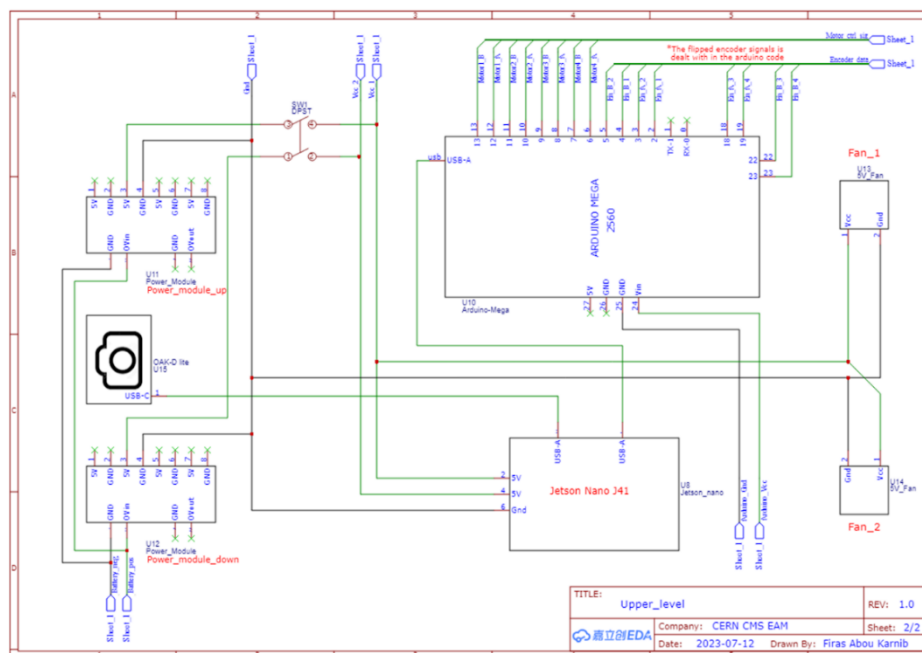


Figure 4 Schematic of the upper level of the robot

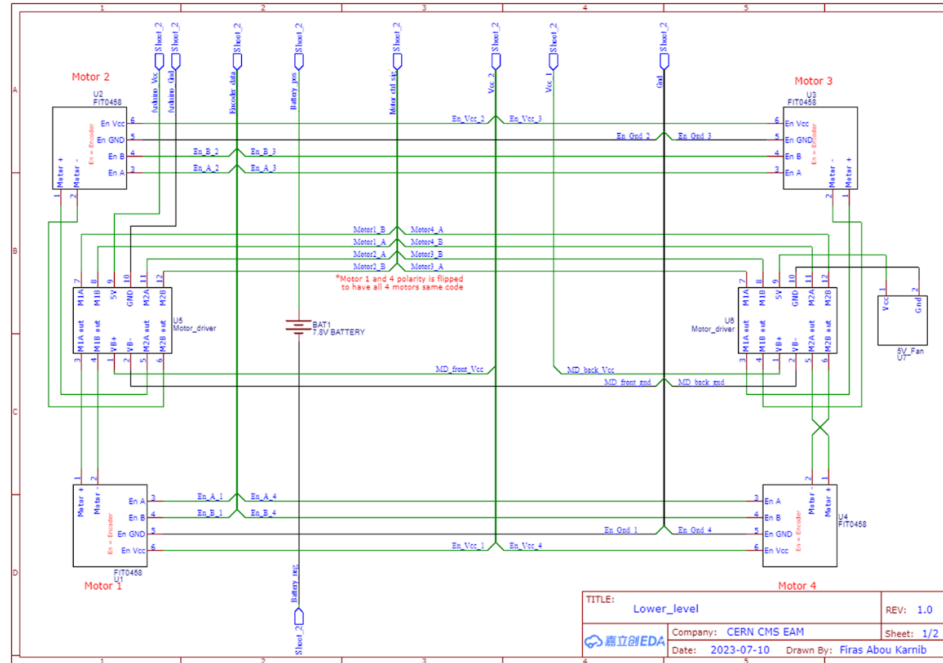


Figure 5 Schematic of the lower level of the robot

Power Issues:

One critical issue to address was the maximum stall current of the DC motors, which was determined to be approximately 1.87A at the 5V supply. However, the total current consumed by all electronics and motors under worst-case conditions was estimated to be around 9.998A, still within the 10A power module limit. Therefore, it was unlikely that the robot would face this issue during practical use. The team also considered the battery life, and even with a 6000mAh LiPo battery, they achieved a battery lifetime of about 2- hours due to the lightweight design and moderate current consumption of the robot on standby.

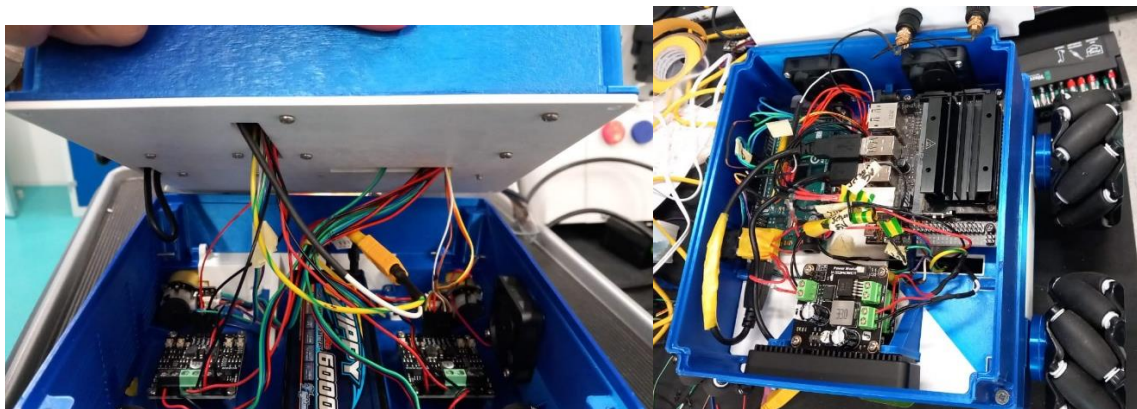


Figure 6 Wiring of the robot in real life

Despite the hardware challenges, the prototype was functioning well, and all components worked safely, indicating successful progress in the hardware design of the robot.

Controller:

Overview:

- Arduino interfacing with the hardware (motors and sensors).
- Serial communication between Arduino and Jetson Nano. The Arduino receives commands from the Jetson and relays the sensor data back to the jetson.
- Jetson nano acting as the main controller. ROS2 was used to program the controller on the Jetson.
- Flask framework which serves as the backend for our web interface
- React.js library which serves as our frontend allowing us to deploy our web application on the cloud for anyone to use.

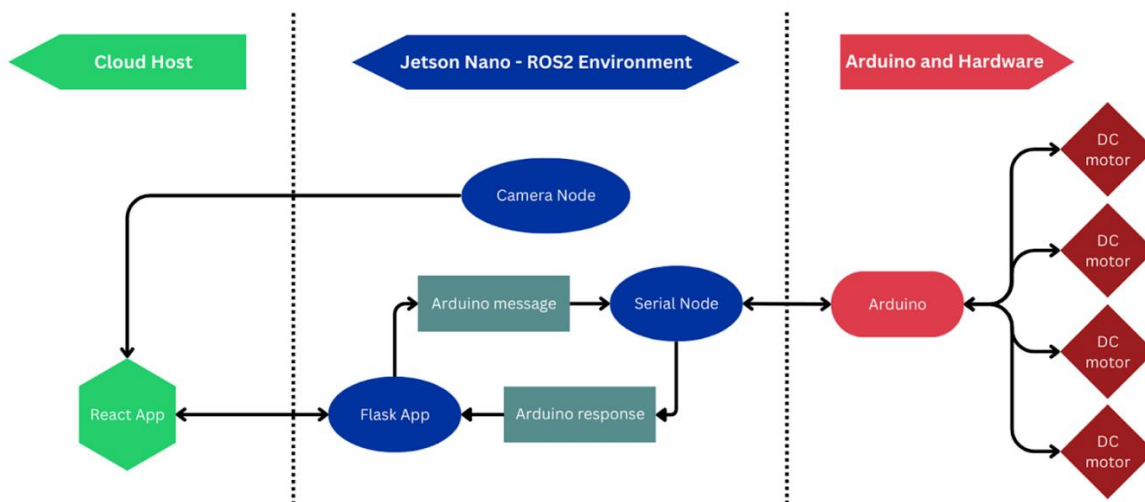


Figure 7 Flowchart of the Robot Control System

Arduino:

Why an Arduino:

The project involved the examination and integration of hardware, specifically the Jetson Nano, into the system. However, several drawbacks with the Jetson Nano led to the decision of using an Arduino for the hardware instead. Firstly, the Jetson Nano lacked PWM support, crucial for motor driving, although software PWM implementations existed, they were unreliable. Secondly, the Jetson Nano's pins lacked sufficient overcurrent protection, causing shutdowns if excessive current was drawn, while the Arduino had better protection and would simply restart. Lastly, since the project was done in Python, achieving high sampling speed from sensors and encoders was unlikely due to Python's nature, making a C-based Arduino a more suitable choice for the hardware.

Mecanum Wheels:

To facilitate the robot's movement in tight spaces, the project utilized Mecanum wheels, a type of omnidirectional wheel that allows movement in any direction without changing wheel orientation. These wheels consist of rollers attached at a 45-degree angle to the wheel's rotational axis, and they enable complex movement patterns, such as sideways, diagonal, and precise rotations.

Arduino Codes:

The Arduino was used as an interface for almost all hardware, actuators, and sensors in the system. The main code "CMS_Arduino" handled serial communication with the Jetson Nano, processed encoder data of DC motors, and controlled the robot movement using Mecanum wheels. It received messages from the Jetson Nano with direction, speed, and parity information, and based on that, moved the robot in the specified direction and speed for 100ms intervals to achieve precise movement. Several other codes were developed for testing and debugging purposes such as "CMS_testing_1", "CMS_encoders", and "CMS_measure_speed".

Software:

This section is the works of my teammate Aljoharh, so I will not be explaining it. As a summary, we collaborated on developing the ROS2 nodes by learning ROS2, working on a suggested architecture for the robot controller, and brainstorming the means and logistics of execution of the nodes. Afterwards, Aljoharh worked on creating a really good controller and then moved on to creating a web app that can allow users to manually control the robot from a web browser over the Wi-Fi. This app also has live camera feed that allows the user to see the objects in front of the jetson.

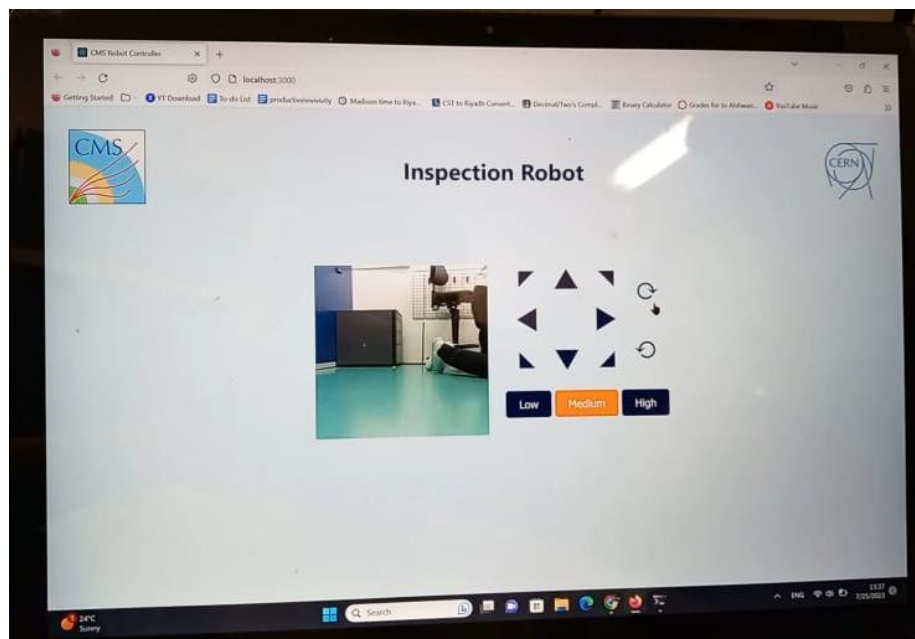


Figure 8 Web application preview

Deploying and testing:

This prototype was tested in normal conditions in multiple locations randomly, mainly in IdeaSquare, during the poster session 7/25/2023, in our office... The performance in normal conditions exceeded expectation, it can stay on battery power for extended periods of time as we only charge the battery once or twice a week even with all the testing of the prototype. It can traverse harder terrains. This was satisfactory as we were not required to have such a performance under harsher conditions such as the magnetism and radiation of the caverns.

On Thursday 27 July 2023, our supervisors arranged for a test deployment of the robot that the experimental CMS caverns, the beam was down due to the failure of magnets at the LHC, but the CMS magnets were still on, so we were able to test the robot in the caverns and look at the effects of magnetism on the potential failure of the robot. Firas and Aljoharh were in the control room using the web application due to access restrictions, while our supervisor Mr. Zein took the robot down to the caverns to deploy it in the experimental caverns.

Surprisingly, the robot performed normally with magnetism in various sections of the LHC, with the magnetic field strength reaching up to 40-45 mT. Unfortunately, testing higher magnetic field strengths is not possible as our advisor was not fond of going farther into the CMS detector center, which is a responsible decision, but further testing is needed to check whether the robot can deal with the magnetic fields in the entire cavern or not.

The only failure in this deployment was the DC fans stopping their functionality in the magnetic field, and I would assume that our magnetic encoders were also not working.



Figure 9 Pictures from the deployment of the robot in the CMS experimental caverns

Results and Conclusion:

Overall, we have successfully developed a commendable prototype that lays a solid foundation for future students to build upon and enhance. The physical robot we have constructed marks a significant milestone in our project, offering a starting point for subsequent students to continue its development and make further improvements.

In addition to the physical prototype, our comprehensive technical documentation provides an in-depth account of all the design decisions made throughout the project. This documentation serves as a valuable resource, enabling future students to understand the rationale behind our choices and easily pick up where we left off. It provides a clear roadmap for further iterations and improvements, ensuring that subsequent teams can effectively build upon our work.

Our efforts have not been confined to just the robot and technical documentation; we have also diligently identified areas for improvement and outlined the next steps for future students. These suggestions encompass various aspects that can be enhanced, expanded upon, or optimized to elevate the robot's performance and capabilities.

By addressing all the requirements set forth at the beginning of the project, we have achieved successful completion of our initial objectives. The prototype's functionality aligns with the project's original goals, demonstrating our ability to follow through and meet the project's specifications effectively.

In summary, the current prototype and accompanying documentation provide a strong foundation for future students to embark on further developments. It serves as a testament to our team's dedication and proficiency in meeting project requirements. With our insights and suggestions as a guide, we are confident that subsequent students will be well-equipped to take this project to even greater heights, pushing the boundaries of what this robot can achieve. As a result, we believe that our efforts will leave a lasting impact and contribute significantly to the ongoing progress and success of this project.