Department of Mechanical Engineering

UNIVERSITY OF BATH

Project Manager Technical Report
Group 14 – Team CERN

Ege Arabul (12521)
Project Manager & Integration Lead

Summary

The project aimed to develop a surveillance robot, that relays live visual and audio, to be operated within the harsh CMS cavern environment. While initially manual control was expected, further discussions led the potential of a fully autonomous robot to be realised, which could complete surveillance routines. The project features unique technical challenges relating to the CMS cavern, such as strong magnetic fields, ionising radiation and cavern topography. Other unique challenges regard to the robots' requirements such as the need to achieve sophisticated robot intelligence and increased safety requirements. After determining the key challenges, a Product Design Specification and a Design Validation Plan were formed. Based on the specification, work packages were allocated, which includes; powertrain, robot navigation, power supply, inspection, system testing and integration.

Work packages deliver results relating to different domains of engineering, which are hardware, mechanics, and software. For each domain, a system integration concept was to be developed. Hardware integration featured system interfaces that modularised subsystems. This practice allowed for hardware-independent software development. Furthermore, a Power PCB had to be developed for the integration of integrated circuits and provide power distribution. Mechanical integration involved the development of a CAD model which reflects decisions made in the subsystem level and the physical interfaces. "Design for X" practices were utilised to ensure the quality of the model, which are Reliability, investigated through DFMEA, Safety and Maintenance. Software integration involved the use of ROS, a middleware used to pass messages between nodes, which are software functionalities. This was achieved by determining the links between nodes, after which, a proof of concept scenario was investigated that provided insights on the implementation of ROS. Along with the integration work, project management facilitated the day to day activities within the project. While initial approach involved the use of the V model for Systems Engineering and Gannt charts, this approach had to be adapted for the unique challenges of remote working. This led to adopting an agile framework, which utilised online tools, Kanban boards and daily monitoring meetings.

Based on all project outcomes, a final proposal was achieved. The final proposal features an omnidirectional robot with enhanced autonomous capabilities that satisfied all the initial hardware requirements with a final price of £1485. Analysis of Solution Design Specification shows 52% of all "must" requirements have been successful, with varying successes and limitations of each subsystem. Based on this insight, the different domains of the robot were reviewed with suggestions for future implementations.

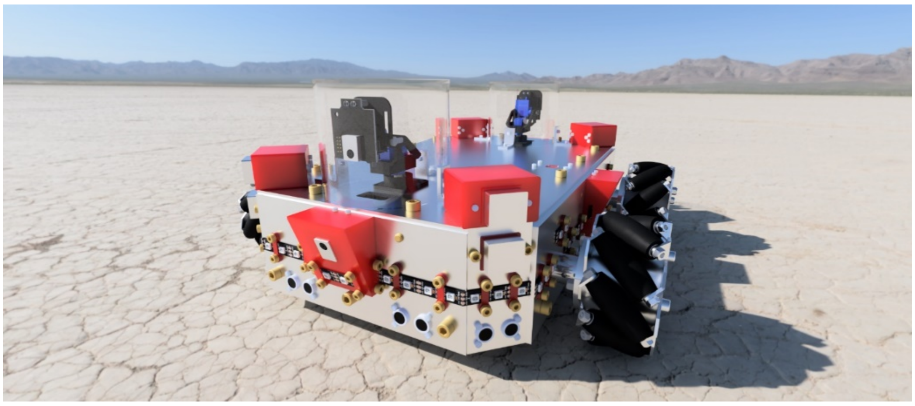


Table of Contents

Introduction

Background

CERN is a European Research Organisation that operates the largest particle physics laboratory in the World. CMS is one of the experiments situated within Large Hadron Collider, operated by CERN. At the start of the project, CMS stated their wish to implement a surveillance robot which could relay live audio and visual within the Compact Muon Solenoid (CMS) cavern. The CMS cavern, as represented in figure 1, is a complex and hazardous environment, with a strong magnetic field and ionising gamma radiation. Furthermore, many services such as high voltage, low voltage, water cooling and fibre optic, highlighted in figure 2, run through the CMS itself where a failure or leakage could lead to damage to CMS and shutdown of the entire Large Hadron Collider, which would mean lost science data and time[1].

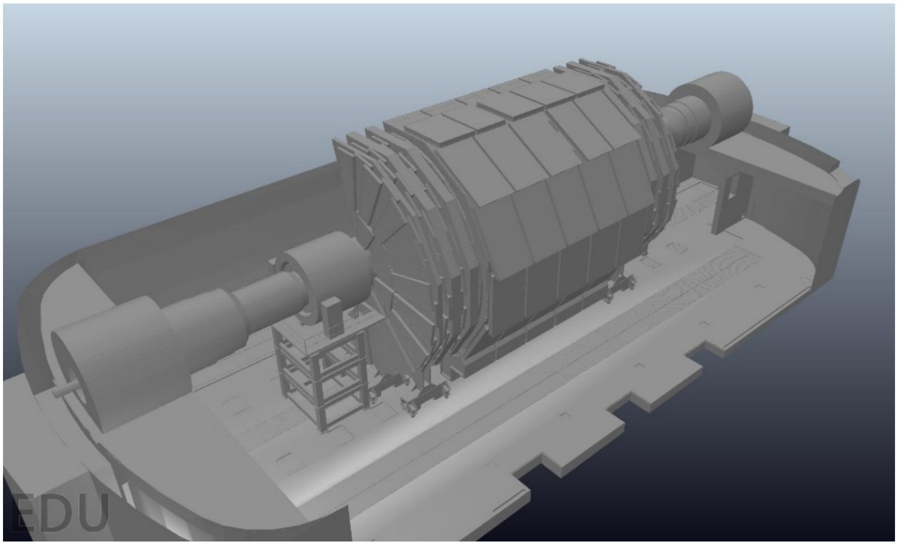


Figure 1 - Representation of the CMS Cavern in a virtual environment [2]

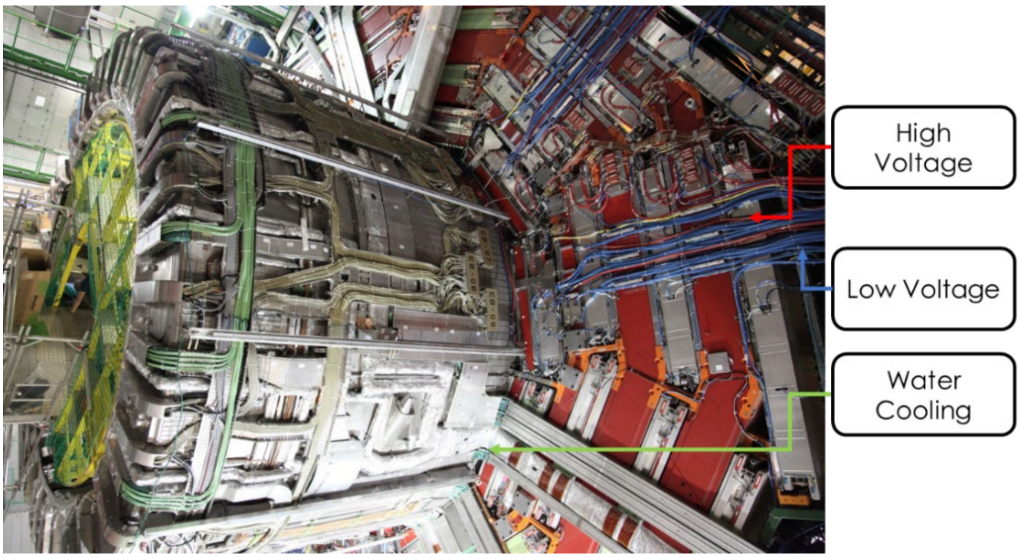


Figure 2 - Key services critical to the operation of the CMS

The initial purpose of the surveillance robot was to aid in the current mitigation plan implemented at CERN, further detailed in figure 3, as stated in the design brief. When an existing alarm is triggered, the robot would be remotely controlled above ground and be driven to its' location and the surroundings of the alarm would be surveyed. This would allow for a situational mitigation plan to be implemented, avoiding the shutdown of the complete detector when possible, preventing data and time losses[3].

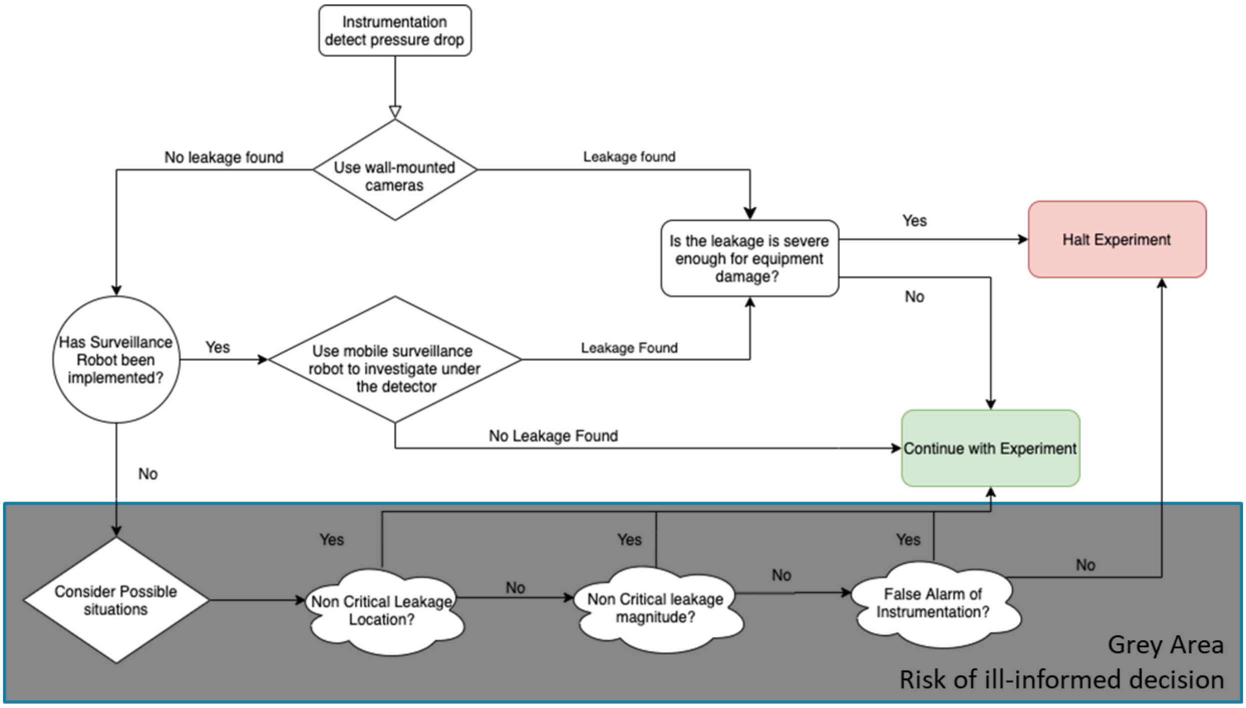


Figure 3 -The Decision-making methodology for the CMS Experiment in the case, illustrating the importance of a surveillance robot for the accurate decision-making process.[4]

As the project progressed, the design brief evolved as well. Further discussions led to another potential of the robot to be realised, which was the development of autonomous functionalities. With higher autonomous capabilities, the robot could patrol the cavern, collect ground truth information by itself while an operator could intervene when necessary. Such capabilities could allow for a more optimised and standardised surveillance procedure to be implemented, where results of the surveillance operation would be more comparable and the process could be streamlined.

Technical Challenges

Early investigations of the task led to the determination of challenges and conditions unique to the CMS cavern environment, where some are represented in Figure 4. These include the stray and localised magnetic field ranging up to 100mT, gamma radiation that occurs during particle collusion[5], reduced maintenance cycles up to 6 months and the unique cavern topography, where gaps of 60mm and steps of 5mm would need to be overcome, as well as accounting for the movement of CMS Slices during maintenance [6].

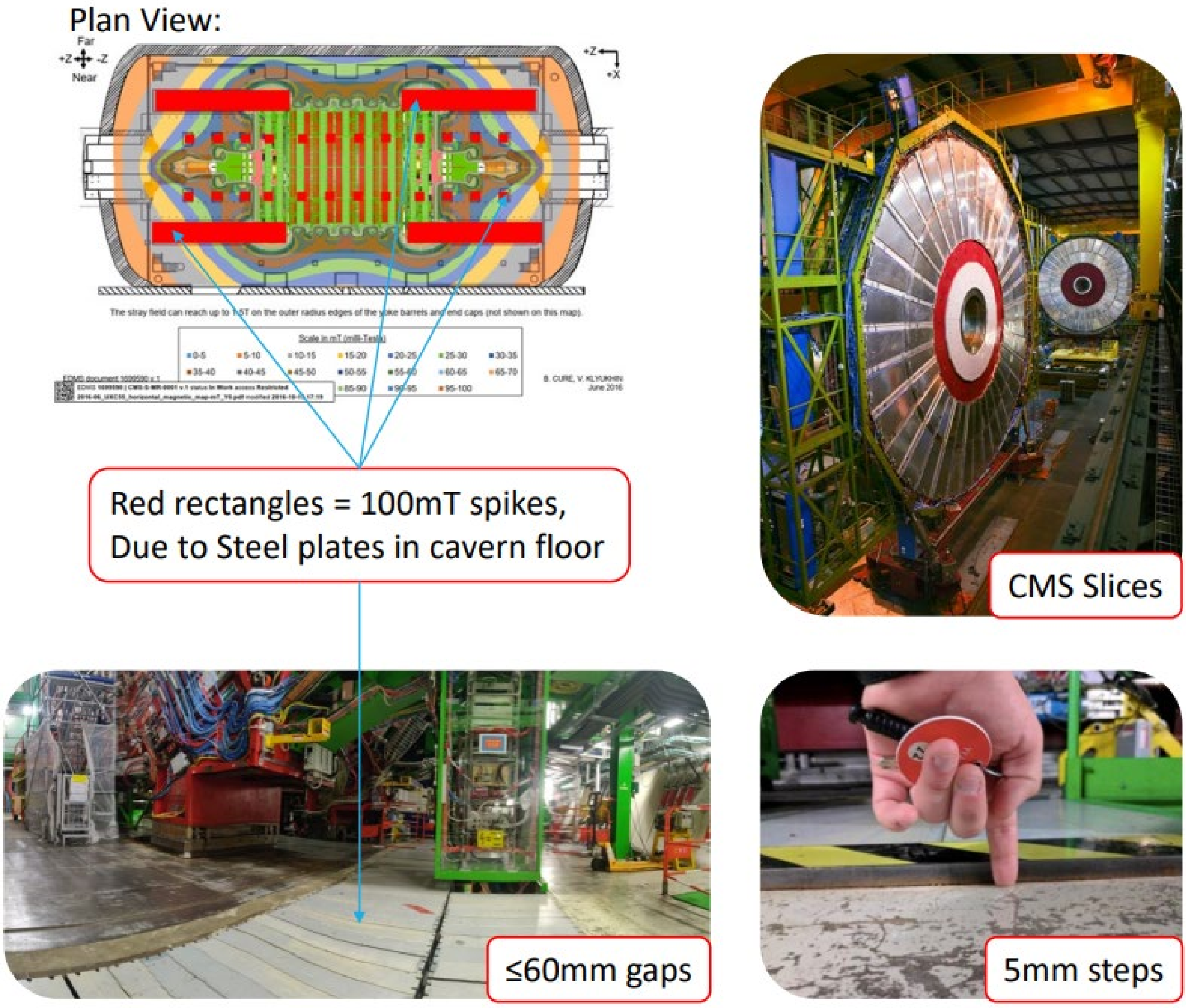


Figure 4 - Different Challenges faced within the Cavern Environment

With the progression of the project, more sophisticated technical challenges were determined. While the initial challenges regarded the circumstances within the cavern, technical challenges regarding the functionalities of the robot needed to be considered as well, such as automated surveillance and navigation scenarios. Such complexity would need to be reflected in hardware as well which can be exampled by the implementation of accurate positioning control of the robot. Along with increased autonomy of the robot, the safety requirements of the robot had to be considered, not just for the hardware but for the robot intelligence as well, which led to the development of an accurate internal monitoring system to obstacle avoidance.

Specification

After determining the initial customer requirements and technical challenges, the initial Product Design Specification (PDS) was formed that accurately reflected the technical needs that evolved with the project. Along with the PDS, a Design Validation Plan (DVP) was formed to ensure the achieved results would reflect the design specification, where the layout is as shown in figure 5. Complete PDS and DVP can be viewed in Appendix A and B respectively.

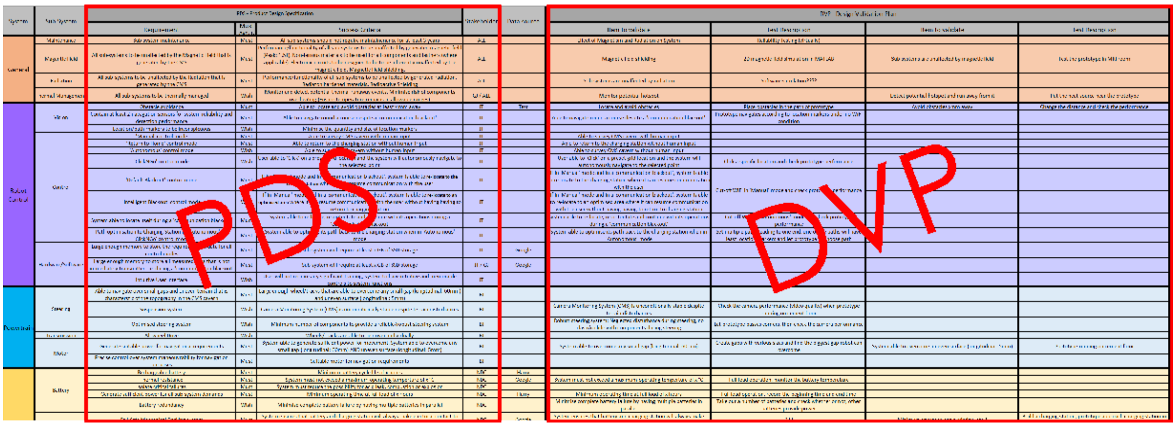


Figure 5 - The PDS and DVP Layout

Work packages

The system has been split into 6 sub-systems, which include Robot Navigation, Inspection, Energy Supply, Powertrain, Integration and System Testing as shown in figure 6. The development occurred concurrently at different levels of the product, which are sub-system, system, and product-level activities.

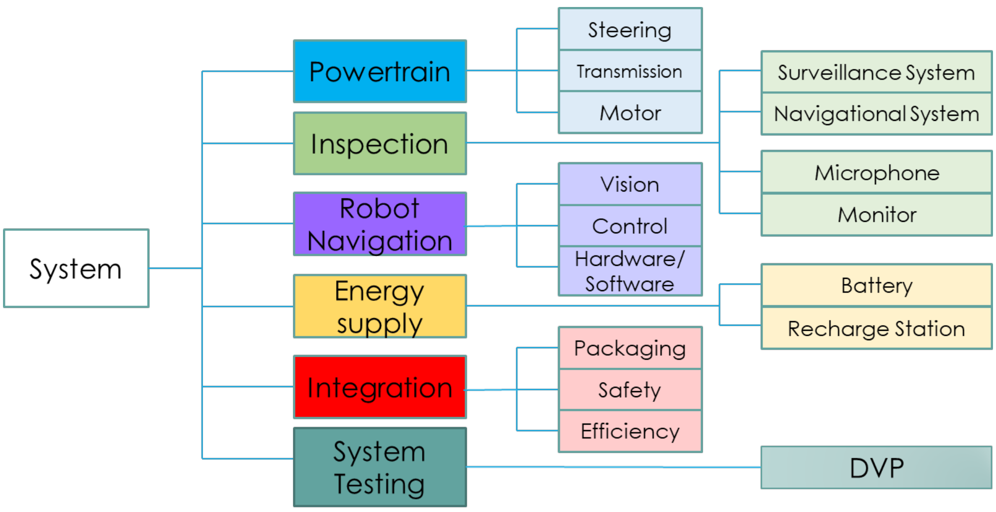


Figure 6-Work Packages

Powertrain

Powertrain subsystem is involved with the development of locomotion of the robot, which included component selection for a magnetic field resistive powertrain and its' mechanical validation, as well as providing positional feedback.

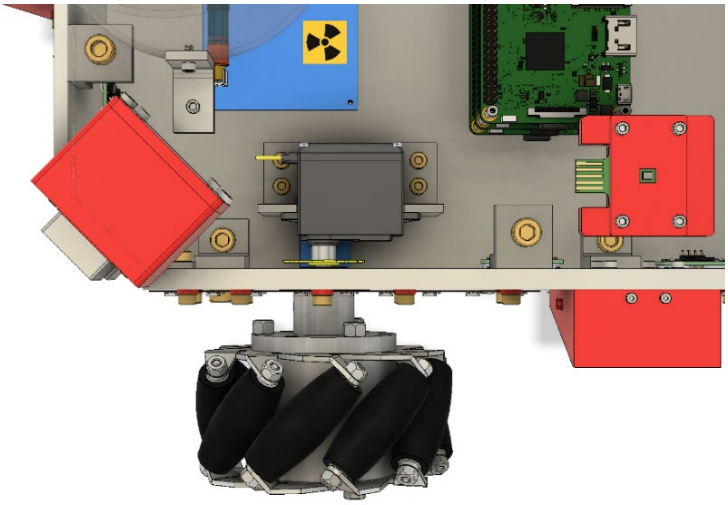


Figure 7-Hardware Implementation of the Powertrain Subsystem [7]

Robot Navigation

Robot Navigation relates to the development of navigational functionalities of the robot. Initially planned to be achieved through hardware, the subsystem evolved into following a software-based approach where scripts were developed through the use of simulated environments that were used to test algorithms.

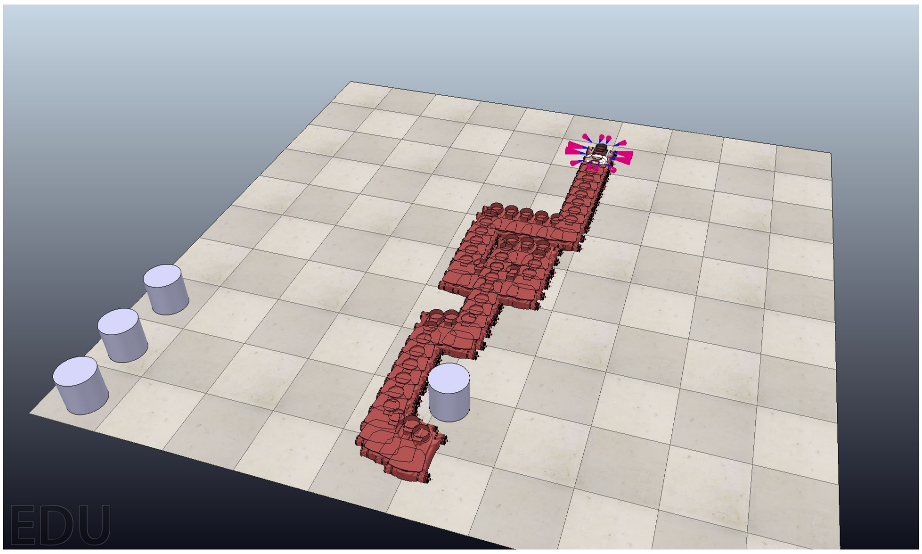


Figure 8- An example scene used for the development of Robot Navigation[8]

Inspection

Inspection relates to all sensory aspects of the robot including the visual and audio systems as well as internal monitoring systems. This subsystem featured component selection for on-board sensors, software development for manual and autonomous use cases and data storage.

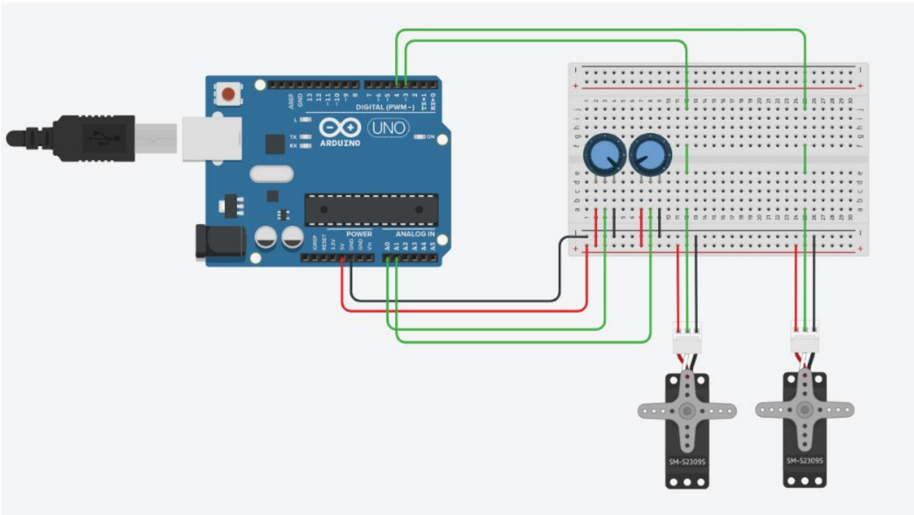


Figure 9-Implementation of Manual Surveillance Camera Control [9]

Power Supply

Power supply subsystem relates to all power-related concepts; such as the development of a recharge station concept, robot intelligence for the docking process and specification and component selection for on-board electronics such as the battery.

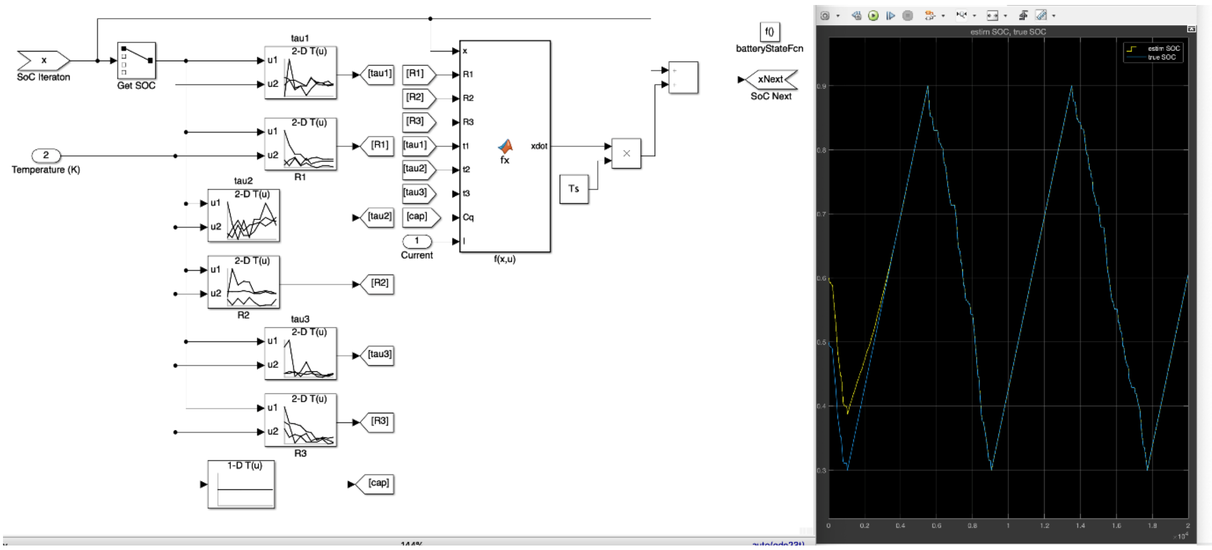


Figure 10-State of Charge Model for on-board batteries [10]

System Testing

System Testing is a system-level activity, initially responsible for validation of items on the Design Validation Plan using physical test setups. The focus of system testing was shifted into conducting the system tests in simulated environments which represent the CMS cavern environment. These results were used to optimise individual subsystems and develop an understanding of system constraints.

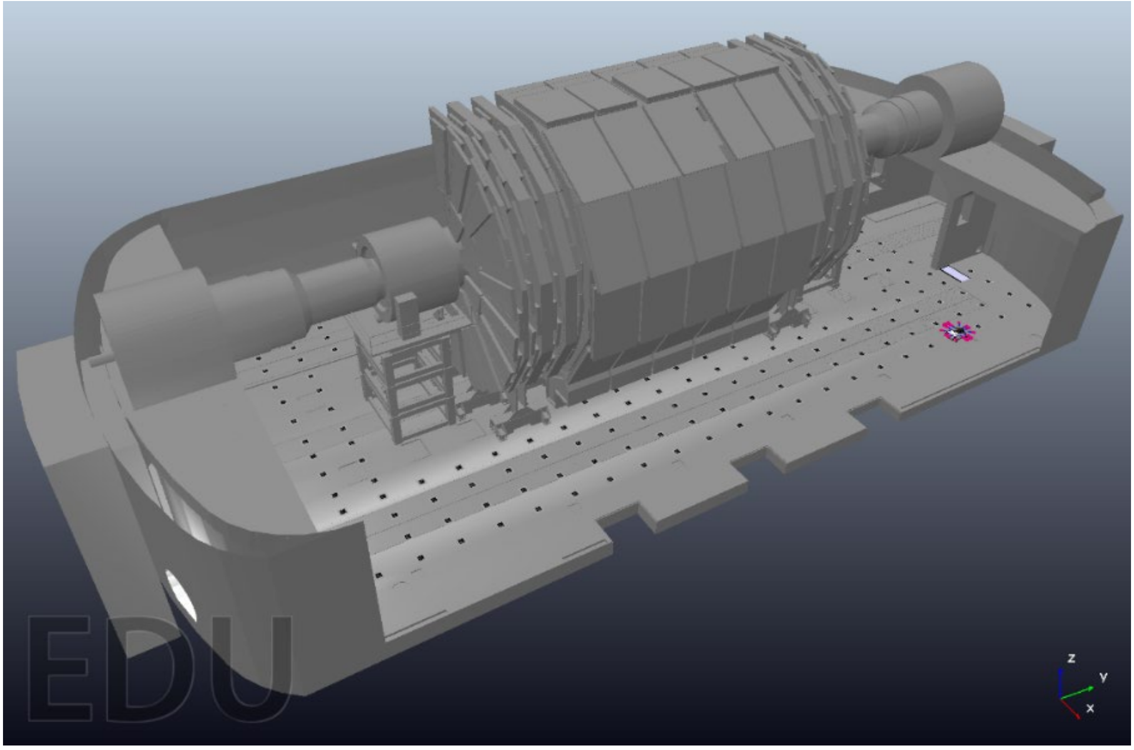


Figure 11-CMS Cavern Model used for System Testing[11]

System Integration

System Integration was initially responsible for mechanical integration, the packaging of the robot, and hardware integration, the design of hardware interfaces and the integration of onboard electronics. Later, this included software integration as well, which was achieved through the use of ROS (Robot Operating Software), leading to complete System Integration.

System Integration

Hardware Integration

Hardware integration involves the design of hardware interfaces and integration of on-board electronics components. In Stage Gate 3, a potential system architecture, shown in Appendix C, was proposed which would have satisfied the needs of the subsystems at the time. However, with further development of subsystems and considerations, this architecture needed to be changed.

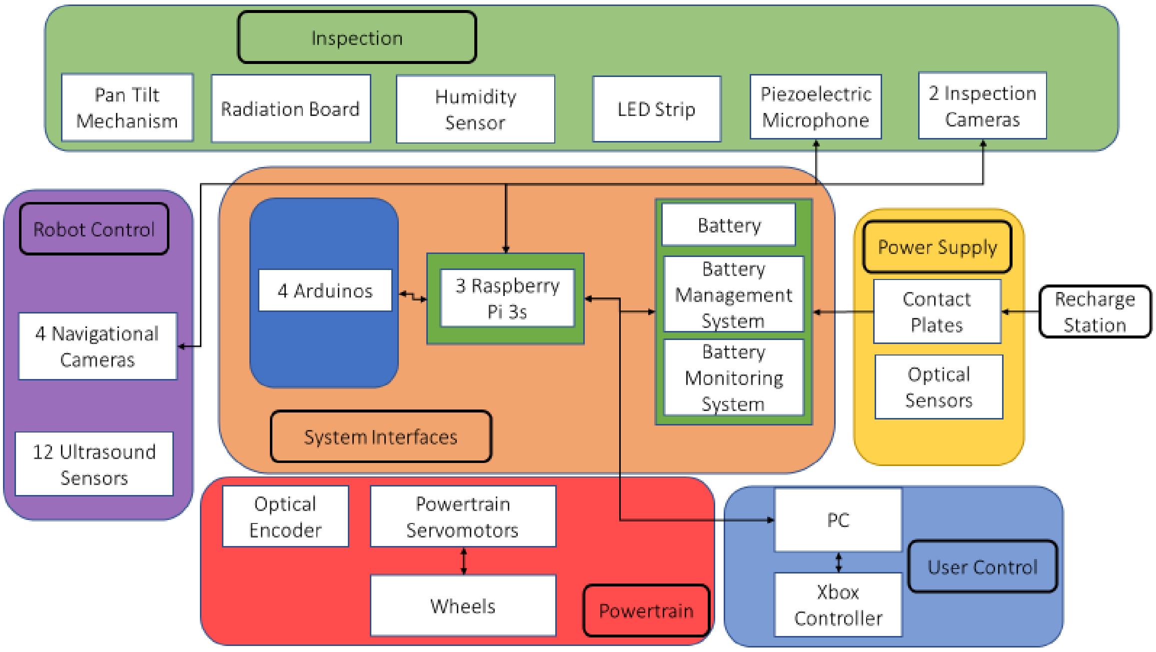


Figure 12- Proposed Hardware Architecture. Note all components that do not feature an explicit connection are connected to the Arduinos

Figure 12 features the current hardware architecture of the robot. From a systems perspective, this architecture features 3 Raspberry Pi's, which are embedded systems[12], controlling the USB powered interfaces, microphones and the Arduino's. The Arduino Unos, which are microcontrollers, is used to control all the sensors within the robot, where each Arduino controls one subsystem. As for the power distribution, a bespoke PCB, named "Power PCB", manages all the battery management and monitoring systems and powers the Raspberry Pis and External sensors. Details of the rest of the system interfaces are shown in Appendix D.

Compared to previous architecture, this iteration provides simplification and relies on industry-standard components. This reflects the Product Design Specification, which highlights compatibility, ease of platforming and computing in real-time. The design process was governed by two design principles, modularisation and hardware-agnostic approach.

Modularisation[13] refers to a division of subsystems and USB interfaces to dedicated hardware. Such configurations allow for ease of troubleshooting and maintenance along with higher reliability as single point failures are avoided[14]. Furthermore, such division allows for easy upgrades as connections between interfaces are standardised which allows for the addition of more sensors, microcontrollers or increase of computational power by combining more Raspberry Pi's [15]. Furthermore, this facilitates concurrent development where, by using the minimum amount of required component, subsystems can be individually developed and combined.

Hardware agnostic approach refers to the practice of developing software that is hardware-independent[16]. Using industry-standard components which can be easily programmed using high-level programming languages provides flexibility. As sub-systems are developed separately, such system interfaces facilitate the software development process, as opposed to the use of bespoke components which would limit potential applications and offers seamless integration. In an actual implementation, this architecture could be enhanced such as the inclusion of more Raspberry Pi's for higher computational power and allow for complete hardware abstraction.

These system interfaces, are to be placed in stacks, as shown in figure 13. While such configuration allows for thermal hotspots, as Raspberry Pis can heat up to 82 C^{0} [17], it allows for easier risk mitigation implementations, where, for instance, the boards can be covered with a lead box for radiation protection or a fan can be positioned directly next to the boards, as well as saving space.

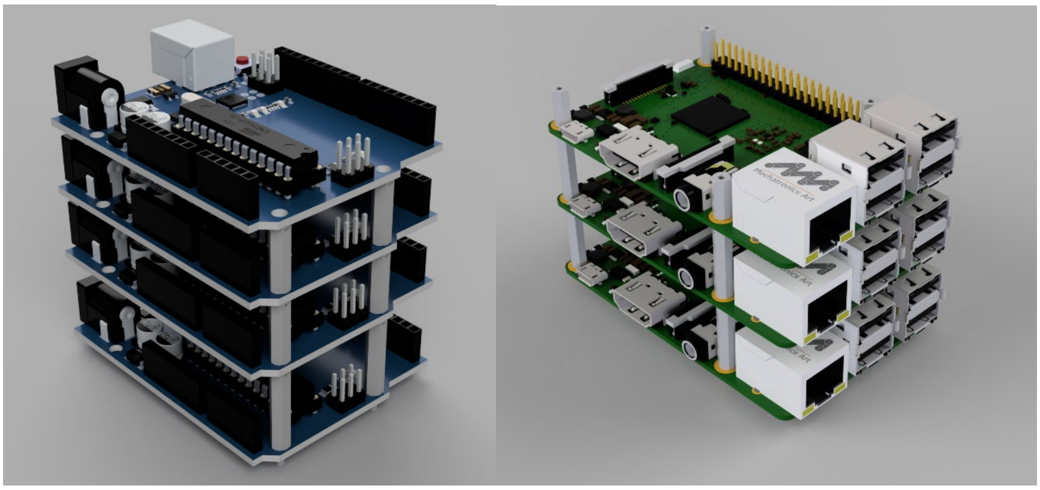


Figure 13- Hardware Implementation of the System Interfaces

The Power PCB refers to the bespoke PCB designed to manage and monitor the power drawn from the recharging station to charge the onboard batteries. Initially a subsystem activity, integration of individual circuit components on a platform led for this activity to be treated on the product level. While some off-the-shelf PCB's offered similar functionalities[18], none of them reflects the unique system requirements of the CERN Robot. Furthermore, another functionality needed by the PCB was to power individual sensors. This is to avoid drawing overcurrent from the Raspberry Pi [19], which already operates individual cameras, microphones, and Arduino's.

The design process of the Power PCB involved component selection by subsystem leads for battery monitoring and battery management systems which reflected functionalities required. These components were connected using schematics that illustrate the logical connections and board views were created by tracing connections on PCB. Individual sections on Power PCB are highlighted in figure 14 and figure 15 shows the integration of the board. For more detailed schematics and board views, refer to Appendices E and F.

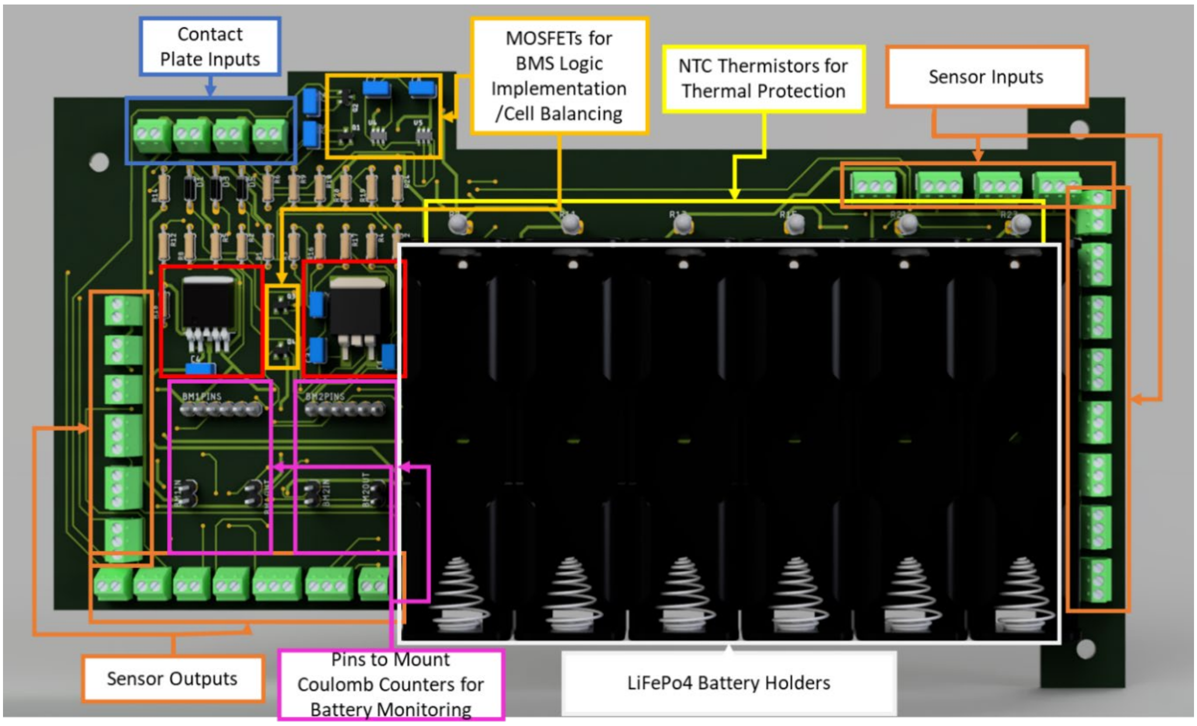


Figure 15- Components and their related functionalities of the Power PCB

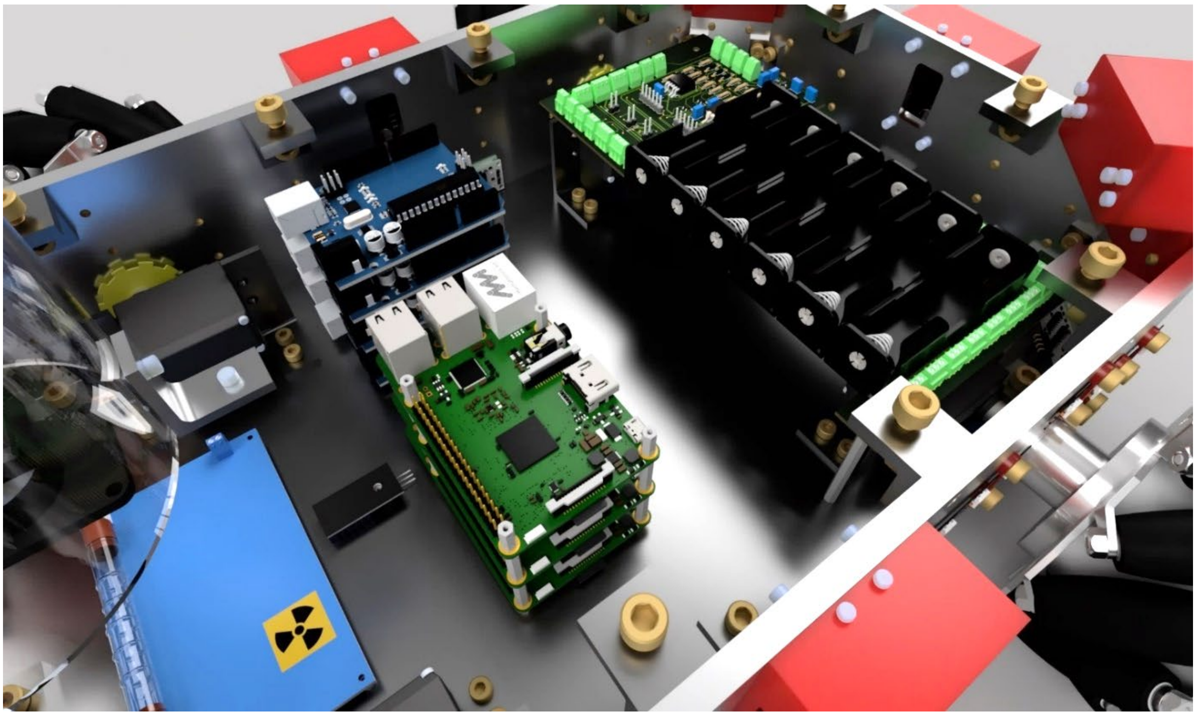


Figure 14- Hardware Integration the System interfaces

Mechanical Integration

Planned layout

Mechanical integration features the development of a CAD model that reflects the decisions made in the subsystem level and integrates them in a robot solution. Furthermore, Mechanical integration is responsible for designing any physical interfaces between subsystems.

The mechanical integration process involved design of abstract layouts which formed the basis for CAD models, where early iterations can be seen in appendix H. Early realisation of the iterative nature of this activity allowed for many iterations to be undertaken, which improved the quality of the model. The final layout of the robot CERN robot is as shown in Figure 16.

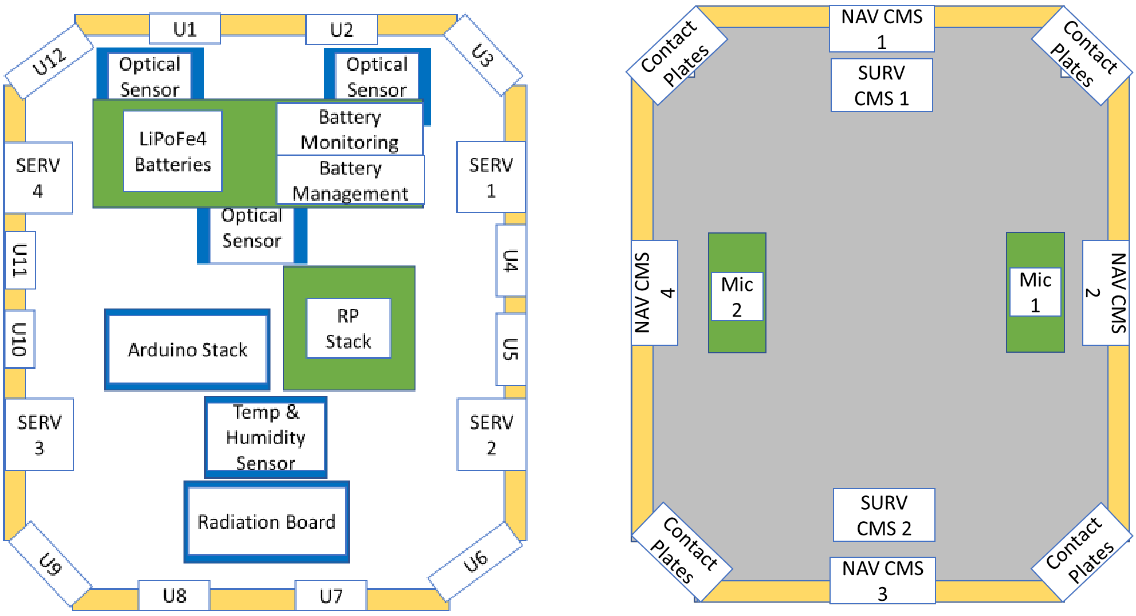


Figure 16 - Final Layout of the CERN Robot. The figures show component being analysed in two layers. The dimensions do not reflect reality.

Another mechanical integration activity involved material selection, where which was critical due to magnetic field considerations. While previous CERN projects used 3d printed chassis[20], as shown in appendix H, such design was suboptimal due to the durability and maintenance requirements. Therefore, non-ferromagnetic metals and alloys were preferred which included brass for fasteners[21] and Aluminium Sheet metals for frame [22], which allows for easy machining and higher build quality. Other practices include plastic screws for lower stress applications and 3d printed parts for subsystem integration which required bespoke components.

During the development of the CAD model, mechanical subassemblies were realised that needed to be developed for successful integration. These subassemblies are detailed in the assembly drawings, shown in appendix G.

The design process has been influenced by “Design for X” concepts. One example includes the design for reliability, which was essential for achieving the reliability requirements. A related practice involved sensor redundancy[23], which allows for the system to function even when a sensor onboard fails, illustrated in figure 17. Similar practises can be extended to mechanical components as well, such as fasteners. Another implementation includes emphasising on the omnidirectional[24] characteristics of the robot, achieved through the use of Mecanum wheels. By accounting for sensor placement in different orientations, a fully omnidirectional robot can be achieved where should one subsystem fail in one orientation, other orientations can be used until maintenance.

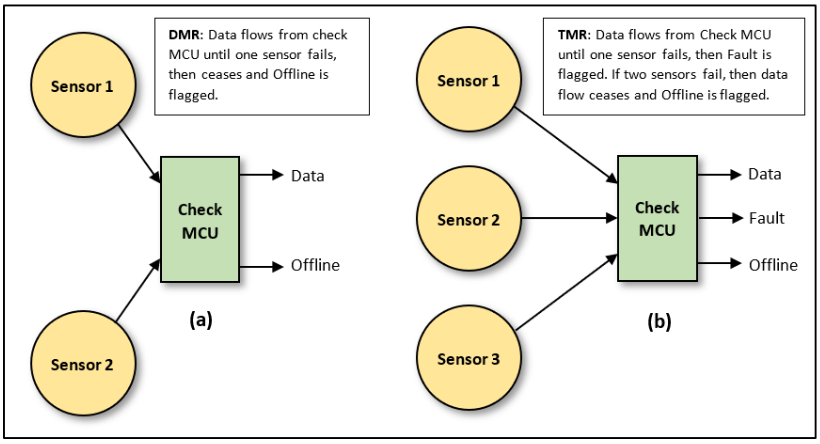


Figure 17-Design for Redundancy architecture used in Robot

With respect to reliability considerations and continuous improvement, DFMEA was conducted on subsystem and product levels. The process involved developing subsystem fault-trees, used to determine failure modes, for which possible mitigation scenarios were proposed. Fault trees and the complete DFMEA registers are shown in appendix K.

Design for Safety was another approach for avoiding any potential harm to CMS. Examples of such practices included ensuring non-flammability and water-resistivity, exemplified in figure 18.

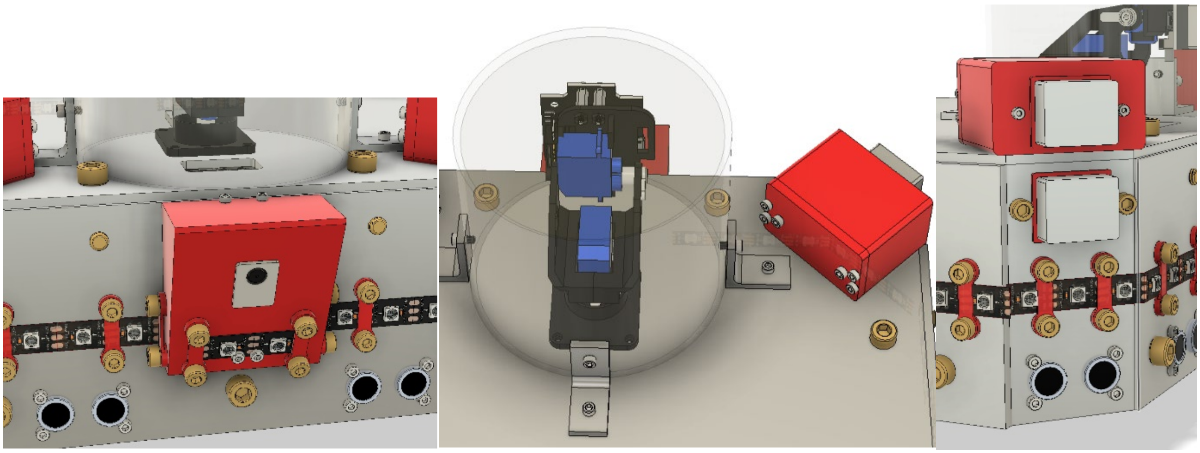


Figure 18- Practices of Design for Safety. The images show examples of design where damage to electronics is either avoided or minimised by limiting external contact.

Maintenance cycles for the CMS are limited, requiring the implementation of Design for Maintenance practices. These include ensuring the subsystems can be accessed and components are modularised for fast troubleshooting and replacement procedures. Inspired by 10 golden rules of Luttropp and Lagerstedt [25], practices of design for maintenance are exemplified in figure 20, where modularisation was exemplified in figure 19.

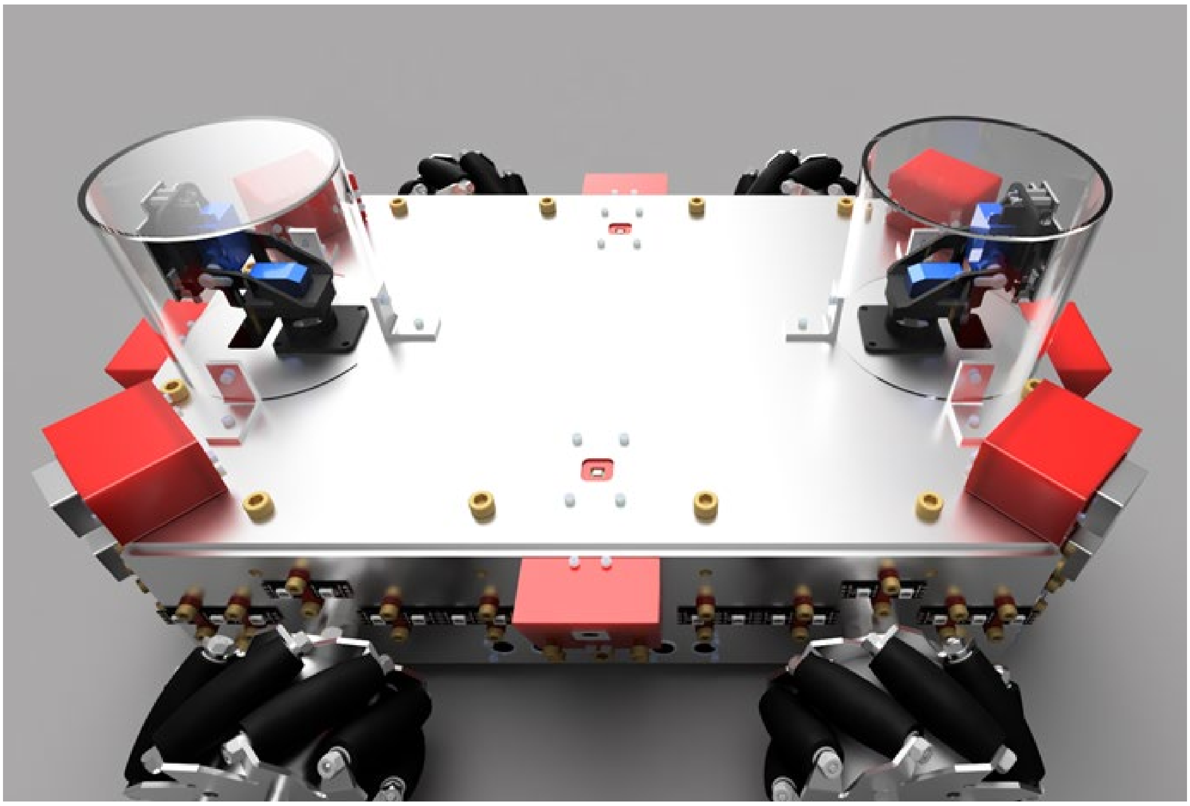


Figure 19- An example of design for maintenance. Notice how the components within can be easily accessed by removing the top plate and external components can be removed individually

Software Integration

Software integration is concerned with the compatibility of software functionalities and containment within one framework. The need for a software integration emerged in later stages of design, where inputs and outputs from functions needed to interact to achieve autonomy and robot intelligence. Software integration is concerned with the development of a middleware, where information can be passed between subsystems, for instance, from inspection to robot navigation.

For integrating functions, two alternatives methods were considered. Initial concept included using a generalised script, in Python for ease of adaptability, which would combine all aspects of the robot intelligence sequentially based on the robot intelligence algorithm, shown in appendix L. While this method could be successful where a hardware implementation is already achieved, it was not very likely to be actualised due to project limitations, imposed reduced flexibility in subsystem level and concurrent nature of the project, where subsystems were developed simultaneously with integration.

Another approach includes treating functions as nodes, which would communicate using a middleware, named Robot Operating System (ROS). ROS is a middleware[26] used to pass commands between functions. It allows scripts to be developed in different programming languages which can be continuously integrated through the use of well-defined system interfaces[27]. Furthermore, ROS provides a hardware abstraction layer[28], where hardware could be viewed as inputs and outputs, which offers adaptability to robots and allows the robot intelligence to be developed using simulated environments. Another advantage is the abundantly available scripts in the open-source community[29], as well adaptability of almost any script to ROS framework through simple modifications.

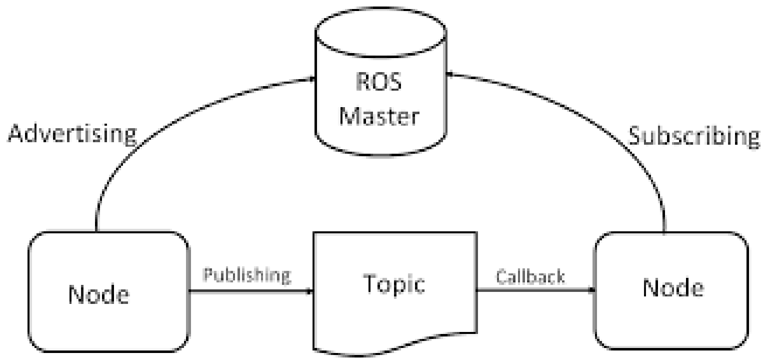


Figure 20-Publisher Subscriber Relationship of ROS

ROS is built on the Publisher-Subscriber relationship where messages are passed between nodes, monitored by the ROS Master, shown in figure 20. The process involves a node publishing a topic, a message that can feature unique message types such as string or joystick commands. This topic is called by another node, which subscribes, allowing two individual nodes to communicate without any interdependency to their functionalities.

A successful ROS implementation for robot intelligence would involve nodes that fulfil different functionalities. These nodes are managed by their own language-specific ROS node, which feeds these topics to the ROS Master environment. The relationships are shown in figure 21.

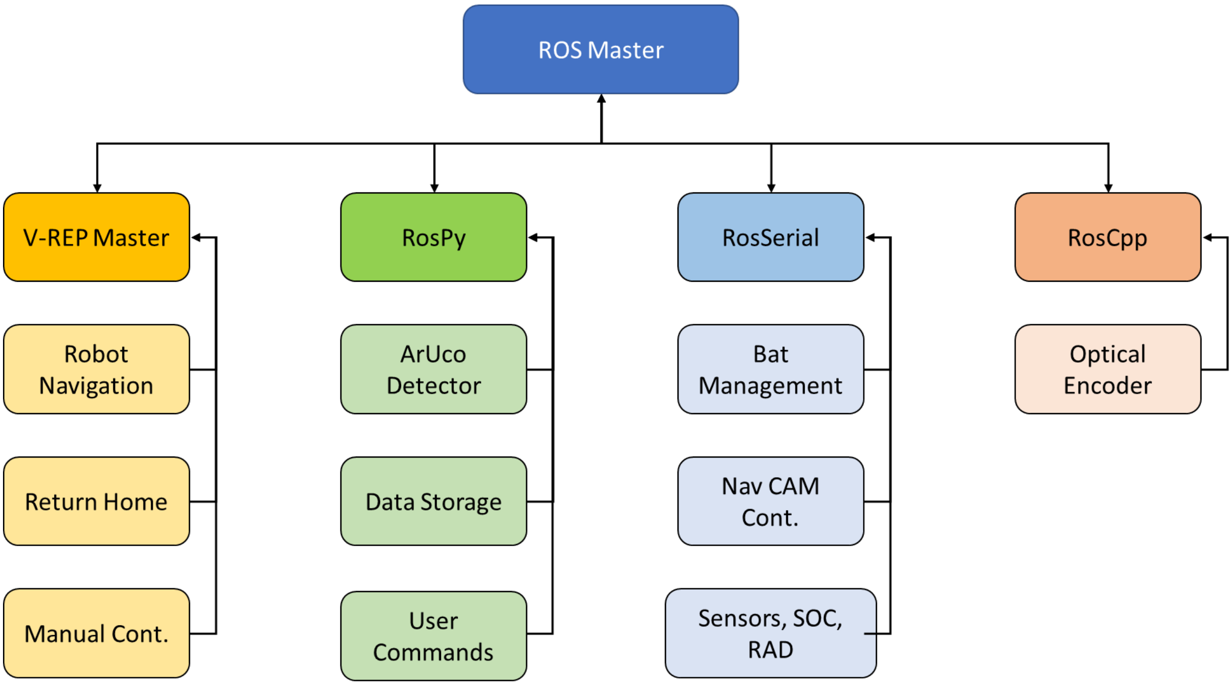


Figure 21- Nodes required for ROS implementation. Master nodes, shown in bold colour, manage individual topics from nodes based on programming language/software used.

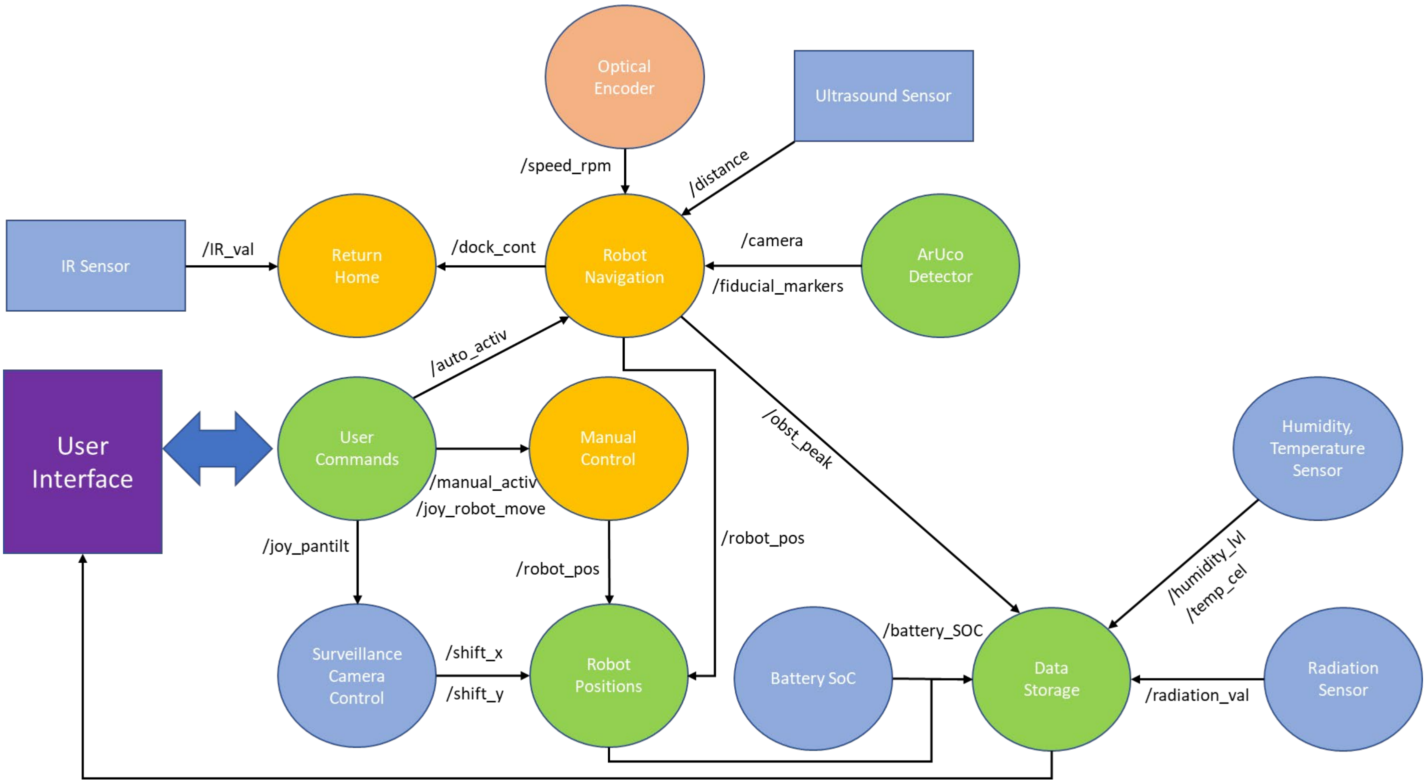


Figure 22-The simplified version of the proposed software architecture. Individual Functionalities are shown as nodes and connections in between relate to the topics to be communicated

Once the functions are communicating with the ROS Master, complete software integration can be achieved by building the relationships between nodes, summarised in figure 22. Details for node functionalities are investigated in individual technical subsystem reports, whereas for the detailed implementation of the framework, Appendix M can be referred.

While the complete implication of ROS is yet to be achieved, a proof of concept test was conducted to illustrate how such integration would work. The test involved use of a real ultrasound sensor, an Arduino and a ROS ready PC (Linux 18.04 Bionic Beaver), with CoppeliaSim, used for robot navigation software development and Arduino IDE, for reading sensor data.

The test included a script that read data from the ultrasound sensor in real-time using the Arduino IDE. The outputs were published under the node “Serial_node”. Using the ROS Master, the topic was called by a CoppeliaSim native script, which subscribed to the “Serial_node” and printed the sensor data to the CoppeliaSim Environment. Details regarding the test are in Appendix N.

The test case provides insight into how functions would be integrated using ROS. Similar to how CoppeliaSim native script subscribes to a real ultrasound sensor, the robot intelligence scripts can switch between simulated and real sensors, make intelligent decisions and provide outputs to peripherals, such as simulated or real servo motors, explained in figure 23. This confirms the validity of the integration method and provides a framework for future robot software integration.

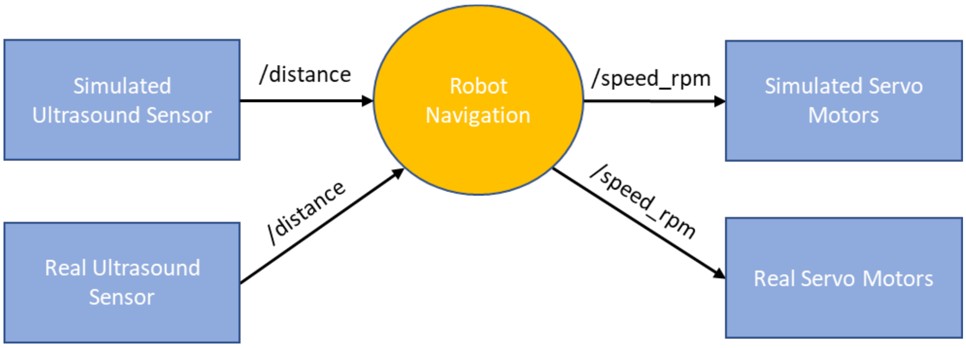


Figure 23- Hardware Abstraction illustrated by the Proof of Concept test

Furthermore, a partial python script is available, developed using catkin_make and Rospy modules, aimed to provide the groundwork for a potential user interface implementation. The script is available in Appendix O.

Project Management

Project Management includes the planning and organisational activities undertaken to achieve a successful product, utilising design methodology and tools.

For the organisation of tasks, a hybrid design model between the V-Model and Concurrent Engineering was selected, shown in figure 24. The V-Modelallowed for an effective breakdown of work structure which allows for validation of the product. Conducting activities concurrently (such as developing the integration of the product alongside the sub-systems) allows for fast adaptability [30].

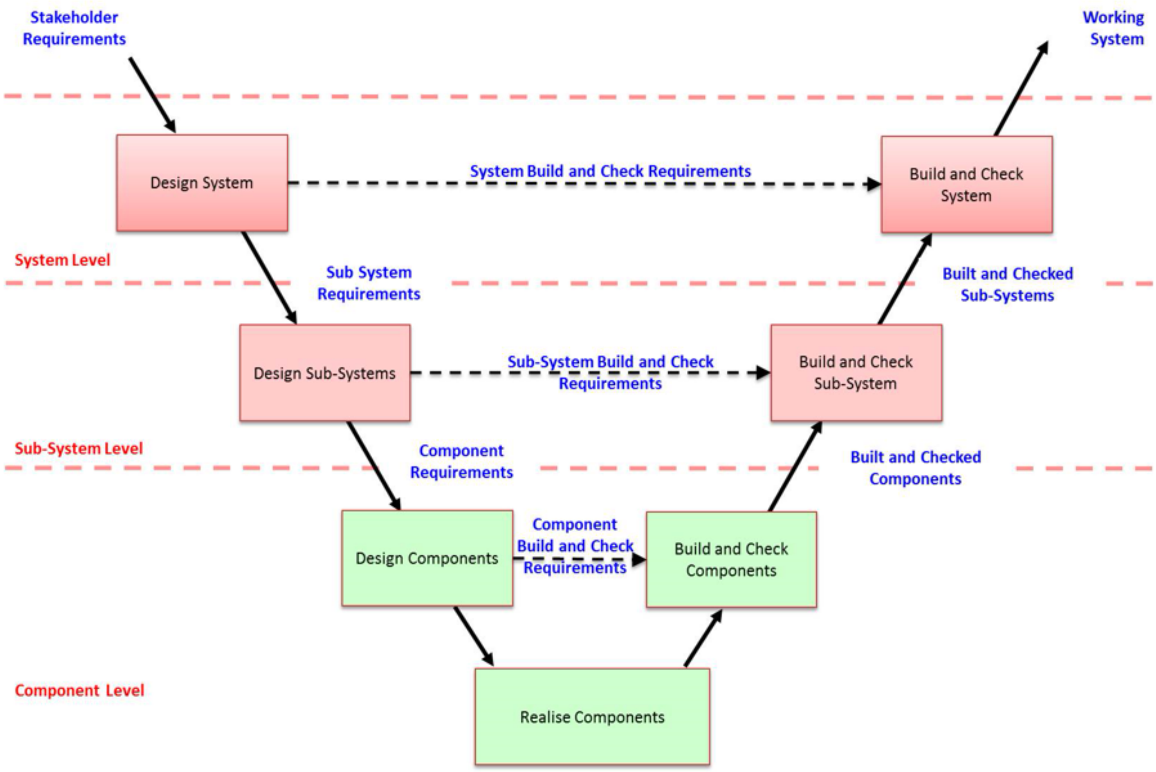


Figure 24- V model of Systems Engineering

Initial tasks regarding project management included conducting BELBIN tests and establishing a team charter, featuring rules of conduct and promote integration, transparency and collaborative decision-making. Establishing such ground rules allowed for clarity and accountability in the later stages of the project.

Other project management activities included the use of Risk Registers and Gannt Charts. The initial risk registers detailed project-wise challenges, mainly relating to resource limitations and inability to produce an accurate solution. The Gannt chart, available in Appendix P, provides a general overview of the project start to finish which allocated time slots for activities.

While such project management methodologies were successful, most long-term planning was made redundant due to the COVID-19 outbreak. This required reflection in the project planning, where project goals had to be more disassociated (unlike how prescribed in the V model and Gannt Chart.) Furthermore, a new framework for the project had to be introduced that could accommodate the new remote working environments.

Due to these reasons, the project structure was changed to a “lightweight” framework, based on examples from the industry that relied on online tools [31], illustrated in Figure 25. The framework emphasised on autonomy, transparency, and active monitoring of the team through the use of common platforms. Shorter planning intervals were utilised to accommodate the changing circumstances, which utilised the Outlook calendar for weekly and project planning, rather than the Gantt Chart. An example week and an iteration of the Kanban Board is shown in appendix Q.

On the subsystem level, this approach aimed to achieve separate work packages whereas, in system and product level, the aim was to establish frameworks that could accommodate them. This process was sustained through daily sit-down meetings, where active alignment and monitoring was achieved.

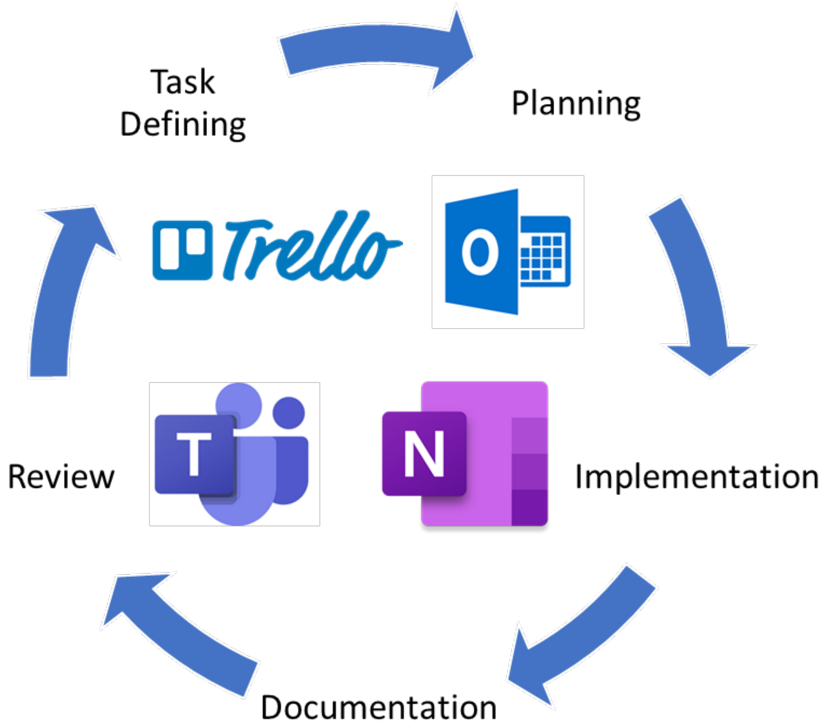


Figure 25- The workflow within the team. Trello allowed for Kamdan Styled project management where technical leads defined their own tasks an active documentation approach

Remote working circumstances resulted in more project risks, which are concerned with the wellbeing of the members. These risks are shown in Appendix R.

Final Proposal:

The project features outcomes at different levels of the design process, illustrated in figure 26. The final proposal consists of all these aspects, which are illustrated within a CAD Model.

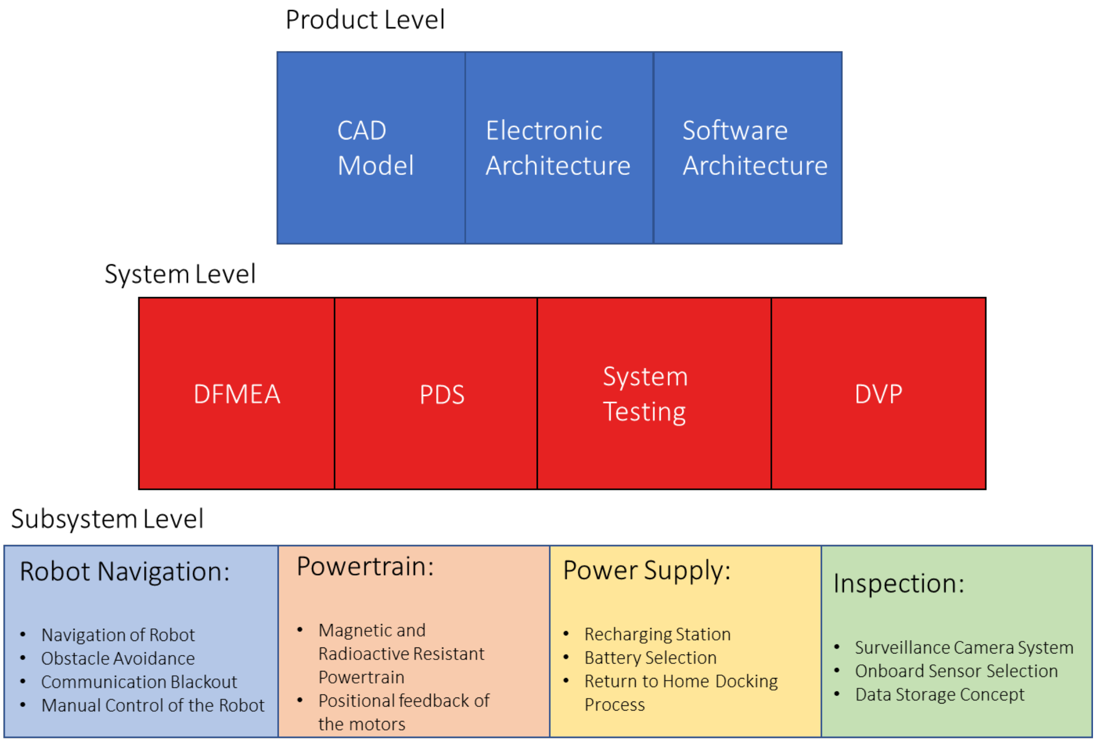


Figure 26-Project Outcomes

Figures 27 and 28 illustrate key components within the CAD model that embody concepts from different subsystems. The complete parts list is in appendix S, along with a cost estimation, which is £1485.

The proposed solution is an omnidirectional inspection robot featuring autonomous capabilities. The robot achieves all the system requirements, which were, being below 20cm, non-flammability and ability to overcome small obstacles of 5mm. An ideal inspection operation would involve autonomous surveillance, where the robot would be controlled through embedded systems onboard, that control all onboard surveillance systems; microphones, sensors, cameras etc. The robot would navigate the designated path of ArUco Markers placed on the floor of CMS and automatically survey the cavern using the surveillance cameras and stereo microphone system. Once the operation is completed, the robot would return to the closest charging station, placed in multiple corners of the cavern for added reliability.

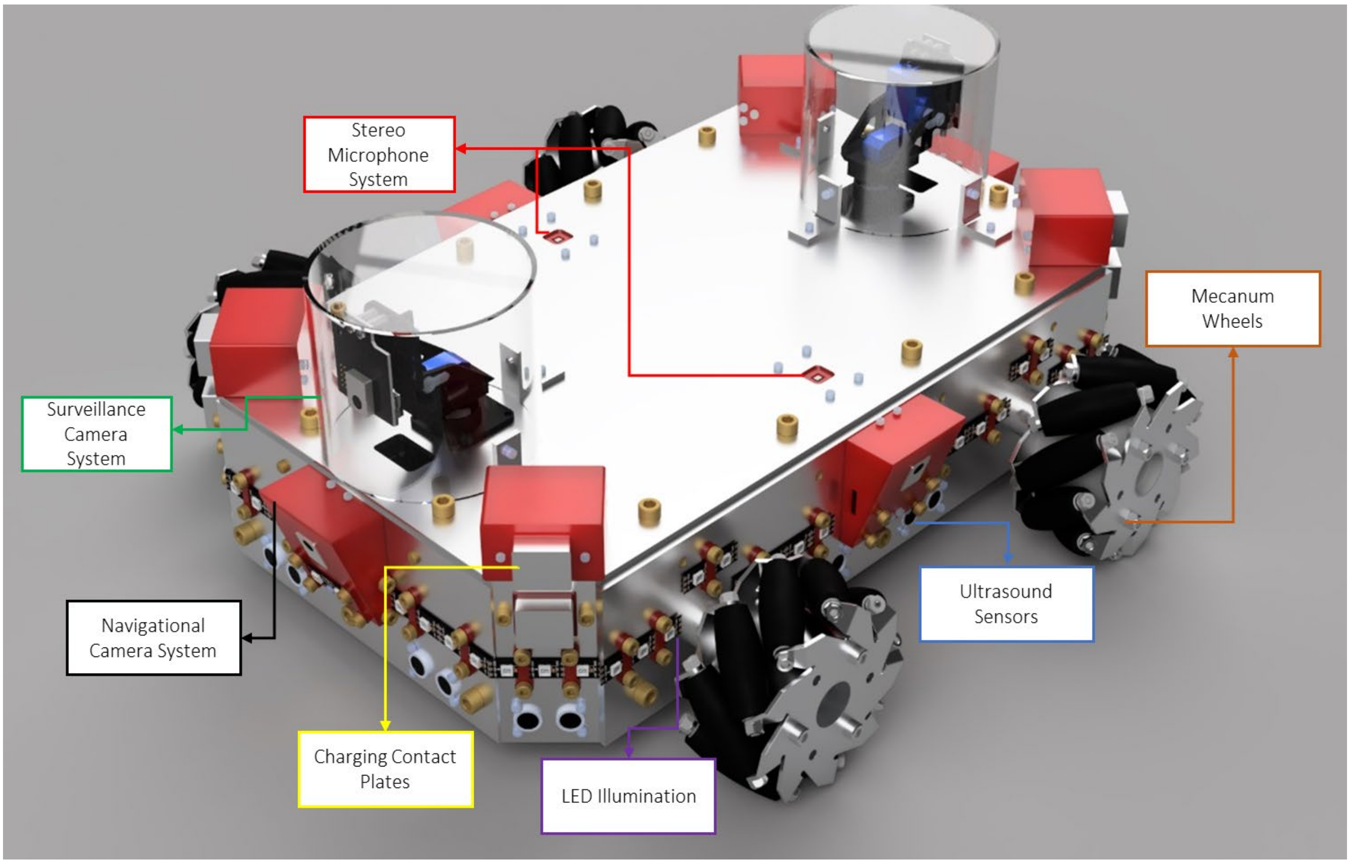


Figure 27-The proposed Robot Solution, with its' main components annotated

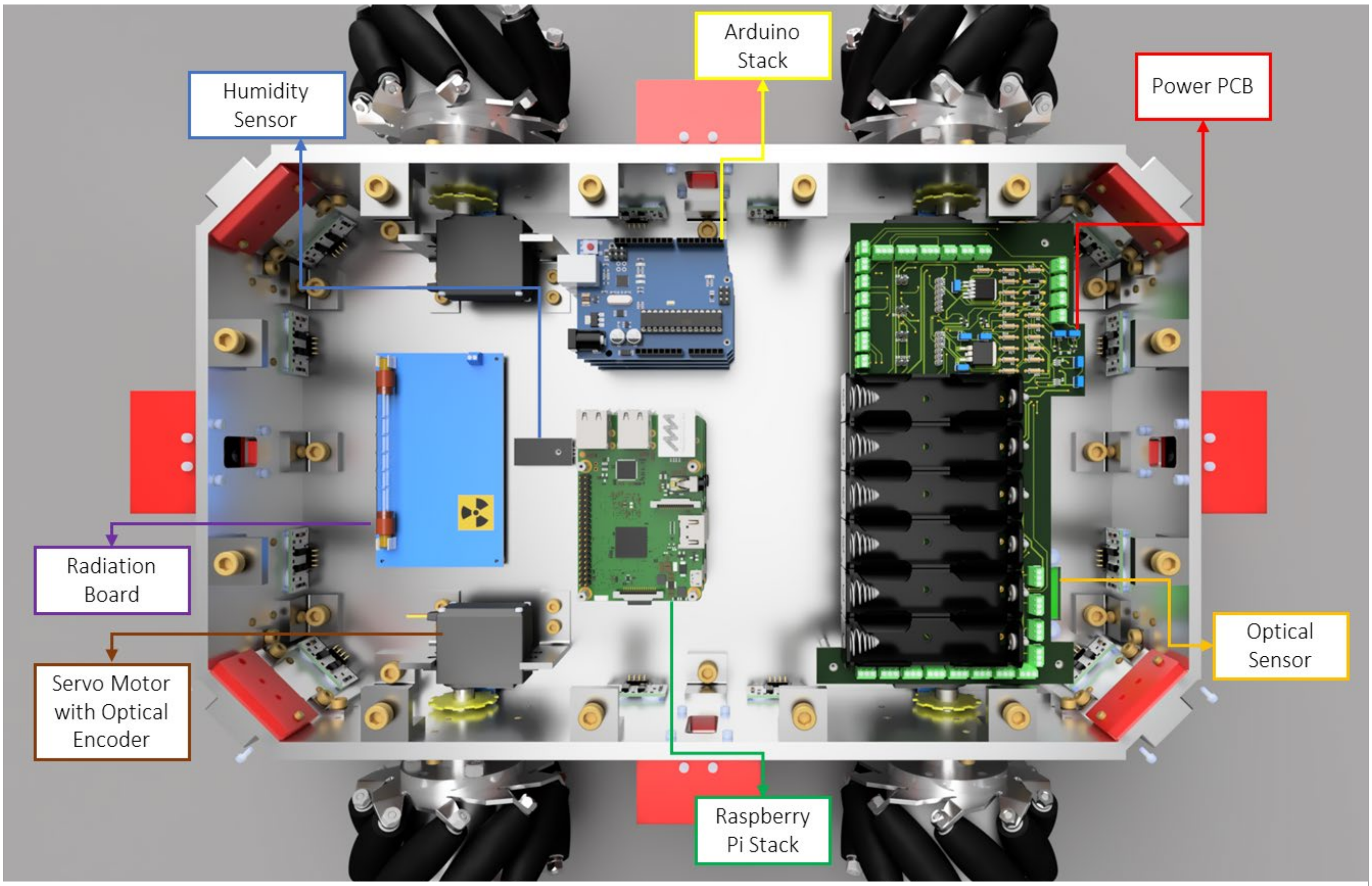
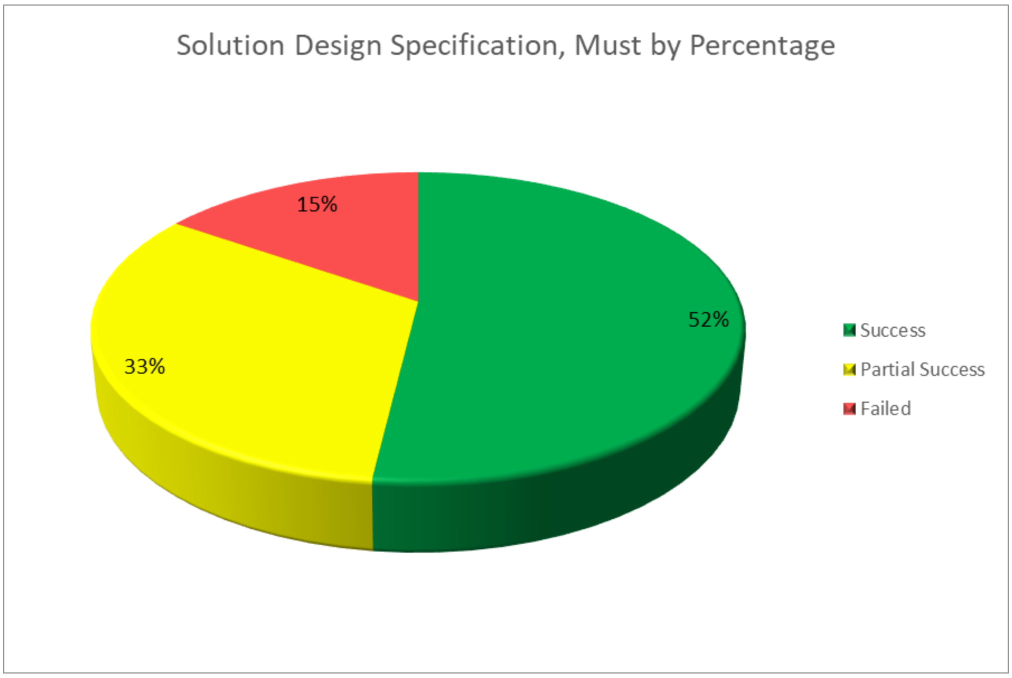


Figure 28-The inner components of the Robot with annotations



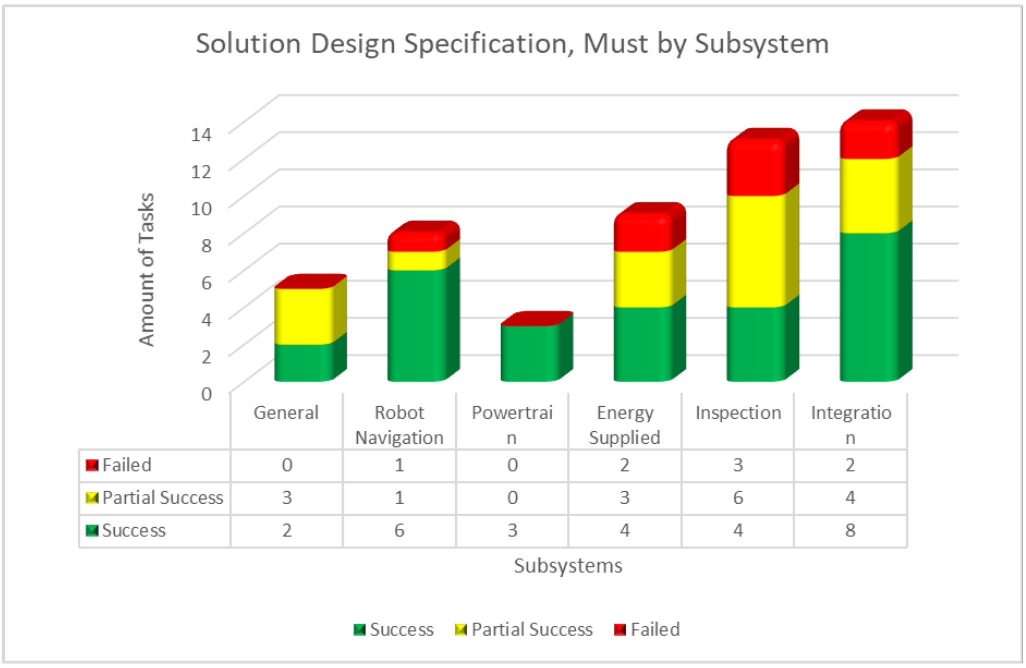


Figure 29 and 30 - Analysis of Solution Design Specification "Must" Criteria

Figures 29 and 30 refers to the Solution Design Specification (SDS), where requirements were evaluated regarding the PDS criteria. 52% of the “must” requirements were satisfied on the subsystem and system levels. Partial Successes refers to requirements that need further development/testing, and failure refers to inadequate development work. The complete Solution Specification is be viewed in Appendix T, with similar analysis conducted for wish requirements.

The analysis provides insights regarding the successes and limitations of subsystems, which is essential for the continuous improvement of the design process. These results are further investigated regarding the individual domains of the robot, which are hardware, mechanical and software.

Final Proposal Review

Hardware Development

Hardware development efforts were driven by the minimum hardware requirements needed for CERN; a camera, microphone, and control of the robot over Wi-Fi. During the design process, hardware implementation was expanded beyond the brief. Compared to the previous CERN project [32], the current iteration features more sophisticated components such as programmable cameras and optical encoders. Furthermore, modularisation of subsystems and the concept of sensor redundancy provides higher reliability.

While the hardware meets the initial requirements, limitations are present. These relate to the lack of physical validation, reflected in high amounts of partial successes in SDS for hardware-intensive subsystems such as Inspection. Under ideal circumstances, this could have been accounted for by running unit tests at different levels of the design process, prescribed in the Double V model, shown figure 31. For instance, during the design of Power PCB, this process could have been implemented by building sub-functionalities of the board using breadboards, after which these sub-assemblies would be combined and translated into a PCB, achieving a validated solution.

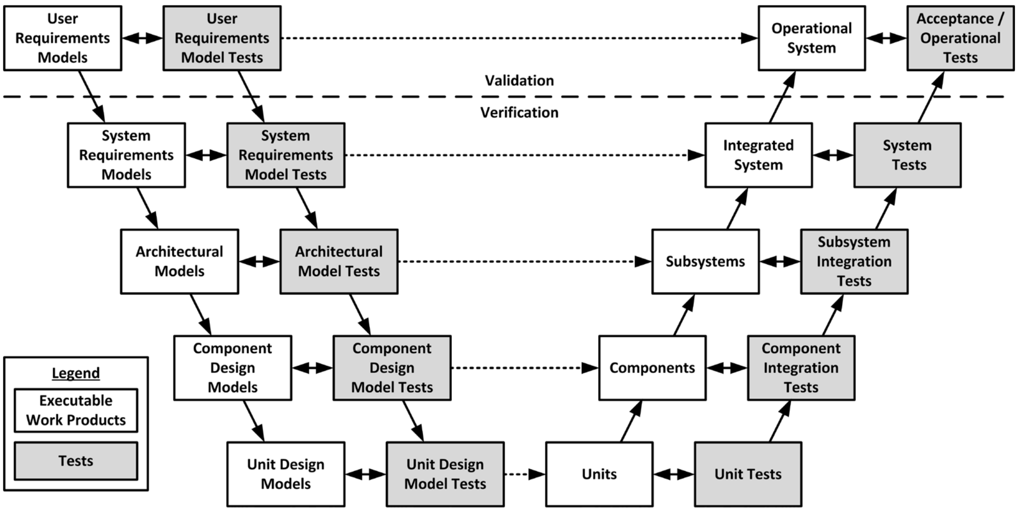


Figure 31 -The Double V Model

Another limitation is the implementation of the DFMEA Results. While the DFMEA considerations provided an insight into sophisticated issues for future iterations, their implementation and evaluation could have yielded a more reliable final proposal, specifically regarding the implementation of redundancy principles and thermal management.

Different approaches to hardware development could be undertaken, should the project were to be rerun. It can be said, while the resources and potential validation processes are limited, the outcome of a hardware implementation would yield similar results e.g. similar sensors/motors will be selected. To avoid a future exact rerun of the project, a higher emphasis on hardware abstraction can be placed, especially in earlier stages of design. This would involve focusing on the functionalities the hardware provides, similar to the structure used in H-ROS [33], where an actual hardware implementation would be considered in later stages of design. This could lead to the exploration of more advanced hardware concepts through extensive use of virtual environments and facilitate the development of sophisticated robot intelligence.

Another method to enhance future results could be through platforming [34], where the current robot architecture would provide a base model, which would be upgraded through the existing, well-defined system interfaces. This can be achieved by the addition of more boards, similar to the power PCB, and stacking more microcontrollers and embedded systems should the system requirements increase.

Mechanical Development

The aim of the mechanical implementation was to build a robot that can withstand cavern conditions. This was achieved by implementing two risk management methods: avoidance and mitigation. Avoidance strategy involved precise component selection, for instance avoiding to use components with inductors such as buck converters. Mitigation strategies involved implementing countermeasures; such as the application of Magnetic Shielding material to high-risk components as embedded systems. Free space within the robot allows for further mitigation implementations; such as placing a lead box on the embedded systems for gamma radiation resistance. This process could be further optimised iteratively within the CMS cavern.

Compared to the previous CERN robot, the robot offers more advanced mechanical solutions such as Mecanum wheels and machined parts. These increase the durability of the final proposal aimed to satisfy the strict maintenance and environmental requirements. Other benefits include the implementation "Design for X" considerations, which are reliability, maintenance, and safety which improve the quality of the proposal.

The design process showed that the quality of the mechanical model increased with each iteration. The CAD environment provides a faster means of exploring ideas, especially in earlier stages of design. However, as the CAD model increased in parts count, such design iterations became harder to perform due to computational limitations. An ideal design process would have included prototyping as well, where lightweight CAD models would be utilised in earlier stages of design and partial prototypes would have been utilised to validate individual concepts within the CAD model. Furthermore, in earlier stages of design, mechanical development processes could be extended to virtual environments, where different concepts could be modelled, specifically in powertrain development.

A unique challenge faced during the design process involves the optical design, which could have been considered as the sub-system level activity. Optics, which involves the selection of cameras and illumination concepts, was realised to be an essential consideration for a surveillance task. While solutions were offered for both illumination and cameras, these results require further validation. A software approach for such development could involve use of Zemax [35], which is an industry common tool for simulating optical conditions and parameters such as image quality.

Software Development

Initially, due to the more obvious, physical technical challenges faced within the cavern, the software aspects of the project were less prioritised. However, the development of individual software packages led to the potential of developing a fully autonomous robot to be realised, which was validated by CERN. While these outcomes do not represent the initial brief nor the previous CERN projects, it provides unique benefits such as continuous surveillance routines.

Software development in subsystem level consists of developing individual work packages that contribute to the robot intelligence, the umbrella term used for non-low-level software activities. Based on the SDS, Robot Navigation has been able to satisfy most of its' "must" criteria. This success can be attributed to the use of simulated environments in the design process, which allowed functions to be developed with respect to their use cases and allowed unit tests to be conducted. These results validate the importance of virtual tools in design processes, which could be extended to other subsystems through principles of hardware abstraction. In addition, during the design process, low-level scripts, such as sensor read-outs, were developed to achieve individual functionalities, such as detecting an ArUco marker. A better approach would have been importing these files from ROS libraries and allocating more time to the development of the high-level robot intelligence functionalities.

Product Level software activities included the establishment of the ROS framework that illustrates the communication between nodes, as proved by the test case. While the proof of concept scenario illustrates how would a ROS implementation work, a better test case could have included tethering real sensor data to a robot model in the CoppeliaSim Environment and evaluating its' performance tp simulated ultrasound sensors within the software. Furthermore, the test case could have been extended to feature other onboard sensors, such as the optical sensors. The software integration approach includes the use of ROS architecture that allows for fast integration between nodes. There are no apparent disadvantages to ROS as it is highly modular and customisable.

The main limitations relate to the application of scripts in a real robot. While software functionalities can be validated in simulated environments, hardware errors are expected which can range from sensor defects to misalignment between the Mecanum wheels. Due to the safety requirements within the CMS Cavern, these scripts should be tested before any application.

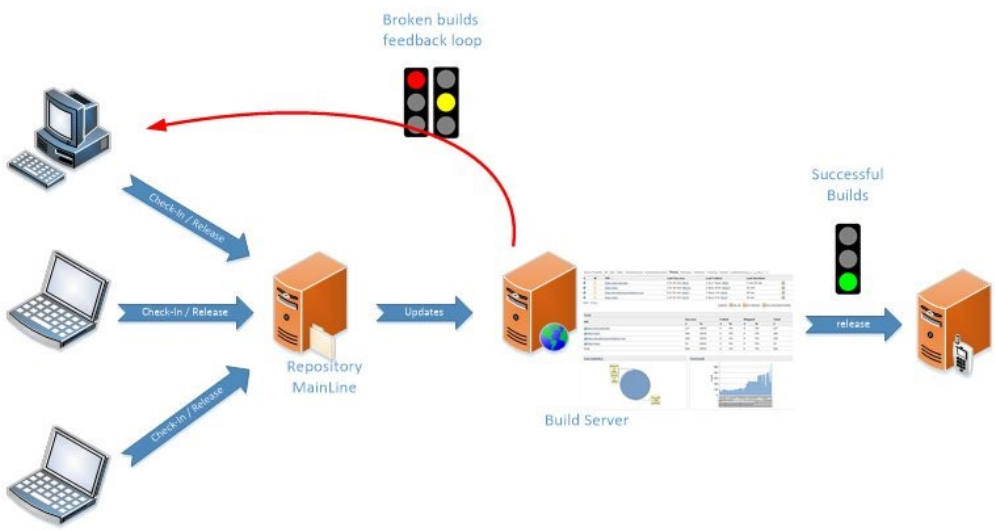


Figure 32-The Workflow for Continuous Integration

In future iterations, the project structure should reflect the software development processes as well. This can include the use of collaborative virtual machines[36], which is an emulation of a physical computer. The virtual machine could provide a common workplace for all team members and could potentially avoid mismatches between the operating environments. Another implementation could feature the use of repositories for version controlling and the continuous integration of the software packages. Continuous Integration refers to the practice of merging individual software packages to the main repository constantly through a mainline after the package is inspected by an automated acceptance test, explained in Figure 32. Extending Continuous Integration principles to the project could involve producing an automated test framework that would check the software packages through the use of virtual environments. In addition, the customer validation process can be accelerated by sharing the repository with CERN, where the customer can check and provide feedback regarding the software outcomes on a rolling basis.

Project Review

While considerations regarding hardware, mechanical and software development relate their own domain, project considerations relate to the approaches taken for the complete robotics development project.

The V model, facilitating the division of tasks, formulates a methodology from start to finish of the project. As the project was aimed to deliver a specific solution, a surveillance robot, this approach was the logical choice to ensure a product is delivered at the end of the project. While this approach was successful, its' limitations must be critiqued. These include long integration periods, even when compensated through concurrent engineering, increased cost of changes at later stages of design, apparent isolation between system-level activities and subsystems and versioning issues.

An alternative approach could have included the implementation of principles of continuous development[37], illustrated in figure 33, inspired by Continuous Integration. This includes an iteration process on subsystem level until acceptance conditions are met, which is followed by a system acceptance test process, followed by a quicker release cycle, where individual aspects of the project could be validated by the customer. Such implementation could feature a focus on hardware abstraction where faster development cycles can be conducted using virtual environments with an automated testing process that checks the functionality achieved, as well as the conformity of the individual function to the project framework, reducing the integration effort needed on the product level.

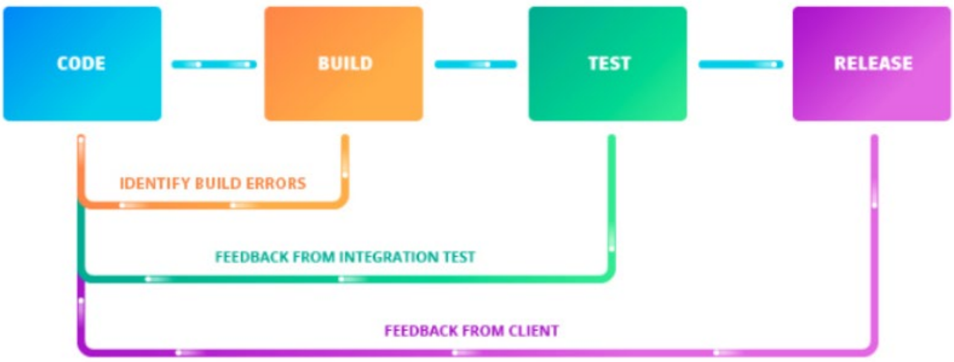


Figure 33-Implementation of Continuous Integration Framework as a Product Development Tool

Furthermore, improvements to the existing project methodology could include an active task tracking process through the use of burndown charts[38], that monitors the progress of each task completed within a sprint. This information could be used to determine the team velocity and the projected completion date, explained in figure 34, and lead to identifying bottlenecks within the project.

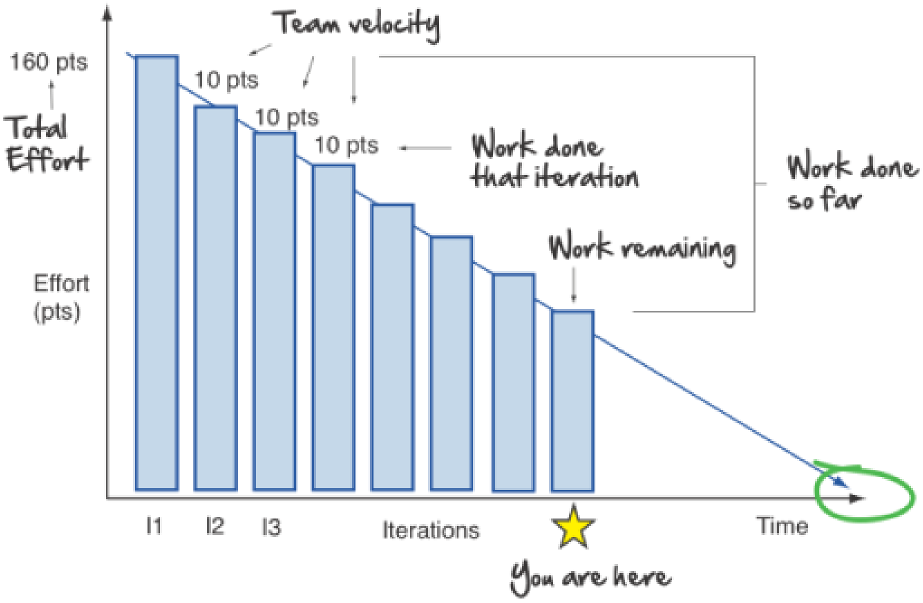


Figure 34-An example burndown chart that could be used in combination with the Kandan board methodology

Conclusion

Designing a surveillance robot for the CMS Cavern requires the implementation of multiple engineering domains, which are mechanics, electronics and software. Implementation of these domains had to be accounted for in every subsystem, as well as on the product level.

On the product level, three main project outcomes can be presented; Hardware Architecture, Software Architecture and a CAD model. The Hardware Architecture features a flexible system concept where subsystems are modularised. In addition, the architecture allows for future upgrades and customisation to facilitate a hardware-agnostic software development process, where the hardware can be expanded based on the functionalities required. Software architecture proposes the use of ROS, a middleware used to pass messages between nodes, which are localised software functions. ROS allows for a modularised, hardware abstracted and language-independent software development process and an integration framework. Furthermore, ROS is essential for the actualisation of the scripts developed in virtual environments, as proven by a test case. The CAD model visualises all the design decisions taken on subsystem level, which results in an omnidirectional inspection robot featuring autonomous capabilities. The model satisfies all system requirements, which are being below 20cm, non-flammability and ability to overcome small obstacles of 5mm.

With the conclusion of the CERN project, these results could form a basis for any future work. While a full robot solution was not actualised, exploration of the design space allowed the discovery of new project goals, such as the implementation of robot intelligence. Any future work should reflect on these outcomes and through the iterative nature of design, a complete surveillance robot solution can be achieved.

References:

[1] A. Ege, “20200304_IndividualFeasibilityReport_EA_04.pdf.” Bath, 2020.

[2] T. Sakuma, “SketchUp 3D model of CMS detector - CERN Document Server,” 2019. https://cds.cern.ch/record/2677903 (accessed May 27, 2020).

[3] S. Harry, “CMS Project Codes.” p. 100, 2016.

[4] A. Ege, “20200324_EPRAPRESENTATION_GRPWRK_01.” Bath, 2020.

[5] NASA, “How Gamma-rays are Generated,” 2010. https://imagine.gsfc.nasa.gov/science/toolbox/gamma_generation.html (accessed May 27, 2020).

[6] S. Harry, “CMS Intro Presentation,” pp. 401–406, 2017, doi: 10.1201/9780203741771.

[7] B. Sun, “Powertrain Subsytem Technical Report,” 2020.

[8] J. Tattershall, “Robot Navigation Subsytem Technical Report,” 2020.

[9] G. Jackson, “Inspection Subsytem Technical Report,” 2020.

[10] N. di Cagno, “Power Supply Subsytem Technical Report,” 2020.

[11] R. Liang, “System Testing Technical Report,” 2020.

[12] M. Rouse, “What is an Embedded System?,” 2020. https://internetofthingsagenda.techtarget.com/definition/embedded-system (accessed May 27, 2020).

[13] M. Björk and E. Hällfors, “THE CONCEPT OF MODULARIZATION AND THE DEFINITION OF A MODULE-An investigation and comparison of two successful companies within the automotive industry,” 2015.

[14] S. Vigeant, “How To Find (and Eliminate) Single Points of Failure,” 2015. https://www.dataev.com/it-experts-blog/how-to-find-and-eliminate-single-points-of-failure (accessed May 27, 2020).

[15] S. J. Vaughan-Nichols, “Build your own supercomputer out of Raspberry Pi boards | ZDNet,” 2013. https://www.zdnet.com/article/build-your-own-supercomputer-out-of-raspberry-pi-boards/ (accessed May 27, 2020).

[16] C. Miller, “How a device-agnostic approach could improve your design,” 2019. https://uxdesign.cc/how-a-device-agnostic-approach-could-improve-your-design-190585fdb0e7 (accessed May 27, 2020).

[17] R. Tyrsina, “How to prevent the Raspberry Pi 3 from overheating,” 2017. https://windowsreport.com/fix-raspberry-pi-3-overheating/ (accessed May 27, 2020).

[18] AA Portable Power Corp, “Smart LED Balance Module for 3.2V LFP Cell with 250mA Balance Current for LFP-G40 LFP-G60 LFP-G100.” https://www.batteryspace.com/Smart-LED-Balance-Module-for-3.2V-LFP-Cell-with-250mA-Balance-Current-for-L.aspx (accessed May 27, 2020).

[19] “Power Supply - Raspberry Pi Documentation.” https://www.raspberrypi.org/documentation/hardware/raspberrypi/power/README.md (accessed May 27, 2020).

[20] A. Madesi, “UXC55 Inspection Robot,” 2019.

[21] Non-Ferrous Fastener Inc., “Non-Ferrous Fastener Inc.” https://www.non-ferrousfastener.com/metal_specs.php (accessed May 27, 2020).

[22] MetalsCut4U, “Which Sheet Metal is Magnetic?,” *2018*. https://metalscut4u.com/blog/post/which-sheet-metal-is-magnetic.html (accessed May 27, 2020).

[23] B. Marshall, “When Redundancy is a Good Thing,” 2019. https://www.rs-online.com/designspark/when-redundancy-is-a-good-thing (accessed May 20, 2020).

[24] ROBOTEQ, “Driving Mecanum Wheels Omnidirectional Robots.” https://www.roboteq.com/applications/all-blogs/5-driving-mecanum-wheels-omnidirectional-robots (accessed May 27, 2020).

[25] C. Luttropp and J. Lagerstedt, “EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development,” 2006, doi: 10.1016/j.jclepro.2005.11.022.

[26] “Industrial - ROS Wiki.” http://wiki.ros.org/Industrial (accessed May 25, 2020).

[27] ROS, “ROS.org | Core Components.” https://www.ros.org/core-components/ (accessed May 27, 2020).

[28] ROS, “Hardware Abstraction Layer [Real-Time Robotics Framework].” https://wiki.eeros.org/eeros_architecture/hal/start (accessed May 27, 2020).

[29] ROS, “ROS Index.” https://index.ros.org/packages/ (accessed May 27, 2020).

[30] A. Ege, “SG-1 Presentation,” 2020.

[31] Mendix, “Agile Framework – A Quick Introduction & Overview of Agile Project Management Methodology.” https://www.mendix.com/agile-framework/ (accessed May 27, 2020).

[32] A.B.Ghosn, “UXC55 Inspection Robot - Smart Material.”

[33] “Hardware Robot Operating System (H-ROS) - ROS robotics news.” https://www.ros.org/news/2016/10/hardware-robot-operating-system-h-ros.html (accessed May 27, 2020).

[34] P. Moss, “Product Strategy for GBDP 2020.” 2020.

[35] ZEMAX, “Leading Optical Product Design Software for Engineering Teams - Zemax.” https://www.zemax.com/ (accessed May 27, 2020).

[36] V. Augustine and B. Robinson, “Using virtual machines for collaborative research,” in *ESEM 2010 - Proceedings of the 2010 ACM-IEEE International Symposium on Empirical Software Engineering and Measurement*, 2010, doi: 10.1145/1852786.1852836.

[37] J. Luetgebrune, “Continuous Development: How Iterative Processes Can Improve Your Code,” 2018. https://deploybot.com/blog/continuous-development (accessed May 28, 2020).

[38] Agile in A Nutshell, “Burndown Charts.” http://www.agilenutshell.com/burndown (accessed May 28, 2020).

Appendices:

Appendix A

Product Design Specification

Table 1-Product Design Specification

System	Sub-System	Requirement	Must/Wish	Success Criteria	Stakeholder
General	Maintenance	Sub-system maintenance	Must	All sub-systems should not require maintainenance for at least 6 years	ALL
	Magentic Field	All sub-systems to be unaffected by the Magnetic Field that is generated by the CMS	Must	Performance/functionality of all sub-systems to be unaffected by generated magnetic field (Peak: 100mT). Non-ferrous materials to be used for all components and fastners (where applicable). Electronic circuits to be designed to be to be inherently unaffected by the magnetic field. Magne	ALL
		Robot moving slowly to prevent electeronic devices disfunction due to high induced current generated	Must	The maximum speed of robot is below xx m/s	ALL
	General	Maximum height	Must	Robot should be no more than 20cm in height	ALL
	Radiation	All sub-systems to be unaffected by the Radiation that is generated by the CMS	Must	Performance/functionality of all sub-systems to be unaffected by generated radiation. Radiaton hardened materials. Radioactive Shielding	ALL
	Thermal Management	All sub-systems to be thermally managed	Wish	Monitor and detect potential thermal runaway events. Minimise risk of components overheating (Ensure temperature remains in allowable ranges)	GJ / ALL
Robot Control	Vision	Obstacle avoidance	Must	Able to locate and avoid obstacles at least x mm away	JT
		Contain at least 2 navigation sensors for system reliability and detection performance	Must	Able to navigate round a course despite a 'communication blackout'	JT
		Location/path markers to be inconspicuous	Wish	Minimise the quantity and size of location markers	JT
	Control	'Manual' control mode	Must	Able to survey CMS cavern with human input	JT
		'Return to Home' control mode	Must	Able to return to the charging station without human input	JT
		'Autonomous' control mode	Wish	Able to survey CMS cavern without human input	JT
		'ClickNGo' control mode	Wish	User able to 'Click' on a preset grid location and the system will autonomously navigate to the selected point	JT
		'Default Blackout' control mode	Must	If in 'Manual' mode and in a 'communication blackout', system is able to re-traverse its steps until it has resumed communication with the user	JT
		System able to locate itself during a 'communication blackout'	Must	System able to re-locate, re-oritentate and continue with its operations during a 'communication blackout'	JT
		Path optimisation in ALL control modes	Wish	System able to optimise its path back to the charging station when in ALL control modes	JT
	Hardware/Software	Large enough memory to store the required preset data for all control modes	Must	Sub-system will require at least x GB of SSD storage	JT
		Large enough memory to store all measured data that is not immediately transmitted i.e. during a 'communication blackout'	Must	Sub-system will require at least x GB of SSD storage	JT / GJ
		Intuitive User Interface	Wish	User will not require any significant training; system to have intuitive and memorable controls to system functions	JT
Powertrain	Steering	Able to navigate over small gaps and uneven terrain that is characterstic of the topography in the CMS cavern	Must	Large enough wheel/tracks that are able to overcome any small gap (longitudinal: 60mm) and uneven surface (longitudinal: 5mm)	BJ
		Suspension system	Wish	Camera Monitoring System (CMS) is unconditionally stable despite terrain disturbances	BJ
		Optimised steering system	Wish	Minimum number of components to provide a reliable/robust steering system	BJ
	Transmission	All-wheel Drive	Wish	Wheels/Tracks are able to be driven individually	BJ
	Motor	Generate suitable power for navigational requirements	Must	System able to generate sufficient power for movement. System able to overcome any small gap (longitudinal: 60mm) AND uneven surface (longitudinal: 5mm)	BJ
		Precise control over system maneouvrability for navigation purposes	Must	Suitable motor for navigation requirements	BJ
Energy Supplied	Battery	Rechargeable battery	Must	Minimum battery cycle life of x hours	NDC
		Thermal resistance	Must	System must not exceed a maximum operating temperture of x °C	NDC
		Isolate critical failures	Must	System must reduce the possibility for acid leak, combustion or explosion	NDC
		Generate sufficient power for all sub-system demands	Must	Minimum operating time at full load of x hours	NDC
		Battery redundancy	Wish	Minimise complete battery failure by having multiple batteries in parallel	NDC
	Recharge Station	Fail-Safe Mechanical Docking system	Must	System ensures that battery and charging station will always make electrical contact to maximise transimission efficiency. Minimum approach angle window of x °	NDC
		Fail-Safe Mechanical Release system	Must	System ensures that battery and charging station will always de-couple	NDC
		Support Fast Charging	Wish	Battery charges to x % capacity in y mins	NDC
		Charging station to be unaffected by the CMS Magnetic Field AND not affect the CMS Magnetic Field	Must	Charging station to be able to transmit power to the battery module without to/from disturbance from magnetic field.	NDC
		AC to DC power conversion	Must	Able to convert energy supply from 230V to 12.8V - AC/DC. Safety critical	NDC
		Charging station to remain stationary during recharge process	Must	Evidenced by simulation. Charging station should remain stationary during the recharge process	NDC

Inspection	Positional Sensor	Sensor of sufficient resolution for fiducial marker detection	Must	Ensure sufficient resolution for system to detect fiducial marker. X K resolution	GJ
		Sufficient conditions for fiducial marker detection	Must	Illuminate floor sufficiently for the control system to identify the fiducial markers. Optimal image saturation	GJ
		Sensor stabilisation	Must	Ensure sufficient stabilisation for system to detect fiducial marker	GJ
	Surveillance CMS	Control CMS linear vision	Must	System able to be manipulated about longitudinal axis for linear vision control	GJ
		Control CMS area vision	Must	System able to completely survey the external area of the CMS machine and any input/output pipes/electrical wiring. Multiple rotational axes for area vision control	GJ
		Control camera zoom	Must	Able to view a potential issue at a sufficient (x mm) size and sufficient (K mm) image resolution.	GJ
		Capture quality images for sufficient leak/damage detection	Must	Ensure highest image quality without compromising data transmission time. X K resolution	GJ
		Sufficient light-level for optimum image saturation	Must	Illuminate cavern sufficiently for the user to detect and identify leaks/damage. Optimal image saturation	GJ
		Camera stabilisation	Must	Ensure sufficient stabilisation to control the image quality for the user to detect and identify leaks/damage	GJ
	Microphone	Capture quality sound recording	Must	Ensure best sound quality without compromising transmission time	GJ
		Detect location of source noise	Wish	System able to detect where the source of the noise is from. Acoustic Camera Array	GJ
		Noise analysis	Wish	Analyse amplitude spectra against frequency of the recorded data. Isolate frequency components. Spot anomalous frequencies	GJ
	Battery Monitoring	Determine individual battery levels of battery module	Must	Monitor the battery module charge accurately. Estimate time remaining before the 'Return to Home' control mode is executed	GJ
		Determine individual battery healths of the battery module	Wish	Monitor the time to re-charge, capacity and discharge rate of the batteries in the battery module and suggest to user when a new battery module is required	GJ
		Determine individual battery temperatures of the battery module	Must	Monitor AND manage the battery temperature	GJ
		Determine individual battery voltage and current levels of the battery module	Must	Monitor the battery current AND voltage output and sub-system current AND voltage inputs	GJ
	Temperature	Monitor temperature of the cavern environment	Wish	Monitor and detect thermal risks within the cavern	GJ
Integration	Packaging	Package all modular sub-systems into system architecture. Optimise sub-system layout	Must	Ensure all sub-systems are completely integrated and installed into the frame of the product. Ensure sub-systems do not clash/collide with each other AND do not impede each others function.	EA
		Meet target dimensions	Must	System must be less than 200mm (longitudinal height)	EA
		Durable materials	Must	All materials to withstand damage for at least 3 years	EA
		Minimise material volume	Wish	Volume of material used in a component is to be kept at a minimum for improved sustainability footprint	EA
		Modular design for all sub-systems	Wish	Modular design for improved maintainability and repair. Improved access to sub-system level components. Allow for easy module substitution if damaged	EA
		Structurally robust and able to withstand impact without sub-system damage	Must	System able to withstand x N of force	EA
		Minimise vibration transmitted to sub-systems	Must	Attenuate all modes of vibration so that there is no significant material/sub-system displacement	EA
		Ease of manufacture and assembly	Must	Ensure system and sub-systems can be built and assembled using conventional manufacturing methods/tools. Minimise the number of tools used	EA
		Weight distribution	Must	System is unconditionally stable during all use-cases	EA
		Aesthetically pleasing with Ergonomics for handling	Wish	System is attractive and minimises strain to user when carrying	EA
	Safety	All electrical component AND wiring fixed in placed and stowed away	Must	All electrical wiring to be enclosed in package	EA
		Ingress Protection for electrical components AND wiring	Wish	All electrical sub-system components to be electrically sealed against water	EA
		Non-Flammable	Must	Non-flammable packaging shell. All sub-system modules to non-flammable (where applicable)	EA
	Efficiency	Optimised structural parts	Wish	Structural parts are geometrically optimised to reduce part count/material	EA
		Cost	Must	The final of price of X is met. The cost of research, design and development is completely covered by the budget	EA
	Product Architecture	Real time Operation	Must	The Control Unit controls robot in real time	EA
		Software can control I/O and analogue outputs	Must	Digital and Analogue outputs can be controlled using the Hardware interfaces	EA
		Efficient Computing	Must	Software/Hardware ran by Control Unit must be efficient to allow for real time computing	EA
		Systems Interface	Must	Components used interface with each other correctly and are compatible	EA

Appendix B
Design Validation Plan

Table 2- The Design Validation Plan

System	Sub-System	Stakehold	ta so	Number	Virtua test	Test Function 1 Item to validate		Function 2 Item to validate
General	Maintenance	ALL	/	/		No test	NO TEST	NO TEST
	Magentic Field	ALL	/	1		Sub-systems are unaffected by magnetic field	Test the prototype in MRI room	NO TEST
	Radiation	ALL	/	/		NO TEST	NO TEST	NO TEST
	Thermal Management	GJ / ALL	/	2		Detect potential hotspot and get avoid from it	Put the heat source near the prototype	NO TEST
Robot Control	Vision	JT	Test	3	√	Locate and avoid obstacles	Place obstacles in the path that the system is attempting, and check if it recognises and avoids	Avoid obstacles with smallest path length
		JT	/	4	√	Able to navigate round a course despite a 'communication blackout'	System navigates with respect to fiducial markers under no Wi-Fi condition	NO TEST
		JT	/	5	√	Size and quanity of fiducial markers	Place ArUco code on CMS cavern in V-REP, quantify linear drift of robot. Size fiducial markers accordingly. Ensure for max drift, fiducial marker is large enough to be located by Positional CMS	NO TEST
	Control	JT	/	6	√	Able to survey CMS cavern with human input	Check if user can survery full cavern area using all joystick controls in V-REP environment	NO TEST
		JT	/	7	√	Able to return to the charging station without human input	Check if system can return to the charging station, without human input, when control mode selected	NO TEST
		JT	/	8	√	Able to survey CMS cavern without human input	Check if system can survey full cavern area, without human input, when control mode selected	NO TEST
		JT	/	9	√	User able to 'Click' on a preset grid location and the system will autonomously navigate to the selected point	Click on a desired grid-point. Check if system navigates and stops at desired location. Repeat for all grid-point locations.	NO TEST
		JT	/	10	√	If in 'Manual' mode and in a 'communication blackout', system is able to re-locate to the charging station whe	Disconnect Wi-Fi in 'Manual' mode and check if system returns to Charging Station	NO TEST
		JT	/	11	√	Position camera can view as many fiducial markers as possible and no fiducial marker is missed	Vary the angle of position camera mounted on the prototype and find out the best angle for it	NO TEST
		JT	/	12	√	If in 'Manual' mode and in a 'communication blackout', system is able to re-locate to an optimised area where	Disconnect Wi-Fi in 'Manual' mode and check if system has found connection to the Wi-Fi module as close to the 'Communication Blackout' point as possible	NO TEST
		JT	/	13	√	System able to re-locate, re-oritentate and continue with its operations during a 'communication blackout'	Disconnect Wi-Fi in 'Autonomous' mode and check prototype performance	NO TEST
		JT	/	14	√	System able to optimise its path back to the charging station when in 'Autonomous' mode	Set multiple paths leading to one end, one of the paths will have least location markers and let prototype to choose path	NO TEST
		JT	/	15	√	Path optimisation in ALL control modes		NO TEST
	Hardware/Software	JT	Google	/		NO TEST	NO TEST	NO TEST
		JT / GJ	Google	/		NO TEST	NO TEST	NO TEST
		JT	/	16	√	Graphical User Interface for User Control	Present different User Interface concepts in 'User trials' event. Pick the solution that is most intuitive and requires little to no pre-requisite training	NO TEST
Powertrain	Steering	BJ	/	/		NO TEST	NO TEST	NO TEST
		BJ	/	17	√	Camera Monitoring System (CMS) is unconditionally stable despite terrain disturbances	Check the camera performance (video quality) when prototype running on cement floor	NO TEST
		BJ	/	18		Robust steering system: Neglected disturbance during steering, no clash/collide with components during stee	Let prototype passes corners, then check the camera performance	NO TEST
	Transmission	BJ	/	/		NO TEST	NO TEST	NO TEST
	Motor	BJ	/	19	√	System able to overcome any small gap (longitudinal: 60mm)	Create gaps with various sizes and find the biggest gap robot can overcome	System able to overcome uneven surface (longitudinal: 5mm)
		BJ	/	/		NO TEST	NO TEST	NO TEST
Energy Supplied	Battery	NDC	Google	20		Number of full recharges needed for mission life	Calculate total number of operations during mission time, both autonomous and RC	NO TEST
		NDC	Google	21		System must not exceed a maximum operating temperture of x °C	Fully discharge battery at full load and CMS cavern temperature and monitor the battery temperature.	NO TEST
		NDC	/	/		NO TEST	NO TEST	NO TEST
		NDC	Harry	22		Operating time at full load of X hours	Full load operation, record the beginning time and end time	NO TEST
		NDC	/	23		Verify that single battery from parallell cell arrangement can support basic operation	Check if the robot can be powered by using one battery	NO TEST
	Recharge Station	NDC	Google	24		System ensures that battery and charging station will always make electrical contact to maximise transimissio	Create prototype of recharge station and verify that robot always makes contact with power supply.	Minimum approach angle window of x °
		NDC	/	25		System ensures that battery and charging station will always de-couple	Create prototype of recharge station and verify that robot always undocks with power supply without getting stuck.	NO TEST
		NDC	Harry	26		Charge time from x% to x% capacity in y mins	Record the beginning charging time and the end time	NO TEST
		NDC	/	27		Check for presence of leakage of dynamic magnetic field into CMS cavern	Measure the dynamic magnetic field strength of the recharge station and see if it leaks from shielding.	NO TEST
		NDC	/	28		Able to convert energy supply from 230V to 12.8V - AC/DC. Safety critical	Use multimeter to measure the voltages of both sides	NO TEST
		NDC	/	29	√	Charging station should remain stationary during the recharge process	Build a charging station and check for station displacement during robot docking	NO TEST

Inspection	Positional CMS	GJ	Google	30	√	Ensure sufficient image quality for system to detect fiducial marker	Change the properties of camera in V-REP, find the best resolution for camera to detect fiducial marker	NO TEST
		GJ	/	31	√	Illuminate floor sufficiently for the control system to identify the fiducial markers	Prototype identifies markers with no external light	NO TEST
		GJ	/	32	√	Ensure sufficient stabilisation to control the image quality for system to detect fiducial marker	Simulate the CMS cavern floor, run the robot and see if the prototype identifies them	NO TEST
	Surveillance CMS	GJ	/	33		System able to be manipulated about longitudinal axis for linear vision control	NO TEST	NO TEST
		GJ	/	34		See if the camera can view at all angles	Using the control system see if any blind spots are loacted in a known room	NO TEST
		GJ	Google	35	√	Able to view a potential issue at a sufficient (x mm) size and sufficient (K mm) image resolution	Prototype identifies an object from xm and check the quality of image, vary x to find the longest distance with acceptable image quality	NO TEST
		GJ	Harry	36		Send data across given bandwidth	Ensure that at the given bandwidth images can be sent with acceptable resolution	NO TEST
		GJ	/	37	√	Illuminate cavern sufficiently for the user to detect and identify leaks/damage	Turn off lights in V-REP and check the distance dected by the camera under iluumination	NO TEST
		GJ	/	38	√	Ensure sufficient stabilisation to control the image quality for the user to detect and identify leaks/damage	Prototype running on CMS cavern in V-REP environment	NO TEST
	Microphone	GJ	/	39		Record sound and transmit	Ensure that at the given bandwidth sound can be sent with acceptable clarity	NO TEST
		GJ	/	40		System able to detect where the source of the noise is from	Put a noise source near the prototype and use camera to identiy source location	NO TEST
		GJ	/	41		Analyse amplitude spectra against frequency of the recorded data.	System automatically highlights an frequency out of the normal	NO TEST
	Battery Monitoring	GJ	/	42		Monitor the battery module charge accurately. Estimate time remaining before the 'Return to Home' control	When in full set up battery levels accurately shown	NO TEST
		GJ	/	43		Monitor the time to re-charge, capacity and discharge rate of the batteries in the battery module and suggest	Compare the time shows on the monitor with that recorded in testing	NO TEST
		GJ	/	44		Monitor AND manage the battery temperature	Compare the temperature shows on the monitor with that recorded in testing (full set up battery)	NO TEST
		GJ	/	45		Monitor the battery current AND voltage output and sub-system current AND voltage inputs	Compare the current and voltage show on the monitor with that recorded in testing (full set up battery)	NO TEST
	Temperature	GJ	/	46		Monitor and detect thermal risks within the cavern	Get the robot to go in a room of known temperature and validate the sensor	NO TEST
Integration	Packaging	EA	/	47	√	Ensure sub-systems do not clash/collide with each other AND do not impede each others function.	NO TEST	NO TEST
		EA	/	/		NO TEST	NO TEST	NO TEST
		EA	/	/		NO TEST	NO TEST	NO TEST
		EA	/	/		NO TEST	NO TEST	NO TEST
		EA	/	/		NO TEST	NO TEST	NO TEST
		EA	Google	48		System able to withstand x N of force	FEA	NO TEST
		EA	/	/		NO TEST	NO TEST	NO TEST
		EA	/	/		NO TEST	NO TEST	NO TEST
		EA	/	/		NO TEST	NO TEST	NO TEST
		EA	/	/		NO TEST	NO TEST	NO TEST
	Safety	EA	/	/		NO TEST	NO TEST	NO TEST
		EA	/	/		NO TEST	NO TEST	NO TEST
		EA	/	/		NO TEST	NO TEST	NO TEST
	Efficiency	EA	/	/		NO TEST	NO TEST	NO TEST
		EA	rry/Johnp	/		NO TEST	NO TEST	NO TEST

Appendix C

Proposed Stage Gate 3 Architecture

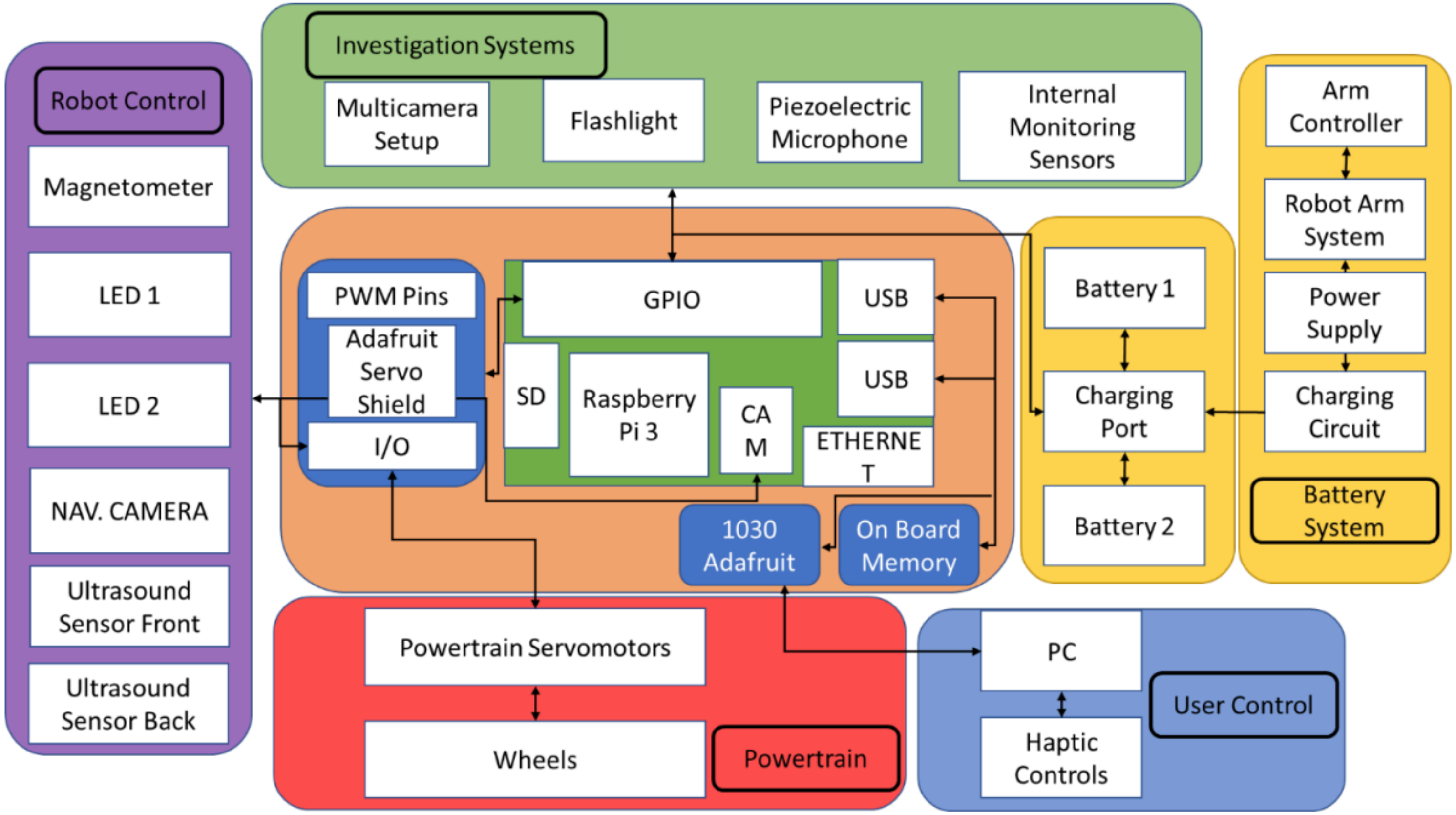


Figure 35- Proposed SG3 Architecture

Appendix D

Systems Interfaces Schematic

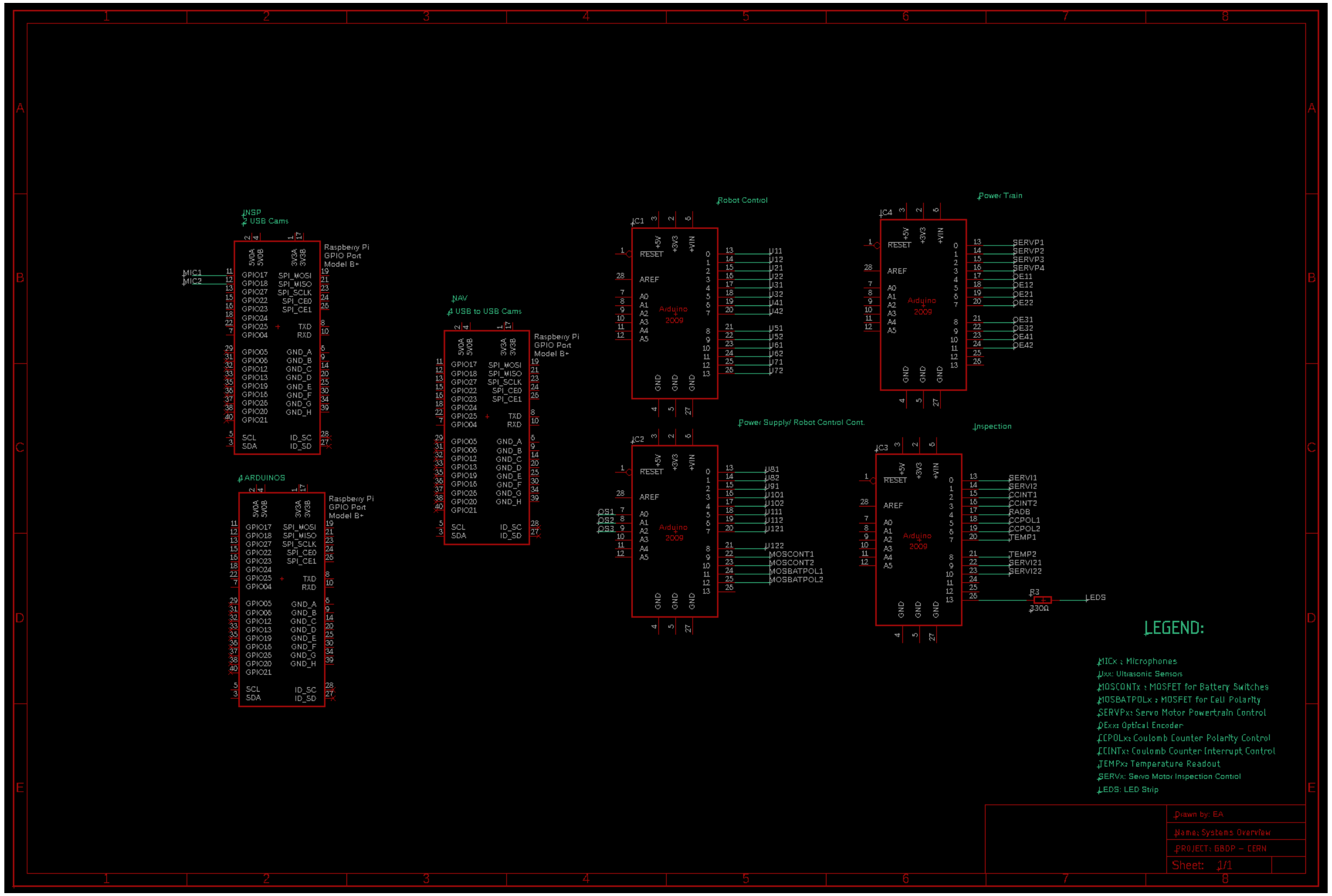


Figure 36- Systems Interfaces Schematic. Available in: (https://files.bath.ac.uk/index.php/apps/files/?dir=/X%20Drive/MechEng/Final%20Year%20Projects/GDBP-2020/G-14%20CERN%20Robotics/DESIGN%20FREEZE/Integration&fileid=71506456) Alternatively, the schematic can be found in X Drive -> Mech Eng-> Final year Projects -> GBDP 2020 -> G-14 CERN Robotics -> Design Freeze-> Integration -> Robot Technical Drawings)

Appendix E

Power PCB Schematic

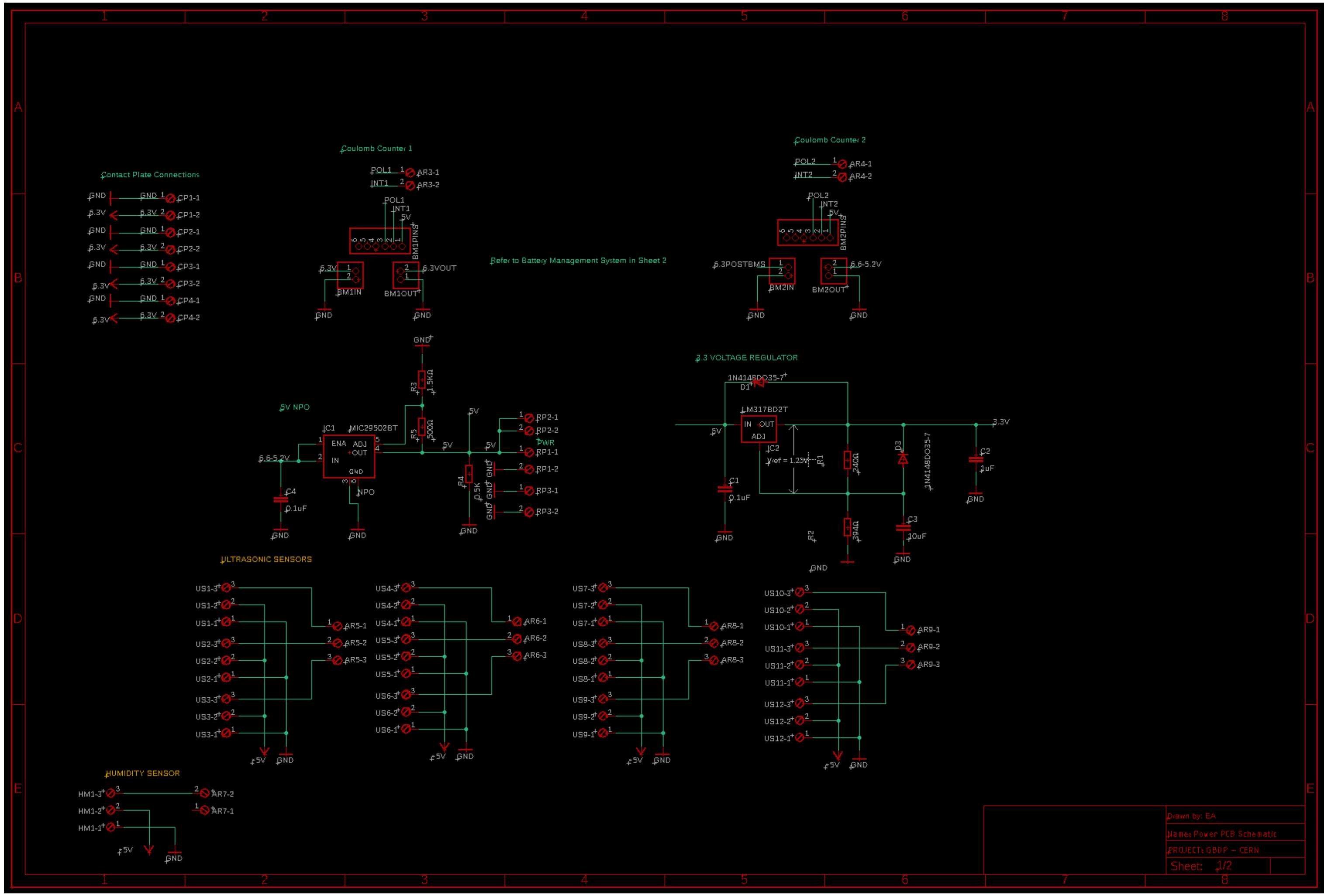


Figure 37- Power PCB Schematic 1. Available in: X Drive -> Mech Eng-> Final year Projects -> GBDP 2020 -> G-14 CERN Robotics -> Design Freeze-> Integration -> Robot Technical Drawings

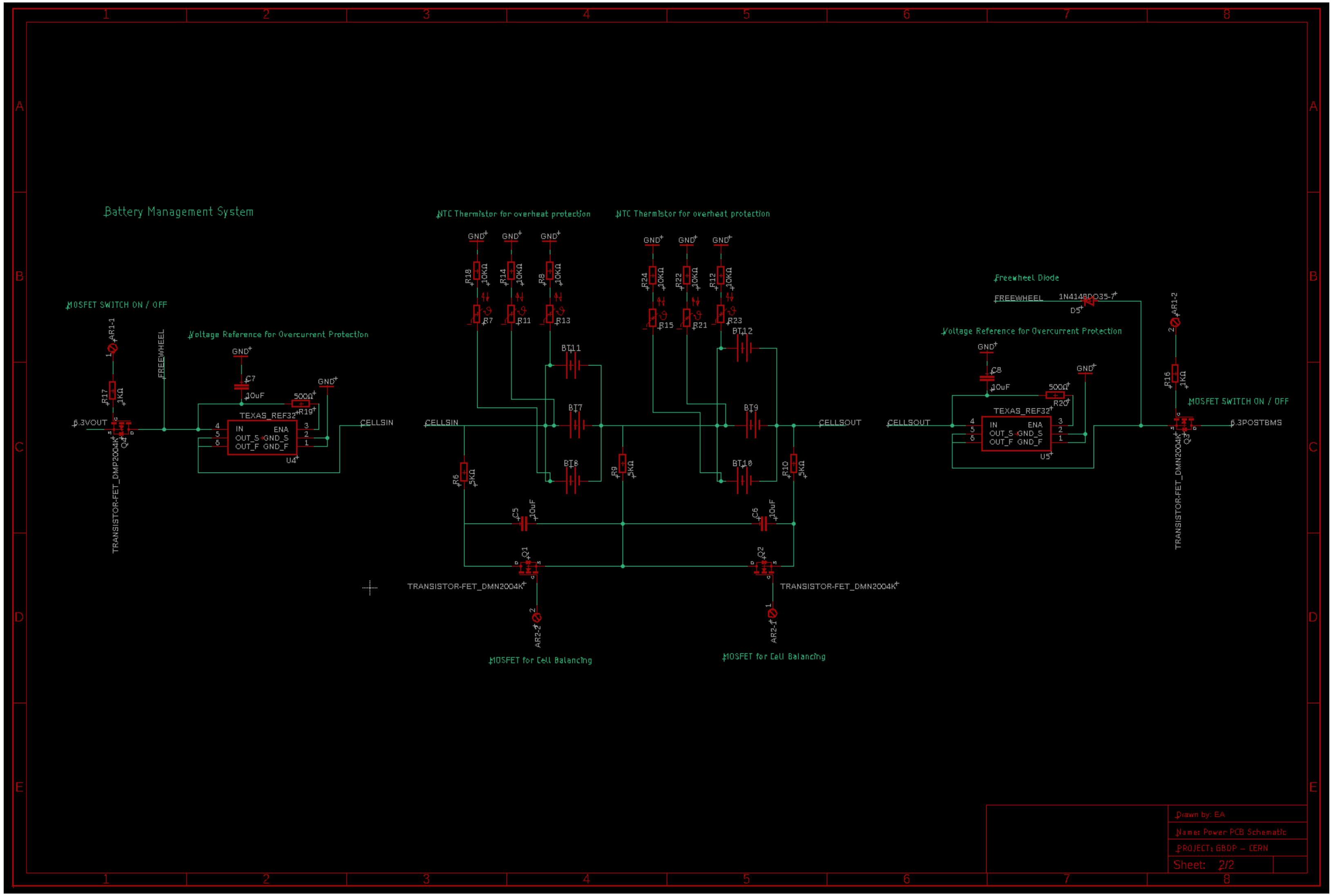


Figure 38- Power PCB Schematic 2. Available in: X Drive -> Mech Eng-> Final year Projects -> GBDP 2020 -> G-14 CERN Robotics -> Design Freeze-> Integration -> Robot Technical Drawings

Appendix F

Board View

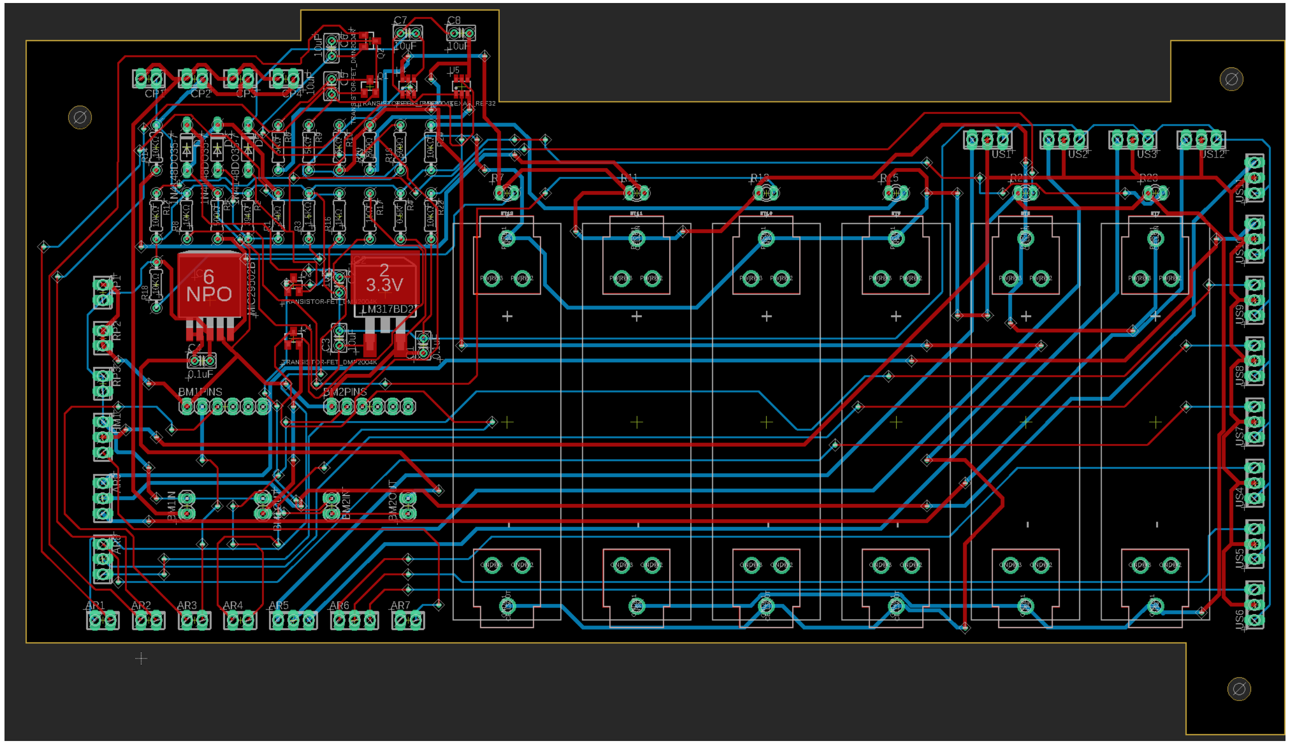


Figure 39- Board view of the Power PCB. Available in: X Drive -> Mech Eng-> Final year Projects -> GBDP 2020 -> G-14 CERN Robotics -> Design Freeze-> Integration -> Robot Technical Drawings

Appendix G

An interim iteration of Robot

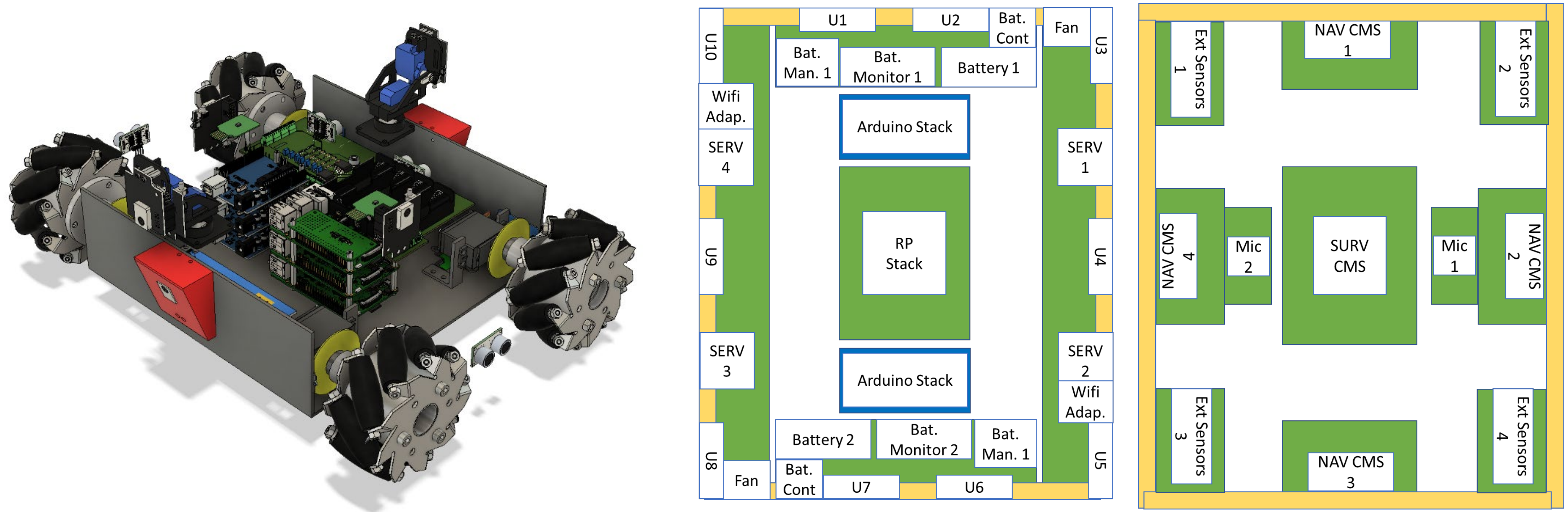


Figure 40- Interim Versions of the robot. Notice tight packaging in the CAD model which hindered development efforts and the excess amount of PCB's planned in the layout

Appendix H

Previous CERN Robot

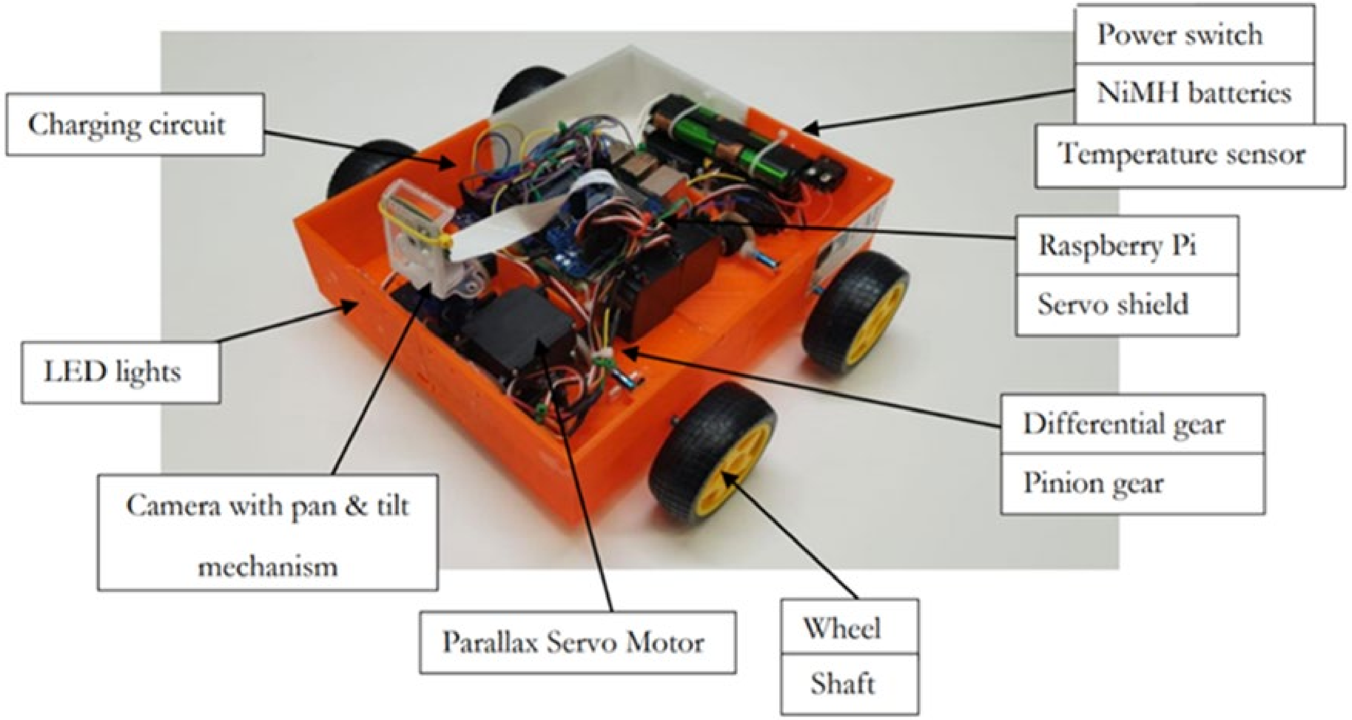


Figure 41- An iteration of a CERN Robot

Appendix J
Subassemblies Developed for the CAD Model

The assembly drawings can be found in:

(https://files.bath.ac.uk/index.php/apps/files/?dir=/X%20Drive/MechEng/Final%20Year%20Projects/GDBP-2020/G-14%20CERN%20Robotics/DESIGN%20FREEZE/Integration&fileid=71506456)

X Drive -> Mech Eng-> Final year Projects -> GBDP 2020 -> G-14 CERN Robotics -> Design Freeze-> Integration -> Robot Technical Drawings)

Appendix K
DFMEA and FTA

All DFMEA and FTA related work can be found in:

(https://files.bath.ac.uk/index.php/apps/files/?dir=/X%20Drive/MechEng/Final%20Year%20Projects/GDBP-2020/G-14%20CERN%20Robotics/DFMEA&fileid=71501391)

Should the link not work, the files can be found in;

(X Drive -> Mech Eng-> Final year Projects -> GBDP 2020 -> G-14 CERN Robotics ->DFMEA)

Appendix L

Generalised Script Integration Plan

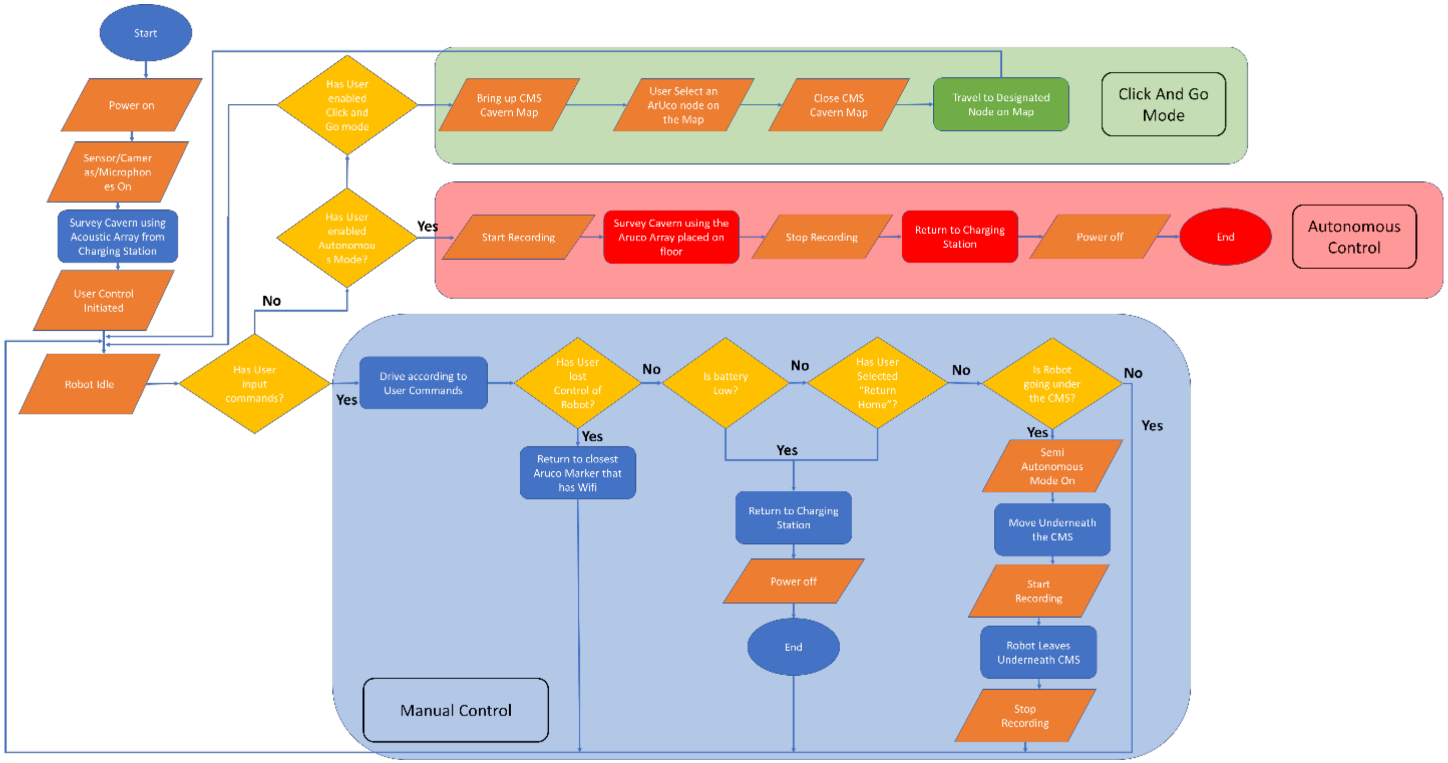


Figure 42- Generalised Script Integration Plan

Appendix M

ROS node details

Table 3 - ROS implementation details.Links refer to available opensource scripts that can be used for the required purpose

Script	Input (Subscribe)	Input Message Type	Output (Publish)	Output Message Type	Link
			auto_activ	std_msgs/String	
			manual_activ	std_msgs/String	
			joy_robot_move	Sensor_msgs/Joy	
User Communication	-	-	joy_pantilt	Sensor_msgs/Joy	Unique
			shift_x	std_msgs/Int32	
Arduino_Robot_Arm_Control	joy_pantilt	sensor_msgs/Joy	shift_y	std_msgs/Int32	https://github.com/SaraCooperAmun/Pan_Tilt_Camera_ROS_Arduino/blob/master/servo_ros/servo_ros.ino
	fiducial_vertices	fiducial_msgs/Fiducials			
	fiducial_transforms	fiducial_msgs/FiducialTransforms			
	distance	std_msgs/Float64			
	speed_rpm (llwheel,lrwheel,rrwhel,rlwheel)	std_msgs/Int16	dock_activate	std_msgs/String	
Robot Navigation	camera	sensor_msgs/Image	str_positionx, str_positiony ,str_positionz,	std_msgs/String	Unique
			camera	sensor_msgs/Image	
	camera	sensor_msgs/Image	fiducial_vertices	fiducial_msgs/Fiducials	http://wiki.ros.org/aruco_detect
Aruco Detector	camera_info	sensor_msgs/CameraInfo	fiducial_transforms	fiducial_msgs/FiducialTransforms	
Ultrasonic Sensor	-	-	distance	std_msgs/Float64	https://github.com/surabhi96/Library-navigating-robot/wiki/Ultrasonic-sensor-with-ROS
Optical Encoder	-	-	llwheel,lrwheel,rrwhel,rlwheel	std_msgs/Int16	http://wiki.ros.org/differential_drive#Published_Topics-3
Docking Process	ReturnSignal	std_msgs/String	dock_complete	std_msgs/Float64	Unique
IR Sensor	-	-	pub_range	sensor_msgs/Range	http://wiki.ros.org/rosserial_arduino/Tutorials/IR%20Ranger
Manual Control	joy1	sensor_msgs/Joy	twistx,twisty	geometry_msgs/Twist	Unique, http://wiki.ros.org/differential_drive#Published_Topics-3
			Current_read	sensor_msgs/Int32	
Battery Management	-	-	bat_temp	sensor_msgs/Temperature	
			Battery_mAH	sensor_msgs/BatteryState	http://wiki.ros.org/battery_monitor_rmp
Battery_SOC	-	-	Battery_percent	sensor_msgs/BatteryState	
			pub_temp	sensor_msgs/Temperature	
Humidity, Temperature Sensor			pub_humidity	sensor_msgs/RelativeHumidity	http://wiki.ros.org/rosserial_mbed/Tutorials/DHT%20Humidity%20and%20Temperature%20Sensor
Radiation_val	-	-	pub_radiation	std_msgs/UInt32	https://hackaday.io/project/158327-geigerros
Audio and Video Feed					
	Battery_mAH	sensor_msgs/BatteryState			
	Battery_percent	sensor_msgs/BatteryState			
	pub_temp	sensor_msgs/Temperature			
	pub_humidity	sensor_msgs/RelativeHumidity			
Data Storage	pub_radiation	std_msgs/UInt32	-	-	Unique

Appendix N

Proof of Concept Test

The proof of concept video can be found in:

(https://files.bath.ac.uk/index.php/apps/files/?dir=/X%20Drive/MechEng/Final%20Year%20Projects/GDBP-2020/G-14%20CERN%20Robotics/DESIGN%20FREEZE/Integration&fileid=71506456)

X Drive -> Mech Eng-> Final year Projects -> GBDP 2020 -> G-14 CERN Robotics -> Design Freeze-> Integration -> ROS)

The filename is: 2020-05-04 19-34-51.mkv

Appendix O

Basic User Interface

earabul@earabul: ~/Desktop/deliverable/catkin_ws_make/src/usercomm/scripts

File Edit View Search Terminal Help

GNU nano 2.9.3 usercomm.py

```
#!/usr/bin/env python

import rospy
from std_msgs.msg import String

command =  input('please input command:')

def signals():
        rospy.init_node('usercomm',anonymous=True)
        rate =rospy.Rate(10)
        if command == 'auto_activate':
                pub = rospy.Publisher('auto_activate', String, queue_size=10)
                while not rospy.is_shutdown():
                        pub.publish('1')
                        rate.sleep()
        elif command == 'robotmove':
                pub2 = rospy.Publisher('robotmove', String, queue_size=10)
                while not rospy.is_shutdown():
                        pub2.publish('1')
                        rate.sleep()
        elif command == 'return_home':
                pub3 = rospy.Publisher('return_home', String, queue_size=10)
                while not rospy.is_shutdown():
                        pub3.publish('1')
                        rate.sleep()
        elif command == 'nav_cam_pos':
                pub4 = rospy.Publisher('nav_cam_pos', String, queue_size=10)
                while not rospy.is_shutdown():
                        pub4.publish('1')
                        rate.sleep()

if __name__ == '__main__':
        try:
                signals()
        except rospy.ROSInterruptException:
                pass
```

^G Get Help ^O Write Out ^W Where Is ^K Cut Text ^J Justify ^C Cur Pos
^X Exit ^R Read File ^\ Replace ^U Uncut Text ^T To Linter ^_ Go To Line

Figure 43 - A partial Script detailing a potential rospy based user interface

Appendix P

Gannt Chart

Table 4- The initial Gannt Chart

G14 -TEAM CERN

Company Name - University of Bath
Project Lead - Ege Arabul

Project Start Date: 04/02/2020

Scrolling Increment: 36

Legend: On Track | Low Risk | Med Risk | High Risk | Unassigned

March | April

11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 1 2 3 4 5

W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T

Milestone Description	Category	Assigned To	Progress	Start	No. Days
ST1 - Target Requirement Specification					
Deliver Presentation	Goal	Name	100%	24/02/2020	1
Prepare Presentation	Low Risk	ALL	100%	20/02/2020	4
Finish Specifications	Milestone	ALL	100%	11/02/2020	1
Quantify Specifications (or define how to)	Low Risk	RL	100%	17/02/2020	1
Specify Requirements for each subsystem	Low Risk	ALL	100%	06/02/2020	6
Concepts Selected for Subsystems	Milestone	ALL	100%	18/02/2020	1
Concept Generation and Evaluation for each subsystem	Med Risk	ALL	85%	12/02/2020	6
Individual Research	Low Risk	ALL	90%	04/02/2020	4
Investigate Competitor products	Low Risk	EA	70%	04/02/2020	17
Define an initial market plan	Milestone	EA	100%	20/02/2020	1
DVP Ready	Low Risk	RL	100%	04/02/2020	15
Early Design Freeze	Milestone	ALL	100%	19/02/2020	1
Risk Assesment done	Low Risk	EA	100%	20/02/2020	2
Generate and Evaluate Integration Concepts	Med Risk	ALL	100%	18/02/2020	2
ST3 - Technical and Commercial Feasibility Studies					
Group Project Proposal Delivery	Goal	ALL	0%	12/03/2020	1
Rasberry Pi/Equipment Ordered	Low Risk	EA	0%	01/03/2020	1
Individual Work Packages clarified (Software/Hardware)	Low Risk	ALL	100%	28/02/2020	1
Feasbility of Subsystems (Individual Work Packages)	High Risk	All	0%	02/03/2020	5
Individual Report Writing	Med Risk	All	0%		
Detailed Testing Plan (Scenerios and Schemes)	High Risk	RL	0%	02/03/2020	5
Group Report Writing	Med Risk	ALL	0%	02/03/2020	10
In-Group Presentation of Subsystem Feasibility	Med Risk	ALL	0%	09/03/2020	1
Individual Technical Feasiblity Study Done	Goal	ALL	0%	12/03/2020	1

ST4 - Group Business Seminar					
Group Business Seminar Delivery	Goal	ALL	0%	23/04/2020	1
Group Business Seminar Preparation	Low Risk	ALL	0%	15/04/2020	8
External Project Review and Advice	Milestone	ALL	0%	25/03/2020	1
Easter Holiday		ALL	0%	06/04/2020	9
Subsystem Design Freeze	Milestone	ALL	0%	05/04/2020	1
I nvestigation of Potential Architectures	Med Risk	EA	0%	12/03/2020	25
Product Architecture Freeze	Milestone	EA	0%	05/04/2020	1
Cost Estimate for Selected Architecture	Low Risk	EA	0%	15/04/2020	8
Safety Analysis for Selected Architecture	Low Risk	EA	0%	15/04/2020	8
Initial Integrated Model	Med Risk	EA	0%	15/04/2020	8
System Testing (Virtual)	Low Risk	RL	0%	12/03/2020	13
Preparation for Physical System Testing	Low Risk	RL	0%	12/03/2020	13
System Testing (Physical)	Med Risk	RL	0%	25/03/2020	11
Documentation/Evaluation of Tests	Low Risk	RL	0%	15/04/2020	8
Planning of Next Set of Tests	Low Risk	RL	0%	15/04/2020	8
Manual Control Mode Achieved	Med Risk	JT	0%	12/03/2020	25
Return to Home Achieved	Med Risk	JT	0%	12/03/2020	25
Default Blackout Mode Achieved	Med Risk	JT	0%	12/03/2020	25
Additional Modes Decided	Low Risk	JT	0%	25/03/2020	11
Initial Work on Additional Features/ User Interface	Low Risk	JT	0%	15/04/2020	8
Detailed Design of Powertrain System	Low Risk	BS	0%	12/03/2020	13
Validation of Powertrain System (Physical or Software)	Low Risk	BS	0%	25/03/2020	12
Optimisation of Powertrain system Based on Validation	Med Risk	BS	0%	15/04/2020	8
Modelling of Power Supply System	Low Risk	NDC	0%	12/03/2020	13
Detailed Design Of Power Supply System	Med Risk	NDC	0%	12/03/2020	13
Validation of Power Supply System (Physical or Software)	Med Risk	NDC	0%	25/03/2020	12
Optimisation of Power Supply System	Med Risk	NDC	0%	15/04/2020	8
Detailed Design of Inspection System	Med Risk	GJ	0%	12/03/2020	13
Validation of Inspection System (Physical or Software)	Med Risk	GJ	0%	25/03/2020	12
Optimisation of Inspection System	Med Risk	GJ	0%	15/04/2020	8

ST5 - Project Business Report					
Project Business Report Delivery	Goal	ALL		07/05/2020	1
Project Business Report Preparation	Low Risk	ALL		30/04/2020	7
Final Design Freeze	Milestone	ALL		03/05/2020	1
Second Integrated Model	High Risk	EA		23/04/2020	10
Development of User Interface/ Additional Features	Low Risk	JT		23/04/2020	10
Semi-Integrated System Tests	Med Risk	EA/RL		23/04/2020	10
Final Changes and Verification of Subsystem -Powertrain	Med Risk	BS		23/04/2020	10
Final Changes and Verification of Subsystem -Power Supply	Med Risk	NDC		23/04/2020	10
Final Changes and Verification of Subsystem - Inspection	Med Risk	GJ		23/04/2020	10
ST6 - Design Freeze					
Design Freeze Delivery	Goal	ALL		11/05/2020	1
Technical documententation of Work Packages (Simulations, Schematics, CAD...)	High Risk	ALL		07/05/2020	4
Final Integrated Model	High Risk	EA		07/05/2020	2
ST7 - Individual Technical Reports					
Individual Technical Report Delivery	Goal	ALL		14/05/2020	1
Documentation of Work Packages (Report)	High Risk	ALL		11/05/2020	3
ST8 - Design Exhibition					
Design Exhibition Delivery	Goal			27/05/2020	2
Preparation of Posters	Low Risk			14/05/2020	13

Appendix Q

Example Work Week and Kanban Board

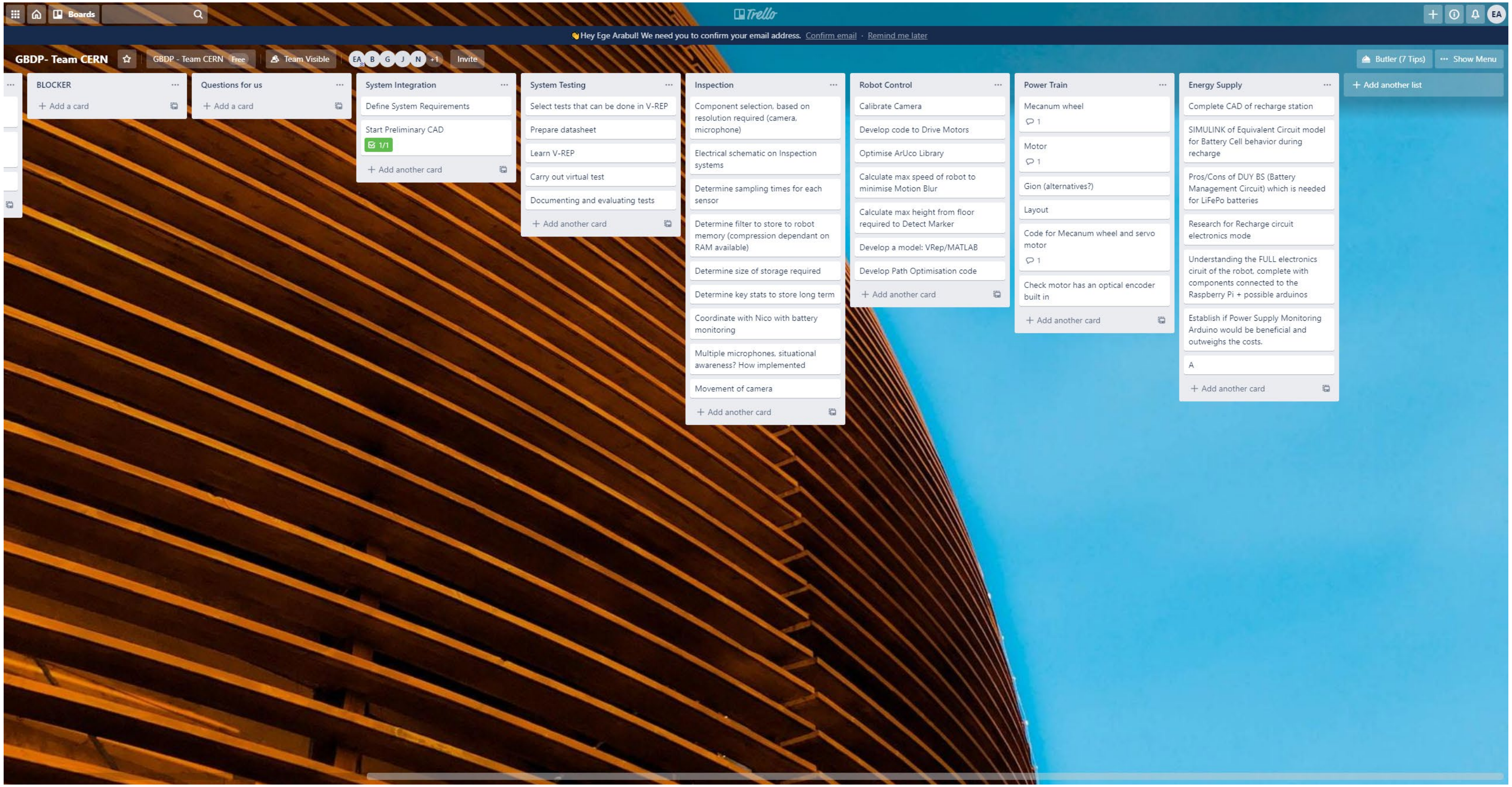


Figure 44- An interim version of online Kandan board used

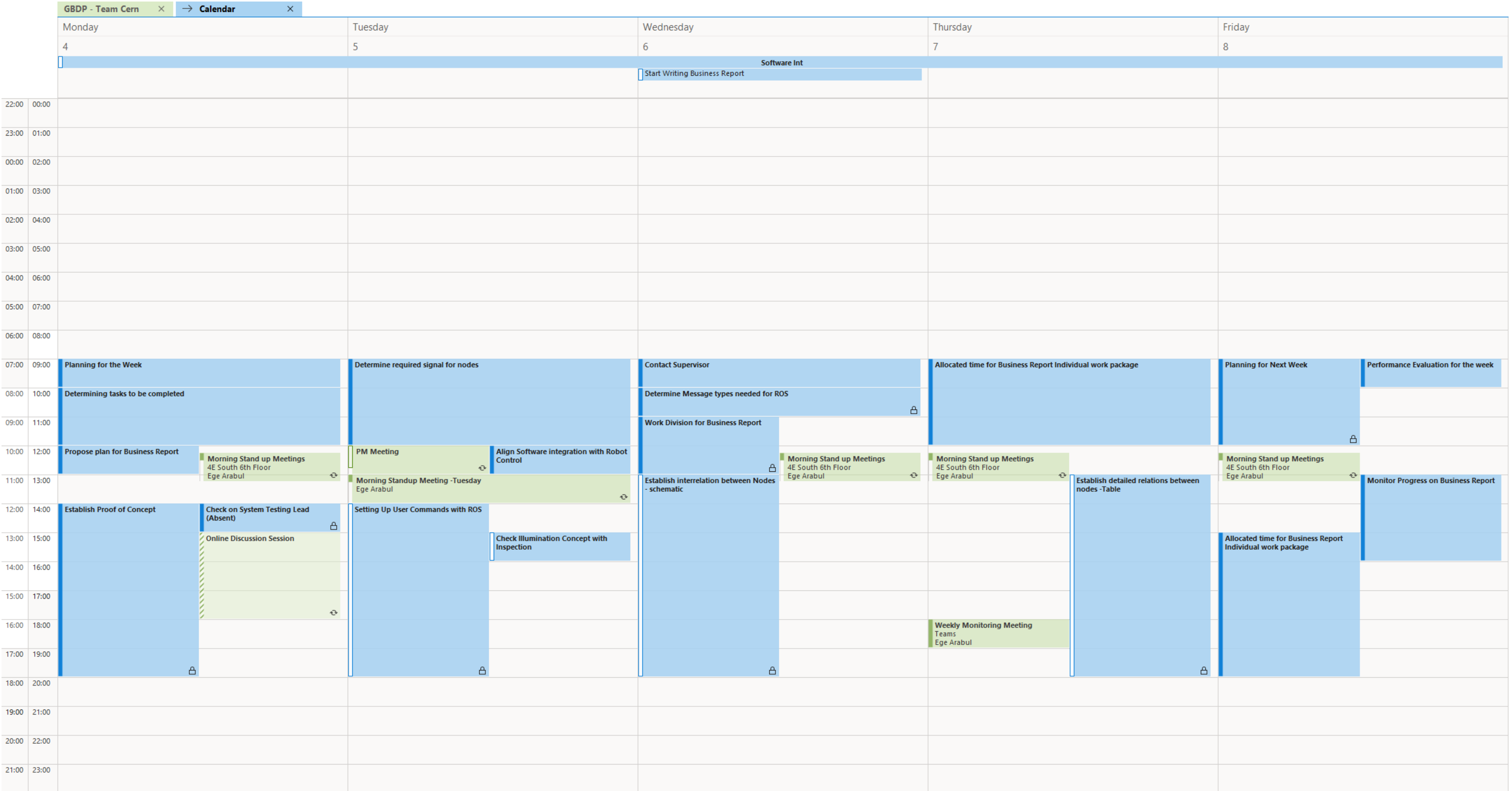


Figure 45- An example work week during project. Notice the within the weekly, daily and hourly planning structure used

Appendix R
The Risk Register

Table 5-The Risk Register used for project management

	No	Hazards Identified	Existing Controls & Measures	Severity (a)	Likelihood (b)	Risk Rating (a x b)	Additional control/action required
	1	Limited Budget	Utilise University Resources, cost savings using bulk buy options	3	3	9	Detailed Cost Analysis
	2	Limited Time	Limiting Scope of project, keeping track of decisions	5	2	10	Identify critical Paths Correctly and prioritise
	3	Immature Supply Chain	Use of University approved Suppliers , use in house resources	2	3	6	Identifying already available resources
	4	Limited Human Resources	Rely on Peer Assistance and prioritise buying in developed components	4	4	16	
	5	Powerful Competition	Development of a viable business strategy	4	3	12	
	6	Limited Customer Communication	Skype meetings with CERN in Irregular Intervals	1	4	4	
	7	Limited Information of Environment	Request CAD files, ask for pictures	2	2	4	Visit to CERN!
	8	Integration Risk	Integrating Subsystems Concurrently with the development activities	3	2	6	Achieving Minimum Viable Product at different stages
	9	Ability to recreate environment (False verification of a test)	Source as much information from CERN as possible and find intuitive way to stimulate	4	4	16	Validate Testing Concepts with CERN
	10	Assumptions on Environment Conditions	Validating Assumptions with Customer	2	4	8	
	11	Skills Risk	Allocated Time for Skills Training (CAD, FEA, etc.)	4	3	12	
	12	Benefit Shortfall	Validating Prouduct with Customer at various Stages of Design	5	2	10	
	13	Health and Safety	Consulting University H&S, Detailing Testing Conditions	5	2	10	
	14	Quality	Validating Subsystems/components via testing	2	3	6	
	15	Project Complexity	Dividing Project in Work Packages and identifying system interconnections	3	4	12	
Pre COVID-19	16	Solving the Wrong Problem	Research dives at different Stage of design, interviews, user testing...	5	3	15	
	17	Work Distruption due to Coronavirus	Digitalisation of project work, daily monitoring meetings, establishing core hours	4	4	16	
	18	Failure to Deliver part of project	Awareness within Project team, Risk Statements, active monitoring	5	3	15	
	19	Falling out within team	Active Conflict Resolution between members, setting sustainable goals	4	2	8	
	20	Loneliness experienced by team members	Daily monitoring meetings, checking on the member even when they don't show up to meetings	5	3	15	Suggest Wellbeing advices and encourage seeking further help if need
	21	Lack of Communication in team	Active use of all communication Channels, ensure members are comfartable and adapt these channels in their routines	3	4	12	
	22	Access to tools	Downgrading tasks to complete tasks with available tools, limitation statements	3	3	9	Alignment with Supervisor when needed
	23	Lack of transparency	Active monitoring of the team, encouraging talks and discussions	3	4	12	Promote use of common interfaces by being anexample
	24	Missing deadlines	ctive monitoring process, distributing responsibility among member, promoting accountabilit	5	3	15	Increased meeting and communication intensity closer to deadlines
	25	Version Control	Utilising platforms more effectively, mentioning correct versioning in the file naming	3	4	12	Use of version control software
	26	Time zone differences	-	2	1	2	
	27	Burnout due to over working	Limiting the intensity of tasks	3	4	12	
	29	Reduced Technical Contents	Encouraging alignment, monitoring, expanding workpackages to different responsibilities	3	3	9	
	30	Lack of Access to Information	Contacting University for assistance	2	2	4	
	31	Distractions within Home Environment	Setting Core hours, checking o team member in regular intervals	2	5	10	
Post COVID-19	32	Member falls short of the required amount of work	Active monitoring of task, encouraging member to set feasible plans	3	4	12	Taking partial responsibility of the task, providing assistance in task planning, implementation

Appendix S

Parts List

Table 6- Parts List of the CERN robot, detailing the cost of each item

Subsystem	Item No	Item	Quantity	Unit Price	Total Price
	1	Ultrasonic Sensors	12	£1.73	£20.74
Robot Control	2	Pixy 2 Camera	4	£60.00	£240.00
	3	Pixy 2 Camera	2	£60.00	£120.00
	4	Servo Motor	4	£4.00	£16.00
	5	Pan and tilt kit	2	£17.50	£35.00
	6	LED Strip	1	£10.00	£10.00
	7	Microphone	2	£1.55	£3.10
	8	Microphone coupon Card	2	£62.50	£125.00
	9	Coulomb Counter	2	£2.00	£4.00
	10	Radiation Board	1	£21.00	£21.00
Inspection	11	Temp& Humid Board	1	£4.00	£4.00
	12	Mecanum Wheel Set	1	£69.12	£69.12
	13	G-ion Flex	1	£100.00	£100.00
Powertrain	14	6mm Set Screw Hub	4	£8.12	£32.48
	15	Lifepo Cells	6	£9.26	£55.56
	16	Power Adapter	1	£40.00	£40.00
	17	Arduino	1	£20.00	£20.00
	18	Compressive Springs	2	£1.00	£2.00
	19	Tensile Springs	1	£1.00	£1.00
	20	Fan	1	£19.00	£19.00
	21	Sharp Optical Sensor	3	£4.30	£12.90
Power Supply	22	Frame for Recharge Station Station	1	£50.00	£50.00
	23	Voltage Regulators	1	£0.94	£0.94
	24	NPO	1	£5.00	£5.00
	25	Voltage Reference	2	£0.30	£0.60
	26	NTC Thermistor	6	£2.58	£15.48
	27	MOSFET	4	£0.25	£0.98
	28	Phoenix Connectors	23	£1.30	£29.90
	29	Bare PCB	1	£30.00	£30.00
	30	Arduino	4	£20.00	£80.00
	31	Raspberry Pi 3	3	£27.70	£83.10
	32	POM M2 Spacer x10	18	£0.12	£2.07
	33	POM M2 Spacer x20	18	£0.12	£2.07
	34	Total Price for Brass Screws	1	£30.00	£30.00
	35	Bespoke LED holders	1	£0.18	£0.18
	36	Bespoke Camera holders	4	£7.59	£30.36
	37	Aluminium Angle Brackets	36	£0.18	£6.59
	38	Corner Connectors	8	£0.18	£1.44
	39	Protective Camera Caps	2	£7.59	£15.18
	40	Bottom Plate	1	£25.00	£25.00
	41	Side Plates	2	£15.00	£30.00
	42	Top Plate	1	£25.00	£25.00
	43	Corner Plates	4	£10.00	£40.00
Integration	44	Front Plates	2	£15.00	£30.00
					£1,484.78

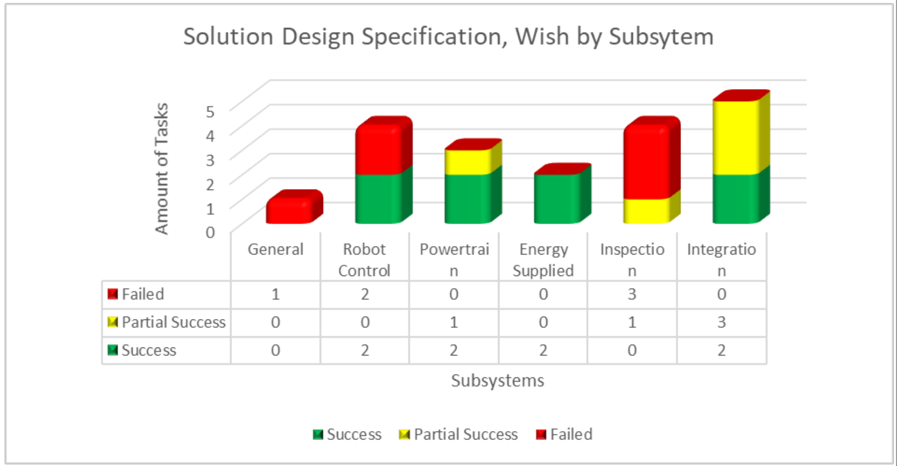
Appendix T

Solution Design Specification and the Wish requirements Analysis

Table 7-The Solution Design Specification

System	Sub-System	Requirement	Must/Wish	Success Criteria	Stakeholder	Criteria Met
General	Maintenance	Sub-system maintenance	Must	All sub-systems should not require maintainenance for at least 6 years	ALL	Design measures implemented but testing is required
	Magentic Field	All sub-systems to be unaffected by the Magnetic Field that is generated by the CMS	Must	fastners (where applicable). Electronic circuits to be designed to be to be inherently unaffected by the magnetic field. Magnetic Field shielding.	ALL	Design measures implemented but testing is required
		Robot moving slowly to prevent electeronic devices disfunction due to high induced current generated	Must	The maximum speed of robot is below xx m/s	ALL	Maximum Speed Determined
	General	Maximum height	Must	Robot should be no more than 20cm in height	ALL	Achieved
	Radiation	All sub-systems to be unaffected by the Radiation that is generated by the CMS	Must	Performance/functionality of all sub-systems to be unaffected by generated radiation. Radiaton hardened materials. Radioactive Shielding	ALL	Design measures implemented but testing is required
	Thermal Management	All sub-systems to be thermally managed	Wish	Monitor and detect potential thermal runaway events. Minimise risk of components overheating (Ensure temperature remains in allowable ranges)	GJ / ALL	Design measures implemented but testing is required
Robot Navigation	Vision	Obstacle avoidance	Must	Able to locate and avoid obstacles at least 200 mm away	JT	Obstacle Avoidance algo developed
		Contain at least 2 navigation sensors for system reliability and detection performance	Must	Able to navigate round a course despite a 'communication blackout'	JT	Sensors available but Sensor Fusion not achieved
		Location/path markers to be inconspicuous	Wish	Minimise the quantity and size of location markers	JT	Suggested future work
	Control	'Manual' control mode	Must	Able to survey CMS cavern with human input	JT	Function achieved
		'Return to Home' control mode	Must	Able to return to the charging station without human input	JT	Function achieved
		'Autonomous' control mode	Wish	Able to survey CMS cavern without human input	JT	Function achieved
		'ClickNGo' control mode	Wish	User able to 'Click' on a preset grid location and the system will autonomously navigate to the selected point	JT	Algo developed, but not tested in CMS cavern
		'Default Blackout' control mode	Must	If in 'Manual' mode and in a 'communication blackout', system is able to re-traverse its steps until it has resumed communication with the user	JT	N/A
		System able to locate itself during a 'communication blackout'	Must	System able to re-locate, re-orientate and continue with its operations during a 'communication blackout'	JT	N/A
		Path optimisation in ALL control modes	Wish	System able to optimise its path back to the charging station when in ALL control modes	JT	N/A
	Hardware/Software	Large enough memory to store the required preset data for all control modes	Must	Sub-system will require at least x GB of SSD storage	JT	N/A
		Large enough memory to store all measured data that is not immediately transmitted i.e. during a 'communication blackout'	Must	Sub-system will require at least x GB of SSD storage	JT / GJ	N/A
		Intuitive User Interface	Wish	User will not require any significant training; system to have intuitive and memorable controls to system functions	JT	
Powertrain	Steering	Able to navigate over small gaps and uneven terrain that is characterstic of the topography in the CMS cavern	Must	Large enough wheel/tracks that are able to overcome any small gap (longitudinal: 60mm) and uneven surface (longitudinal: 5mm)	BJ	Four 100mm diameter wheels are used
		Suspension system	Wish	Camera Monitoring System (CMS) is unconditionally stable despite terrain disturbances	BJ	The stability of the robot is not tested, but the maximum speed of the robot is not very fast
		Optimised steering system	Wish	Minimum number of components to provide a reliable/robust steering system	BJ	Only 6 components for each set of powertrain system
	Transmission	All-wheel Drive	Wish	Wheels/Tracks are able to be driven individually	BJ	Each wheel connects to its own servo motor
	Motor	Generate suitable power for navigational requirements	Must	System able to generate sufficient power for movement. System able to overcome any small gap (longitudinal: 60mm) AND uneven surface (longitudinal: 5mm)	BJ	Servo motor's maximum torque is 95 oz.in, which is enough to overcome any gaps
		Precise control over system maneouvrability for navigation purposes	Must	Suitable motor for navigation requirements	BJ	Servo motor and optical encoder give robot navigation system a good control
Energy Supply	Battery	Rechargeable battery	Must	Minimum battery cycle life of 100 cycles	NDC	Battery cycle life time of 1000-2000 cycles
		Thermal resistance	Must	System must not exceed a maximum operating temperture of 60 °C	NDC	Maxium safe operating temperature of 70ºC
		Isolate critical failures	Must	System must reduce the possibility for acid leak, combustion or explosion	NDC	LiFePo chemistry negates possibility of explosion or acidleak
		Generate sufficient power for all sub-system demands	Must	Minimum operating time at full load of 1 hour	NDC	Estimated maximum operation time of 85minutes
		Battery redundancy	Wish	Minimise complete battery failure by having multiple batteries in parallel	NDC	Battery has 3 cell in parallel
	Recharge Station	Fail-Safe Mechanical Docking system	Must	System ensures that battery and charging station will always make electrical contact to maximise transimission efficiency. Minimum approach angle window of x °	NDC	Phyical Testing required
		Fail-Safe Mechanical Release system	Must	System ensures that battery and charging station will always de-couple	NDC	Physical Testing required
		Support Fast Charging	Wish	Battery charges to 80% capacity in 2 hour	NDC	Recharges to 80% in 50 minutes
		Charging station to be unaffected by the CMS Magnetic Field AND not affect the CMS Magnetic Field	Must	Charging station to be able to transmit power to the battery module without to/from disturbance from magnetic field.	NDC	Recharging does not affect cavern magnetic field
		AC to DC power conversion	Must	Able to convert energy supply from 230V to 12.8V - AC/DC. Safety critical	NDC	Power adpator selected to specification
		Charging station to remain stationary during recharge process	Must	Evidenced by simulation. Charging station should remain stationary during the recharge process	NDC	Physical Testing Required
Inspection	Positional Sensor	Sensor of sufficient resolution for fiducial marker detection	Must	Ensure sufficient resolution for system to detect fiducial marker. X K resolution	GJ	1296×976 resolution can detect markers
		Sufficient conditions for fiducial marker detection	Must	Illuminate floor sufficiently for the control system to identify the fiducial markers. Optimal image saturation	GJ	Unable to tets secnario but should be suffucuent
		Sensor stabilisation	Must	Ensure sufficient stabilisation for system to detect fiducial marker	GJ	Deemed not required due to limited speed
	Surveillance CMS	Control CMS linear vision	Must	System able to be manipulated about longitudinal axis for linear vision control	GJ	Linear vision controlled by robot movement
		Control CMS area vision	Must	System able to completely survey the external area of the CMS machine and any input/output pipes/electrical wiring. Multiple rotational axes for area vision control	GJ	Pan and tilt acheieved
		Control camera zoom	Must	Able to view a potential issue at a sufficient (x mm) size and sufficient (K mm) image resolution.	GJ	Not developed
		Capture quality images for sufficient leak/damage detection	Must	Ensure highest image quality without compromising data transmission time. X K resolution	GJ	Transmssion time of love seconds at 1296x976 resolution
		Sufficient light-level for optimum image saturation	Must	Illuminate cavern sufficiently for the user to detect and identify leaks/damage. Optimal image saturation	GJ	Unable to tets secnario but should be suffucuent
		Camera stabilisation	Must	Ensure sufficient stabilisation to control the image quality for the user to detect and identify leaks/damage	GJ	Deemed not required due to limited speed
	Microphone	Capture quality sound recording	Must	Ensure best sound quality without compromising transmission time	GJ	Trasnition time limmited by video, uable to test microphone quality
		Detect location of source noise	Wish	System able to detect where the source of the noise is from. Acoustic Camera Array	GJ	Suggested future work
		Noise analysis	Wish	Analyse amplitude spectra against frequency of the recorded data. Isolate frequency components. Spot anomalous frequencies	GJ	Suggested future work
	Battery Monitoring	Determine individual battery levels of battery module	Must	Monitor the battery module charge accurately. Estimate time remaining before the 'Return to Home' control mode is executed	GJ	Coulomb counting method delevloped, unable to test to get accurate battery life
		Determine individual battery healths of the battery module	Wish	Monitor the time to re-charge, capacity and discharge rate of the batteries in the battery module and suggest to user when a new battery module is required	GJ / NDC	On-board logbook of battery activity fed back to off-site Simulink model for State of Health analysis
		Determine individual battery temperatures of the battery module	Must	Monitor AND manage the battery temperature	GJ / NDC	Circuit board monitors temperature and safety limits are present, but ventilation was reccomended
		Determine individual battery voltage and current levels of the battery module	Must	Monitor the battery current AND voltage output and sub-system current AND voltage inputs	GJ / NDC	Individual battery cell voltage is monitored and balanced and current output is recorded
	Temperature	Monitor temperature of the cavern environment	Wish	Monitor and detect thermal risks within the cavern	GJ	Not deemed nessecary is highly controlled environment

Integration	Packaging	Package all modular sub-systems into system architecture. Optimise sub-system layout	Must	Ensure all sub-systems are completely integrated and installed into the frame of the product. Ensure sub-systems do not clash/collide with each other AND do not impede each others function.	EA	All systems are integrated withing the frame of the product. Protrusion occurs only on component level which is to be further optimised during manufacturing
		Meet target dimensions	Must	System must be less than 200mm (longitudinal height)	EA	Heigh of the robot is under 200mm
		Durable materials	Must	All materials to withstand damage for at least 3 years	EA	DFMEA and Design for Reliability principles were used for optimisation however further validation is required including real world testing
		Minimise material volume	Wish	Volume of material used in a component is to be kept at a minimum for improved sustainability	EA	however further design iterations are required
		Modular design for all sub-systems	Wish	Modular design for improved maintainability and repair. Improved access to sub-system level components. Allow for easy module substitution if damaged	EA	Easy Substitution of components have been considered. Robot can be easily dissambled
		Structurally robust and able to withstand impact without sub-system damage	Must	System able to withstand x N of force	EA	No structural Validation Performed
		Minimise vibration transmitted to sub-systems	Must	Attenuate all modes of vibration so that there is no significant material/sub-system displacement	EA	No Vibration testing performed
		Ease of manufacture and assembly	Must	Ensure system and sub-systems can be built and assembled using conventional manufacturing methods/tools. Minimise the number of tools used	EA	Robot can be assembled even with basic workshop equipment
		Weight distribution	Must	System is unconditionally stable during all use-cases	EA	Robot's Centre of Gravity is located within 1 cm of the Robot
		Aesthetically pleasing with Ergonomics for handling	Wish	System is attractive and minimises strain to user when carrying	EA	6/6 team members percieve robot to be attractive. Further Ergonomic Considerations are required
	Safety	All electrical component AND wiring fixed in placed and stowed away	Must	All electrical wiring to be enclosed in package	EA	Very limited exposed wiring (LED Strip). Can be optimised during manufacturing or another design iteration
		Ingress Protection for electrical components AND wiring	Wish	All electrical sub-system components to be electrically sealed against water	EA	Electrical but further validation is required
		Non-Flammable	Must	Non-flammable packaging shell. All sub-system modules to non-flammable (where applicable)	EA	Shell used is non-flammable
	Efficiency	Optimised structural parts	Wish	Structural parts are geometrically optimised to reduce part count/material	EA	Fastener count is reduced during the design process however it is still deemed to be excess.Can be further optimised by using different joining methods
		Cost	Must	The final of price of X is met. The cost of research, design and development is completely covered by the budget	EA	Cost of development is covered by the initial budget
	Product Architecture	Real time Operation	Must	The Control Unit controls robot in real time	EA	Hardware used suppots real time control however further testing required
		Software can control I/O and analogue outputs	Must	Digital and Analogue outputs can be controlled using the Hardware interfaces	EA	Digital and Analogue Control is possible
		Efficient Computing	Must	Software/Hardware ran by Control Unit must be efficient to allow for real time computing	EA	Minimum Required Hardware is proposed which can easily be upgraded
		Systems Interface	Must	Components used interface with each other correctly and are compatible	EA	All off the shelf components are compatible with the available user interfaces



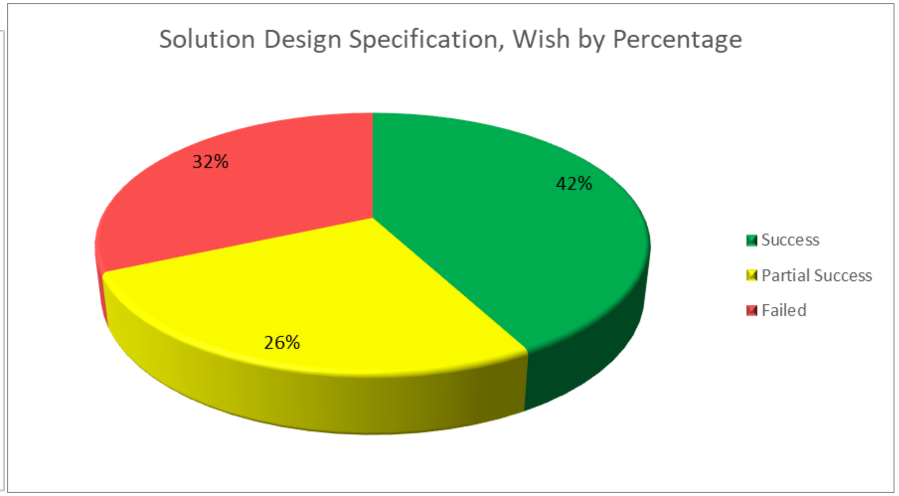


Figure 46 and 47 - Analysis of Solution Design Specification "Wish" Criteria