

Urban Search and Rescue Robot Completion Portfolio

Group 20

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Supporting Statement

The aim of the Urban Search and Rescue Robot project was to deliver a mobile, wirelessly controllable robot. The group inherited the chassis of a robot, however this had a broken powertrain, ill-fitting parts and no electronic control or instrumentation system. Ultimately, the robot is designed to fulfil the requirements for the RoboCup competition and all implemented designs follow a specification adhering to these. A full summary of the project specification is given in Section 1.

The first target was the design and construction of a robotic arm. This aim was fulfilled and the final embodiment of the arm can be seen in Section 4.1. The arm is equipped with a camera and gripper. Six degrees of freedom permit its versatile utilisation in manipulation and surveillance tasks.

Furthermore, the need for powertrain reparation and chassis optimisation was identified. The implemented designs, including dynamic track tensioning, can be seen in Section 4.4 and 4.2. The powertrain structure is designed to fail before the motor itself, since the necessity for motor repair has led to budgetary problems in the past.

To decrease overall system weight the utilisation of composite materials was deemed sensible, however time restrictions led to this being tested for the robot cladding only, see Section 4.5.

Since the inherited robot had no electronic system at project handover, this had to be designed and implemented in its entirety. The robot is powered by 22V batteries, mounted as specified in Section 4.3. A power distribution system, with battery cell voltage monitoring and utilizing bus bars to support high current peaks and direct current voltage converters to step the battery voltage to levels required by instrumentation, was implemented, see Section 4.6.1. A set of 3D printed cases were designed to isolate any voltage carrying devices from the robot's metal chassis, see Section 4.6.2.

The robot is controllable through a wireless local access network. An on-board pico-computer is thus interfaced with a base station computer and a LabVIEW control panel accesses the robot's motor controllers to control track speed and flipper position, see Section 4.7 and 4.8. Additionally, the robot has been equipped with an on-board camera, microphone, speaker, LIDAR and inertial measurement unit, all accessible through the LabVIEW control panel.

To increase system safety, a model to approximate battery state-of-charge was implemented, simulated and tested, see Section 6.

Integrating the implementations outlined above required effective collaboration of the team members to effectively combine mechanical and electronic assemblies into a single design and ultimately a functioning robot, as required by the project aims, was delivered, see Section A. This collaboration further permitted the compilation of deliverables to summarise project progress and outcomes in order to evidence the fulfilment of its learning outcomes, as highlighted in Section B. An image of the assembled robot and an electronic system diagram are shown in Section 1.

Robot functionality was tested by means of a number of movement tasks, as summarized in the test and verification report in Section 5.

Another aim was to secure additional funding, beyond the initial project budget, to allow for satisfactory completion of the aforementioned technical aims. The group secured an additional £5,250 pounds worth of cash, components and training sessions, with approximately £940 pounds remaining. See Section 2 for a detailed analysis of budget management. The additional funding had an effect on the approach taken in delivering the project, most significantly it facilitated the purchase of new motor control units running concurrent software, capable of delivering appropriate power to the motors, see Sections 4.8 and 4.9.

The benefits to project stakeholders and society are outlined in Section 3. These include the use of recycled carbon-fibre cladding and research into battery technology, as per Section 3.1.2., further including a number of outreach activities for non-technical audiences to increase awareness of STEM subjects, as outlined in Section 3.1.3., as well as group members' personal improvement with regards to technical and team working skills, see Section 3.2. The primary benefit to society of search and rescue robotics is the humanitarian aspect, with mobile robots improving safety for both disaster victims and rescuers.

Regardless of the above, the final project specification deviates from what the group set off to achieve and potential areas for further work have been identified, see Section 7.2. These include changes to the motor control system, but most importantly robot weight reduction, for example through utilisation of composite materials. A reflection of project choices made is given in Section 7.1, highlighting some examples of fortunate, as well as unfortunate choices made.

Word Count: 750

Project Close Report

Project Name:	Urban Search and Rescue Robot	
Key Accomplishments		
<i>Accomplishment 1</i>	Wirelessly controllable robot and arm	
<i>Accomplishment 2</i>	Raising £5,250 in sponsorship (both cash and parts)	
<i>Accomplishment 3</i>	Battery State-of-Charge Model implemented and tested	
<i>Accomplishment 4</i>	Optimised design of robotic arm	
<i>Accomplishment 5</i>	Apply course-gained skills in a practical context	
Deliverables		
<i>Deliverable</i>	<i>Achieved?</i>	<i>Impact</i>
Functioning powertrain	Yes	Drive successfully transmitted to axles and tracks
Robot Arm	Yes	First successful robot arm design and production in 5 years
Wireless control	Yes	Robot motors can be controlled remotely
Power distribution System	Yes	Safe and appropriate power supply
Key Milestones		
<i>Milestone</i>	<i>Planned date (week)</i>	<i>Actual date (week)</i>
Design of all parts complete	04/12/17 (10)	15/01/18 (16)
Manufacturing of all parts complete	29/01/18 (18)	23/04/18 (30)
Full construction of robot complete	05/02/18 (19)	26/04/18 (30)
Rigorous robot testing	05/02/18 onwards	Ongoing
Issues/Changes		
<i>Issue/Change</i>	<i>Impact</i>	<i>Mitigation</i>
Delays in manufacturing	Significant delay in the robot's construction	Clear communication and updates during two weekly meetings
Lack of time to create carbon fibre cladding	Unable to implement; less light weighting was achieved	Test method with a prototype before committing to the production of entire cladding
Budget		
<i>Budget</i>	<i>Total cost</i>	<i>Total benefit</i>
£1,400.00 (SoE)	£1,400.00	Able to: implement multiple sensors, purchase motors and controllers, tooling, material and a laptop to run systems effectively
£1,500.00 (Parts)	£1,500.00	Able to purchase essential electronic components and parts critical for dynamic tension system and robot arm
£3,350.00 (Cash)	£2,407.06	Cash left for next year's robot project to implement our recommendations
£400.00 (Training)	£400.00	Learnt and had access to light-weighting software
Further Opportunities		
<i>Opportunity 1</i>	Improve accuracy of State-of-Charge Model	
<i>Opportunity 2</i>	Light-weighting opportunity using carbon fibre	
<i>Opportunity 3</i>	Implement motor encoders for feedback control and ultimately automation	

Contents

Supporting Statement	ii
Project Close Report.....	iv
(A) Evaluation of Project Aims.....	8
(B) Evaluation of Project Learning Outcomes.....	9
1. Summary of Robot Specification and Performance	10
2. Cost Analysis	13
2.1. Costs	13
2.1.1. Sources of Funding	13
2.1.2. Cash Expenditure.....	14
2.1.3. Cost of Labour.....	15
2.1.4. Cost Benefit Analysis	16
3. Potential Benefits to Society of Search and Rescue Robotics	18
3.1. Benefits to Society Provided by WMR.....	18
3.1.1. Benefits to the S&R Robotics Community.....	18
3.1.2. Benefits to General Public	19
3.1.3. Benefits to School of Engineering and WMG	19
3.1.4. Benefits to WMR Sponsors	20
3.2. Professional Development of WMR Students	20
4. Final Specification	21
4.1. Arm.....	21
4.1.1. Base.....	21
4.1.2. Base Joint	22
4.1.3. Elbow	23
4.1.4. Head	23
4.1.5. Assembly	24
4.1.6. Wiring.....	25
4.2. Dynamic Tensioning	25
4.3. Battery Mounting	25

4.4. Powertrain	27
4.5. Cladding	30
4.5.1. Prototype Carbon Fibre Cladding	30
4.6. Electrical System	33
4.6.1. Power Distribution and Battery Monitoring.....	33
4.6.2. Electronics Trays & Bus Bar Box.....	34
4.7. Communications.....	36
4.7.1. Onboard data acquisition and motor control system.....	36
4.8. Processes Controlled by Pico-Computer	37
4.8.1. Motor control	37
4.8.2. Sensors.....	38
4.8.3. Camera	38
4.8.4. LIDAR and SLAM.....	38
4.8.5. Inertial Measuring Unit	40
4.9. Base computer controlling software	41
4.9.1. Base computer Block Diagram	41
4.9.2. Basic Control System.....	42
4.9.3. Full GUI controller	43
4.9.4. Motor Control Systems.....	44
4.9.5. Encoder data and map.....	47
5. Testing and Verification.....	48
6. Battery State-of-Charge Management and Monitoring	57
6.1. Simulink Models	58
6.1.1. DC Motor Control model.....	58
6.1.2. Battery Cell Model.....	58
6.1.3. Full Model	59
6.1.4. Controlling Code	59
6.2. Result of the Models.....	60
6.2.1. SOC plot with Temperature Change.....	60

6.2.2. Internal Temperature with Varying External Temperature	60
6.2.3. SOC with Varying Torque.....	61
6.2.4. Temperature the Torque Change	61
7. Reflection and Recommendations for Further Work.....	62
7.1. Project Reflection	62
7.2. Summary of Recommendations.....	62
References	64
Appendix.....	66
Appendix 1 – Breakdown of the Various Parts and Mouser Electronics Expenses	66
Appendix 2 - Arduino motor control sketch.....	68
Appendix 3 - LabView Occupancy Grid reader.....	69
Appendix 4 - Basic DC Motor Model	69
Appendix 5 - Battery Connection Model.....	70
Appendix 6 - Internal condition for the models	70
Appendix 7 - Torque Control	72
Appendix 8 - Temperature Change	73

(A) Evaluation of Project Aims

Aim	Evaluation
Raise sponsorship for necessary parts	<ul style="list-style-type: none"> - Sponsorship was raised successfully - Success in fulfilling this aim had particularly strong impact on motor control design
Improve chassis cladding and powertrain	<ul style="list-style-type: none"> - Powertrain redesigned and implemented successfully - Motors protected from drive shaft shearing - Chassis inaccuracies were corrected and accessibility of robot internals was improved
Robotic arm	<ul style="list-style-type: none"> - Arm was built and tested
Wireless control system	<ul style="list-style-type: none"> - The robot's motors are fully controllable from a wirelessly connected base station as well as sending sensor data to base station
Reliable power distribution	<ul style="list-style-type: none"> - New battery case was made - Power distributed through central encased bus bar system - Converters step battery voltage to levels required by instrumentation - Emergency power supply for instrumentation implemented, but switching delay is too large
Sensors and motor controls	<ul style="list-style-type: none"> - LIDAR, Inertial Measurement Unit, microphone, speaker and camera interfaced - The CO₂ sensor was found to be non-functional, most likely because of age effects on its electrochemical properties - Sponsorship allowed purchase of reliable motor controllers
Light weighting	<ul style="list-style-type: none"> - Carbon fibre designs were made, but full implementation was delayed
Implement designs	<ul style="list-style-type: none"> - Robot was assembled and functionality tested successfully
Documentation for project handover	<ul style="list-style-type: none"> - Most necessary documentation is provided in the Design Portfolio - Will be finalised following project completion
Compete in RoboCup Competition	<ul style="list-style-type: none"> - Competition clashed with peak assignment and revision period in term 3 - Ultimately no attendance because of lack of funds at sign-up deadline
Additional Achievements	
Battery Research	<ul style="list-style-type: none"> - Understanding of robot power requirements was improved - Extensive dynamic modelling allowed initiation of battery state-of-charge determination algorithm for improved system reliability
Risk Mitigation	<ul style="list-style-type: none"> - Initial risk analysis ensured completion of project aims
Project Outreach	<ul style="list-style-type: none"> - Awareness for the project and the 4th year course was raised at several events, including open days and IET presentations
Improved Teamwork	<ul style="list-style-type: none"> - Team working skills were improved through the project
Personal Growth	<ul style="list-style-type: none"> - Increased understanding of fields outside personal engineering disciplines - Skills acquired throughout course were demonstrated in applied context

(B) Evaluation of Project Learning Outcomes

Learning Outcome	Evaluation
1. Extrapolate existing knowledge and experience and apply them in an integrated systems approach to solve a complex and unfamiliar engineering problem.	<ul style="list-style-type: none"> - Team members had tasks allocated to them according to their skills and work done was integrated to deliver a wirelessly controllable robot
2. Extract and critically evaluate relevant data in order to apply engineering analysis and advanced problem solving skills, in order to complete an engineering project to the satisfaction of a customer and/or user	<ul style="list-style-type: none"> - Requirements identified according to the project brief were fulfilled - Robot power system behaviour was analysed under varying ambient conditions to increase system reliability - Assessments and deliverables were fulfilled through group collaboration
3. Consider the wider context of the project including, risk, ethics, environmental and sustainability limitations, intellectual property rights, codes of practice and standards, product safety and liability, to inform the project specification (problem brief) as relevant to the project	<ul style="list-style-type: none"> - Risk analysis was carried out and evaluated - Ethical impact of the project was evaluated - Emission-free battery technology to power the robot was evaluated - Poster was designed to summarize the project objectives and content concisely - Battery management was considered for robot safety
4. Plan and manage a project from the design process to a deliverable outcome, including managing a budget and costs, and understanding the commercial, economic and social environment of the project	<ul style="list-style-type: none"> - Regular group meetings were held and minutes kept rigorously - Budget was managed and additional funds were raised to allow fulfilment of objectives - Benefits to society, University and individuals were considered and evaluated, beneficiaries of deliverables were identified - Supplier relationships were developed
5. Demonstrate effective communication, both verbal and written, to a technical and non-technical audience	<ul style="list-style-type: none"> - Written deliverables were submitted satisfactorily - Sponsorship applications were successful - Poster was designed to communicate project objectives to a non-technical audience - Portfolios of work outcomes were compiled - Non-technical audiences engaged at many outreach events - Technical academic paper demonstrating novelty of research and the ability to communicate technical contents was demonstrated - Social media accounts and a website were created and maintained
6. Demonstrate the ability to work as a member of a multidisciplinary team to achieve shared objectives within the scope of the project	<ul style="list-style-type: none"> - Team members' skills were evaluated in a group discussion and tasks were assigned according to these henceforth - A robot combining multiple disciplines of engineering was built - Combining multiple disciplines of engineering required effective communication and each team member was required to leave their comfort zone to achieve a joint project objective
7. Use innovative techniques, materials or methods in delivering the project	<ul style="list-style-type: none"> - Approaches specific to the group were taken to deliver project objectives and fulfil assessments - Innovative combination of robot power system aspects lead to deeper understanding of project requirements

1. Summary of Robot Specification and Performance

This section aims to show a top level view and justification of the finished Atlas Legacy robot, while later sections of the completion portfolio focus more on finer technical details. A photograph of the fully assembled robot is given in *Figure 1.1*.

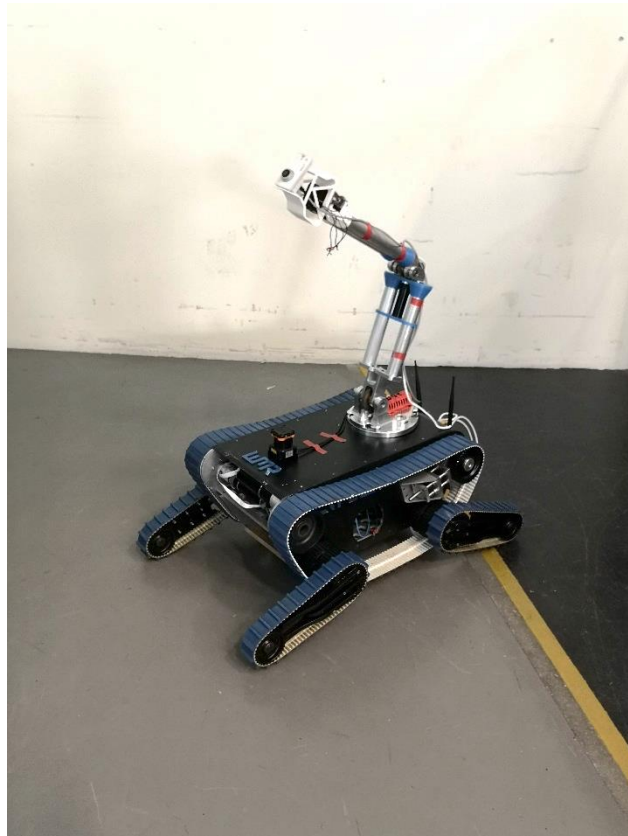


Figure 1.1 Assembled Robot with Arm mounted

Since its inception in 2007, the primary goal of the Warwick Mobile Robotics (WMR) Urban Search and Rescue (USAR) has been to create a robot that is capable of competing at the RoboCup Rescue international robotics competition. Because of budgetary and time constraints the 2017/2018 WMR team did not attend the RoboCup competition, however its rules and requirements were a key driver in the development of Atlas Legacy. The competition trials include three primary challenges: mobility and manoeuvring tasks which require the robot to traverse difficult terrain, sensing tasks which involve gathering and recording data about the robots environment, and dexterity tasks which require the operator to manipulate the robots environment. All of these challenges are tested during time trials where robots are rewarded for completing a task quickly; robots that are automated receive extra time therefore teams are incentivised to deploy autonomous systems and not just tele-operated ones.

WMR has achieved significant strides in meeting these objectives. A robot that is capable of moving completely independently using battery power and following motor commands provided through a wireless communications network has been created. The robot is controlled through teleoperation using a PlayStation controller through a LabVIEW operator interface. The control interface consists of a GUI (Graphical User interface) that displays the view from the robot camera, a 2D map of the robot's surroundings created with a LIDAR and a SLAM algorithm and a wire mesh of the robot that visualises the pitch and roll of the robot obtained from an on-board accelerometer. These sensing abilities embedded onto the robot have enabled Atlas to meet some of the sensing requirements of the RoboCup.

The on-board power system provided Atlas with sufficient power to drive all of its motors, control electronics and sensor. When given a full power forward command by the operator, the power system allowed Atlas to move at an approximate speed of 1 m/s, a comfortable walking speed for a human. The new powertrain of the robot also performed perfectly, producing smooth and unimpeded motion. The front and rear flippers of the robot allow Atlas to push off one of its ends from the ground which can be used to traverse obstacles such as steps, however this capability was not tested extensively in this development cycle. The wireless motor control capabilities, along with the robot power system, main track power train and flipper system has empowered Atlas to face the mobility requirements of the RoboCup.

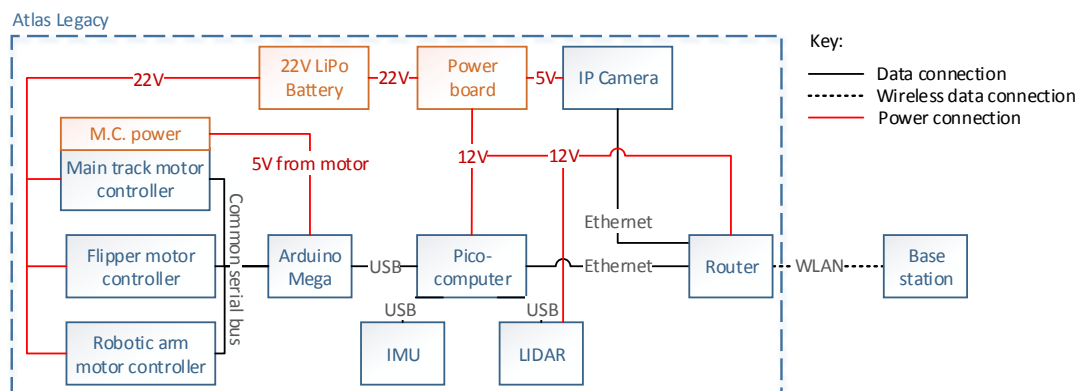


Figure 1.2 Designed Electronic System

A newly developed robotic arm has moved Atlas forward in realising the dexterity challenges of the RoboCup. Because of time constraints the teleoperation of the robotic arm has not yet been tested, hopefully this will have been achieved by the project presentation. At this stage the robotic arm is not equipped with a gripper only a camera. This allows an operator to vary their vantage point to better overcome navigational challenges. Further work is needed by future WMR teams in enabling Atlas Legacy to manipulate its environment.

In conclusion WMR has created a functioning tele-operated robot that is capable of achieving some of the tasks in the RoboCup competition but not all of them. These accomplishments

are significantly more advanced than what has been achieved by previous teams in the past 6 years. This will hopefully enable future teams to attend the competition and to also focus on more concurrent robotics research questions such as automation.

2. Cost Analysis

2.1 Costs

The group attempted to utilise readily available parts as much as possible. This was primarily done because of significant cost savings, but the increased sustainability of recycling was also taken into account. Examples include the use of the basic chassis and drive tracks, two components where replacement would otherwise incur significant cost.

Having said this, budget still had to be kept rigorously throughout the project and as a consequence of this, the team put significant effort into the pursuit of additional funding. Additional funding allowed further development and improvement of ATLAS, beyond what would have been possible on the basis of previously purchased parts and standard project funding.

2.1.1 Sources of Funding

As mentioned above, the team spent a lot of additional time and effort in the pursuit of gaining additional sponsorship this year. For example, personalised sponsorship packs were sent out to prospective sponsors. Fortunately, this additional effort was a successful endeavour because in addition to the given School of Engineering funding the team was able to gain another five sponsors, with a breakdown of the percentages from each company shown below in *Figure 2.1*.

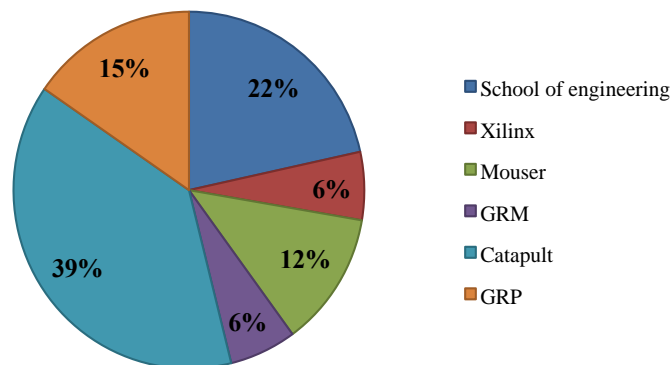


Figure 2.1 - Breakdown of sources of funding

Table 1 shows a more detailed financial breakdown of funds received through sponsorship. With the funds received from Catapult, the team was able to purchase essential components including a new laptop and motor controllers. These ultimately enabled efficient implementation of the whole control system. Xilinx provided WMR with a Nexys4 DDR board. Circuit designs for this were initialised, however the decision was made to abandon the interconnection of the device inside the robot, in order to free up time for work in more pressing areas of the project. It is however recommended that future WMR teams take advantage of its high speed data processing capabilities.

Another important sponsor to highlight is Mouser Electronics, from whom the team gained £795 of credit. This was used to purchase electronic products essential for the robot's remote motor control and other electronic components outlined throughout the report.

Aid in the form of training was received from GRM, providing the team with a training day for three members to attend and learn how to use specialised light-weighting software (Genesis).

GRP provided WMR with £1,000 to use for future development of the project and provided materials and access to their workshop to produce carbon fibre parts, such as the cladding.

Table 1: Funding Breakdown

Source of funding	Type	Amount (£)	Date sponsorship was acquired	Info
School Of Engineering	Cash	1,400.00	Start of Project	Standard student funding
Xilinx	Parts	500.00	25/10/17	FPGA board
Mouser	Credit	795.00	21/12/17	Electrical parts
GRM	Training day	400.00	11/22/17	Genesis software training
Catapult	Cash	2,500.00	23/01/18	Research grant
GRP	Parts	1,000.00	07/02/18	Materials, carbon fibre
Open day	Cash	50.00	26/11/18	University open day
Total cash	All			4,750.00
Total inputs	All			6,650.00

2.1.2 Cash Expenditure

A summary of project expenditures can be seen below in Table 2. Furthermore, a more detailed breakdown of the two sections named 'Various Parts' and 'Mouser Parts' can be found in *Appendix 1*.

Table 2: Breakdown of cash expenses

Item	Cost (£)	Use
Arduino parts	50.57	For sensors
Mouser parts	591.94	Electrical parts
Tooling	150.00	Manufacturing
Material	88.50	Material for powertrain and arm
PCB boards	290.00	Production of boards
Laptop	932.58	Base computer
Various parts	371.53	Mechanical and electrical parts
Motor controllers	399.90	Control of motors
Robotic arm gripper	64.00	Arm end effector
New Motors	700.00	New motors for arm
Soldering iron and Resistors	168.04	For construction
Total cash		4,750.00
Total spent		3,807.06
Total cash remaining		942.94

As can be seen from Table 2, over £3,800 worth of components were purchased to improve the operation of the robot, with the major purchases including a base computer, motors and motor controllers. Throughout this process everything that was purchased was also bought with project handover in mind, as purchased components should also be useful for future groups to continue developing the project, even if parts were not exploited to their full potential this year.

Following this, over £900 of cash remain in accounts that will be available for future years to use. This highlights further that the longevity and the legacy of the project have been considered throughout the project. This is something that is fundamental to the WMR group.

2.1.3 Cost of Labour

The final aspect of project finances to reflect on is the cost of labour, although this is not an explicit cost, the time spent on the project by the group members, technicians and academics still needs to be considered. The student hours spent on this 30 credit project should be around 300 hours, with each credit equating to 10 hours of work. Since this is difficult to assess precisely the amount of hours spent was assumed to be 300 per group member. From here the respective hours of the other individuals involved with the completion of this project have been estimated regarding the time taken for them to complete their tasks. The cost per hour used is a standard value for each of the respective roles. The breakdown of these costs is shown in Table 3.

Table 3: Cost of labour breakdown

Role	Cost/Hour (£/hr)	Individual	Hours	Costs (£)
Students	15	Charles Perera	300	4,500
		Mark Safford	300	4,500
		Tom de Oliveira	300	4,500
		Jan Specht	300	4,500
		Emily Carman	300	4,500
		Eashana Chotai	300	4,500
		Balint Vidos	300	4,500
Technicians	30	Jacob Gates	100	3,000
		David Cooper	25	75
		WMG technicians	15	450
Project Director	75	Emma Rushforth	75	5,625
Other Academics	50	Stefan Winkvist	5	250
Total			2,697	41,350

As can be seen from the Table 3, the total cost of labour amounts to £41,350, which is significant however this 'labour' cost was unavoidable in delivering the project.

Finally, including the cash spent in completing this project the total expenditure of the project combines to a total value of £44,107.06. This cost is significant but unsurprising, considering that the majority stems from student working hours spent on the project.

To conclude, it can be said that project budget was kept rigorously and there is a considerable amount of funding available for the next project group to utilise.

2.1.4 Cost Benefit Analysis

Table 4 shows a summary of the direct purchases of the project and the direct benefits they had on the project.

Table 4: Cost Benefit Analysis of Project Costs

Cost	Benefit
Labours costs	<ul style="list-style-type: none"> - Completion of project, including manufacture of new parts and production of electronic boards to allow the wireless control of the robot. - Final construction of robot and initial design by students, consultation on project direction from technicians and project director.
Electronic components	<ul style="list-style-type: none"> - Implementation of motor control circuits, battery management - Communications to allow wireless and safe running of robot.
Tooling	<ul style="list-style-type: none"> - Essential for manufacture of mechanical parts - Completion of arm and powertrain parts
Materials	<ul style="list-style-type: none"> - Required to manufacture mechanical parts in powertrain and arm - Certain electronic components such as bus bars, essential for running the robot
Laptop	<ul style="list-style-type: none"> - Required for interface to robot to allow remote wireless communication - Running of required control software - This was unable to be done previously because of the age of the old laptop available - Visual feedback from robot, from LIDAR and camera, as well as audio from microphone
Purchase of new motors and gripper	<ul style="list-style-type: none"> - Essential for arm because of age and unsuitability of currently available motors with damaged connections - Allows control in three of the available degrees of freedom - Gripper meets RoboCup requirement for arms to be able to manipulate objects
Soldering iron and resistors	<ul style="list-style-type: none"> - Assembly of electric boards - Control of circuit currents and voltages - Available for future WMR groups to make future modifications to circuitry
Other parts	<ul style="list-style-type: none"> - Includes springs for tensioning system, bearings for arm base, wiring, etc. - Important for construction and completion of robot. - Provision of spare parts for the project in future years.

3 Potential Benefits of Search and Rescue Robotics to Society

The economic, social and human impact of natural and manmade disasters is clearly visible. According to the 2010 Red Cross World Disasters Report (McClean, 2010) in the 2000-2009 period approximately 1.1 million people were killed in disasters, causing direct damages of \$986 billion, not mentioning the opportunity cost because of lost production and growth (Murphy, 2014). A significant portion of these disasters affected urbanized areas causing significant damage to buildings and infrastructure (Murphy, 2014). The consequences of this are twofold; firstly victims may be trapped in damaged/collapsed buildings, secondly rescue workers are impeded in delivering aid to trapped victims because of potentially dangerous rubble and unconfined hazardous materials (Murphy, 2014). The large negative impact of disasters coupled with the challenges of providing disaster relief demonstrates the benefits to society Search and Rescue Robotics can deliver.

3.1 Benefits to Society Provided by WMR

The 2017/2018 WMR project provided a benefit to society by working on the technical challenges of Search and Rescue (S&R) robotics, as well as benefiting the general public and various other stakeholders of the project through non-technical work. These benefits can be categorised into the following groups based on who benefits: S&R robotics community, general public, University institutions and the project students themselves.

3.1.1 Benefits to the S&R Robotics Community

From a technical perspective the 2017/2018 WMR team primarily conducted foundational work by producing a working robot chassis, the hope is that future WMR teams can further develop this general chassis by applying techniques of more concurrent research topics such as advanced signal processing and automation, as well as application of new materials. Now that WMR has created a working tele-operated robot, future teams can focus on more nuanced, but less critical aspects of the project. As such the efforts of WMR in this year can be thought of as an *enabler* of future research and development that can further the cause of S&R robotics. The extensive documentation created by current and past WMR teams has also benefited other S&R robotics researchers and student groups, with previous technical reports having been downloaded 2500 times from the WMR webpage.

Nonetheless, WMR has achieved some novel technical feats, for example as an early adopter in search and rescue robotics, WMR has utilised recycled carbon fibre composite in the cladding of Atlas. As the carbon fibre market continues to grow, its environmental impact is of

increasing importance (Green Alliance, 2017), WMR's use will help GRP in assessing the usefulness of recycled carbon fibre in a 'real world' application.

Society may benefit from the research undertaken on battery state-of-charge modelling and temperature compensation techniques, since batteries under varying ambient temperature conditions are an area of research that is of interest in most applications of mobile electronics. Current examples include battery powered electric cars and mobile phones or laptops, which still suffer from strong fluctuations in battery life depending on ambient conditions in different climate zones.

3.1.2 Benefits to General Public

WMR has directly benefitted the general public at large through conducting various outreach activities. It is important for the project team to generate interest into USAR robot research and development and to inspire the next generation of engineers. Robotic projects exist in a number of universities across the country. However there is very little education and information available on these. Furthermore, in the 2017 government paper, *Industrial Strategy: Building a Britain fit for the future*, an on-going shortage of Science, Technology, Engineering and Math (STEM) skills was highlighted as one of the key challenges faced by the UK economy (Department for Business, 2017). Outreach is fundamental to connect students and schools in order to engage future engineers and increase interest in S&R robotics as well as STEM fields in general. A number of outreach events were attended to promote the project, while simultaneously, social media presence of the project was increased.

- The Science Gala: The project was showcased to aspiring future engineers within the 13-18 age group
- VEX robotics (IET): Invited to speak about the WMR project at the VEX robotic competition for school children between ages 13-18
- Open day and Offer holder days to raise awareness and promote the project with potential future Warwick students and their guardians
- 350 combined followers of Facebook and Instagram pages

3.1.3 Benefits to School of Engineering and WMG

WMR has nourished fruitful relationships with its stakeholders including the School of Engineering and WMG, who have assisted the project financially and with technical support. WMR has publicised these two organisations at an array of outreach events, as well as during external sponsor relations. WMR has helped the School of Engineering in popularising its engineering course by attending multiple Open day and Offer holder day events, where WMR liaised with potential Warwick students and their guardians to show the opportunities available within the departments. WMR has helped WMG showcase the technical capability of its workshop technicians by having their workshop on display and by engaging with visitors to WMG

from around the world including the Education Select Committee and members of World Government. Furthermore, WMRs effective relationship with external sponsors such as Mouser, Xilinx, Catapult and GRM have presented Warwick Engineering students in a competent and professional light, helping spread the Warwick brand as well as improving the employment prospects of its students.

3.1.4 Benefits to WMR Sponsors

WMR has received sponsorship in the form of cash, equipment and training from Mouser, Xilinx, Catapult and GRM. In exchange WMR has provided exposure to these companies at a range of outreach events as well as provided them an opportunity to trial and showcase their technology. For example, the electronics component retailer Mouser published a blog article written by one of the WMR students as a demonstration of the capabilities of their products.

3.2 Professional Development of WMR Students

Finally, the WMR USAR project has provided the opportunity for 7 engineering students to test and develop themselves in a challenging practical project that has developed their technical and transferable skills. The challenge of developing a functioning robot in a multidisciplinary project has hopefully produced more competent engineers which will improve their personal career prospect as well as society as a whole.

The personal benefits gained from the research outlined in the technical academic paper are primarily an improved understanding of battery power supplies, DC motors, as well as dynamic system modelling techniques, as well as cross discipline understanding by the non-electronic based students.

4. Final Specification

4.1 Arm

This section looks at the final arm design specifications. Designs have been assessed against their similarity to initial design, functionality and assembly.

4.1.1. Base

The lower base part, shown in *Figure 4.1*, has been made as closely as possible to the specification set out in the design portfolio. The part comfortably fits around the annulus gear, used to turn the arm, and slides along the ball bearings fitted to the annulus gear, shown in *Figure 4.1*. This will ensure smooth turning.

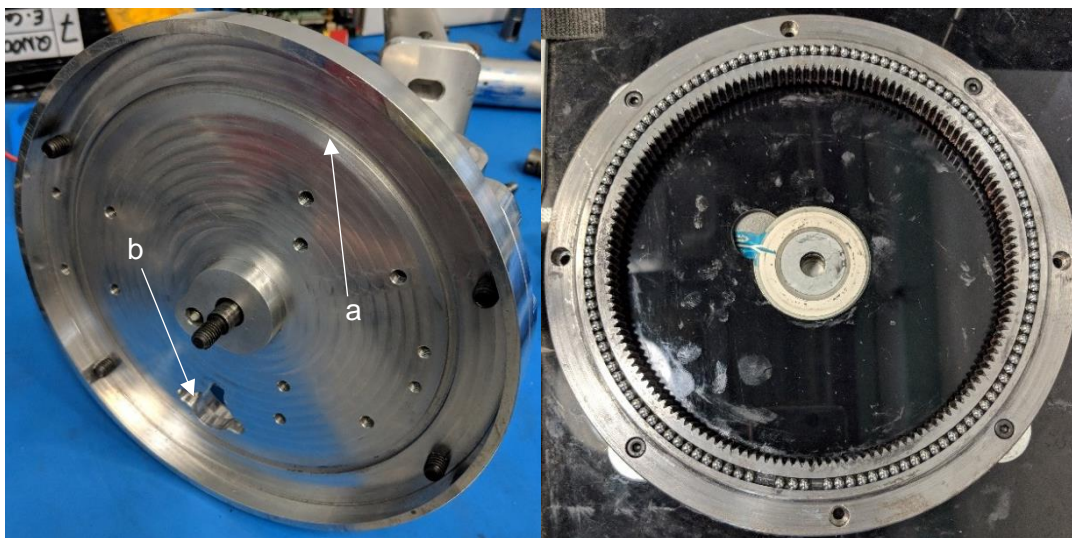


Figure 4.1: Bottom base part when fitted to rest of arm, showing recess to allow fitting of ball bearings (a) and hole to allow turning motor to pass attach to part (b)(left), and annulus gear with ball bearings (right)

After design, the upper base part had to be modified slightly because of machining inaccuracy. This inaccuracy led to a failure in ensuring that the gear mechanism used to raise and lower the arm meshed correctly. This required a minor modification whereby the recesses used to fit the arm components were sunk slightly deeper into the base part. This had no effect on the functionality of the arm.

Overall, the part was made as specified in the design portfolio, with all components, including the raised part of the lower plate needed for the connection of the turning motor, fitting well. *Figure 4.2* shows the fits of this part with the connecting components.

To connect the arm to the robot base, the base fits onto a mounting part, allowing the arm to easily attach or detach, therefore when required it can be used as a demonstration piece separate from the main robot body.

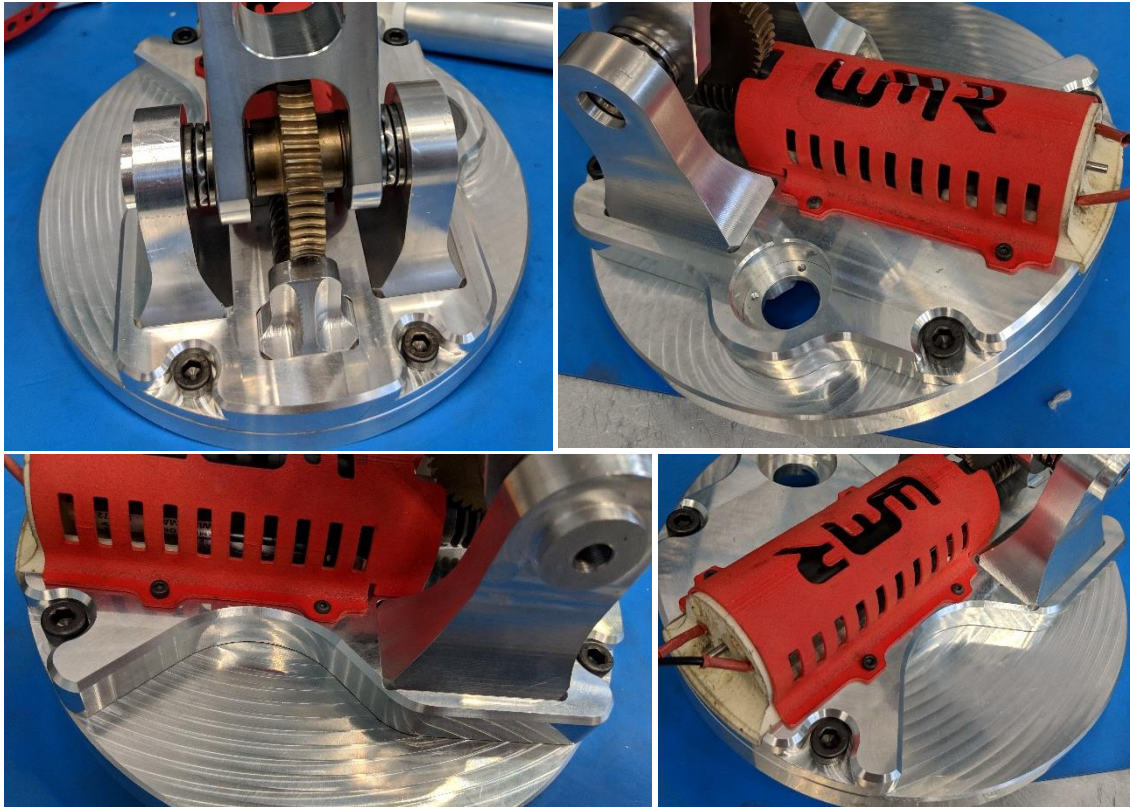


Figure 4.2: Selection of pictures of upper base part in assembled arm base. From Top left clockwise, Assembly of arm connections and connection of worm screw and gear, connection for turning motor with motor cover and cut out to remove weight from part, motor cover and further material removal from light weighting, material removal and side view of arm connection.

4.1.2. Base Joint

The base joint was manufactured in two parts, as in the specification, in order to improve ease of manufacture and therefore the ability to make the arm more modular, making it easier to replace parts.

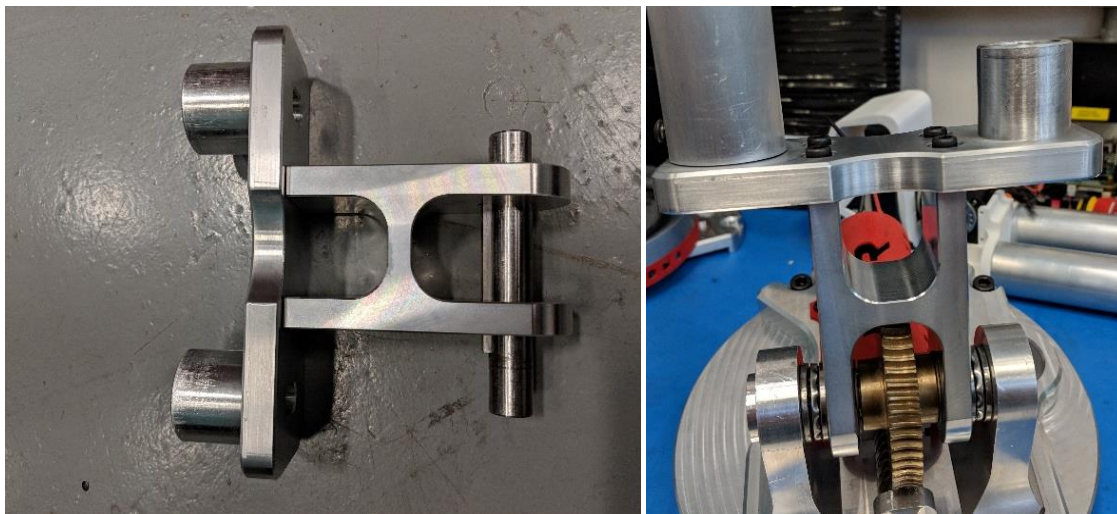


Figure 4.3: Assembled arm base joint parts with keyed shaft used to connect to base connections (left) assembled part, showing bearings used in connectors, and attached Aluminium tube to show connection (right).

Both sections of the part were manufactured as in the specifications, with the connections to the arm tube being machined to a smaller diameter manually in order to ensure a tight fit with the tubes. *Figure 4.3* shows these assembled parts and the part as a whole attached to the base, during the assembly process.

4.1.3. Elbow

The joints used to connect the tubes and the elbow components were manufactured to the same specification as in the design portfolio. The aluminium tubes were machined manually to create a tight fit with the elbow joint parts. All elbow components fit within the slots designed for them. The remaining components for the elbow motor were also manually machined, again ensuring a secure and tight fit to the tubes. *Figure 4.4* shows the parts of the elbow and the final assembly.

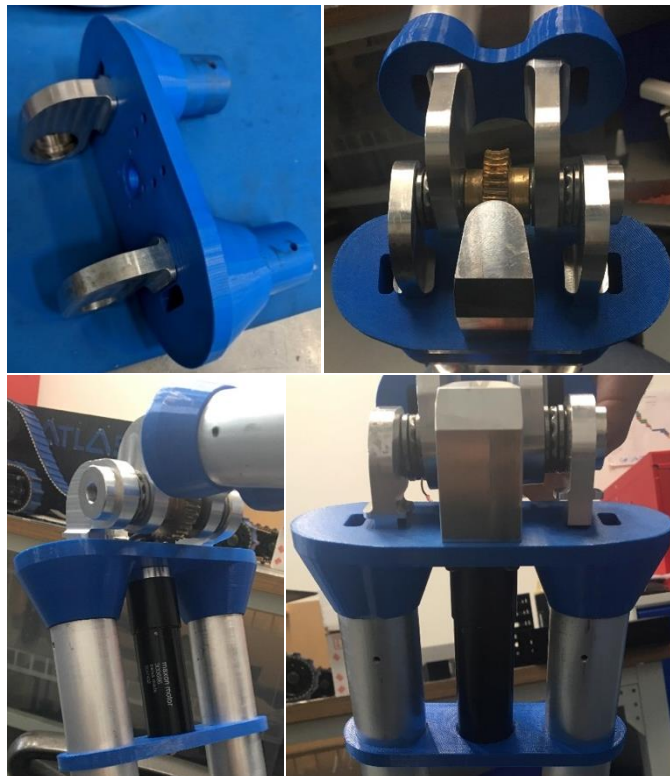


Figure 4.4: From Top Left Clockwise: Lower Elbow Joint with hinge parts attached; end view of assembled elbow showing hinge and gearing mechanism; end view of assembled elbow showing elbow motor and mounting; view showing entire assembled elbow of arm.

4.1.4. Head

The arm head needed modification from the specification because of manufacturing issues. For ease of production, it was decided to modify the old arm design for the connection to the tubes, and use the old stepper motors to control the head. This also meant that the head itself

had to be modified in order to accommodate the new stepper motors. This was successful, with images of the assembled head shown in *Figure 4.5*.

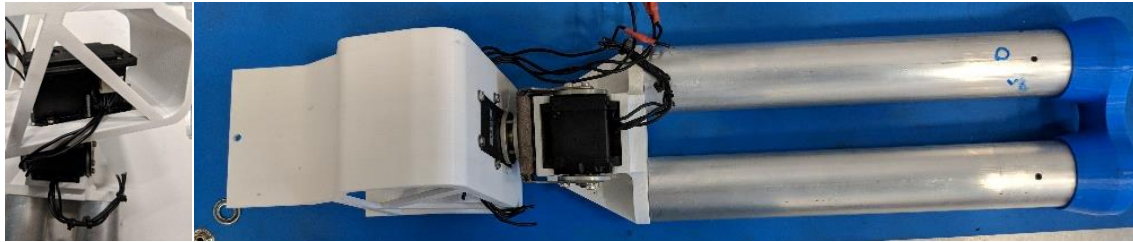


Figure 4.5: (Left) stepper motor assembled within head of arm (Right) View of head connection, containing stepper motor and assembled head, with connected Aluminium tubing.

4.1.5. Assembly

Figure 4.6 shows the fully assembled arm, without wiring or electrical connections, as well as the arm mounted on the robot body. All required gears mesh successfully and all parts fit correctly in their required locations. The arm is stable, secure and there is no wobbling of parts showing good fit. Thereby it can be said to meet the design specifications.

The camera is easily screwed into the head part, and gripper fitted to the front upon wiring of

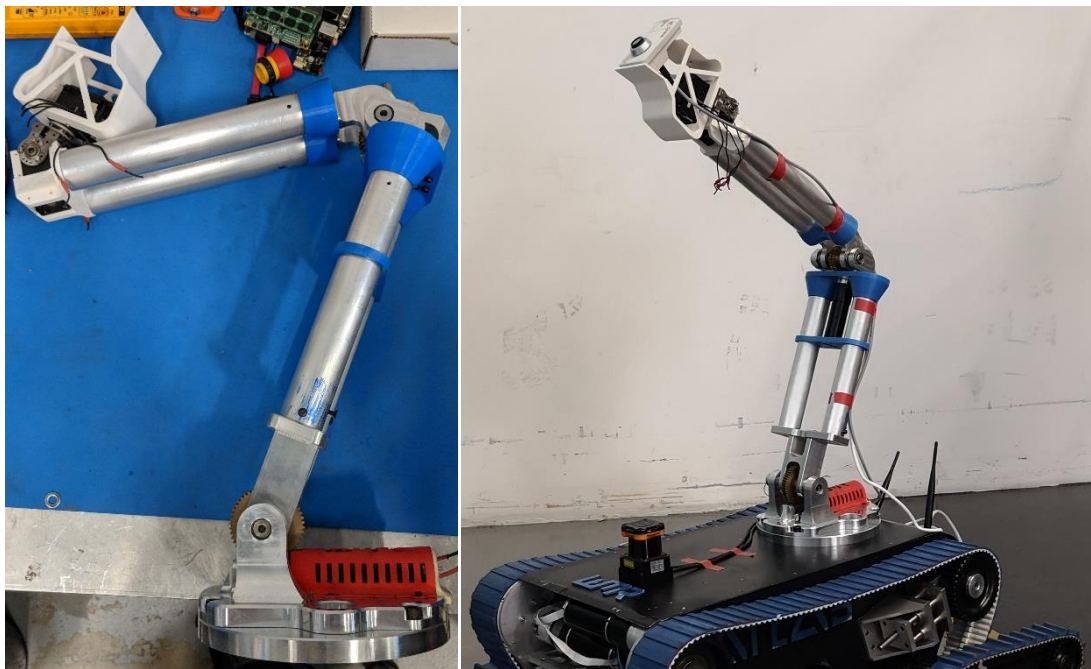


Figure 4.6: Fully Assembled Arm (left) and arm mounted on robot body (right) excluding rotat- the arm, because of the complexity of this task.

4.1.6. Wiring

The arm has been designed so that wires can be passed through the aluminium tubing so as not to restrict the mobility of the arm and reducing the risk of them catching and being dislodged. The arm was wired together successfully, with new motors requiring soldered connections that were performed successfully. As well as this, encoders on the joints of the arm were wired so that the position of the arm could be known through the interface.

Overall, the wiring is much less complex than that of the previous design, making the whole design easier to assemble, disassemble and maintain; thus meeting the criteria for ease of use and modularity set out in the initial specification.

4.2 Dynamic Tensioning

An image of the dynamic tensioning system can be seen in *Figure 4.7*. The springs used exert the correct amount of force to maintain tension. However, friction between the sliders, holding the springs, caused sticking issues, with the springs being stuck at full compression, seen in the *Figure 4.7*. This was remedied with the use of further lubrication. For the majority of testing, the static tensioning system was used, as it was easier to remove when modifications to parts needed to be made.

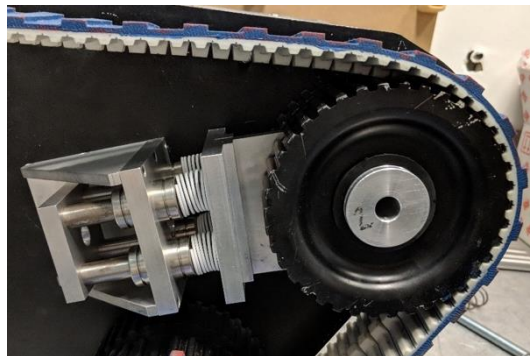


Figure 4.7: Assembled Dynamic Tensioning System

4.3 Battery Mounting

The cladding and side panels were modified allowing the batteries to be mounted in the bottom of the robot, creating extra space for electronics in the top part of the robot. This involved cutting panels on both sides, as detailed in the design portfolio and shown in *Figure 4.8*, to allow the fitting, removal and changing of batteries from the sides of the robot. This modification also allows the addition of cooling fans to the side of the robot, necessary to mitigate the risk of overheating. Furthermore it was successfully designed and made so that an easy access hinge could be added to the hole. This was unfortunately not able to be implemented in time for this report.

It was also realised that the original battery mounting system was slightly too large to allow two batteries to be fitted in the bottom section.

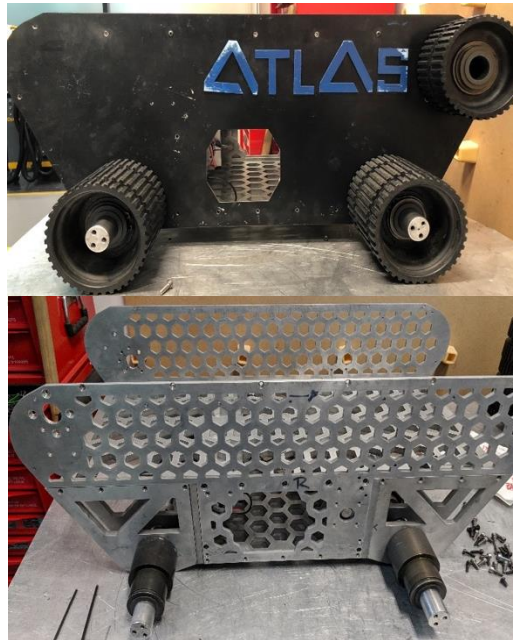


Figure 4.8: Modified cladding (top) and modified side panels (bottom) showing cuts to allow battery mounting.

Figure 4.9 shows components of the battery mounting system, and how this fits within the robot



Figure 4.9: Two-part battery mounting system consisting of slider and mounting cage respectively.

4.4 Powertrain

The final specification of the redesigned powertrain was kept the same as the designs outlined in the design portfolio as they had been shown to several WMG technicians and necessary changes had already been made ensuring manufacturability. This further ensured that components operated and assembled together correctly.

A small adjustment was made, however, in making the bolt holes tapped to allow bolts to screw into the correct parts in the construction of the powertrain sub-assembly. The key fundamental parts of the powertrain are shown below in *Figure 4.10*.



Figure 4.10: Powertrain Components

Once assembled, the sub-assembly of the powertrain components fit together well, and parts needed no further adjustment to ensure correct assembly. However, because a single key had to connect the motor to the drive shaft but also the driveshaft to the output gear, this meant that a standard key would not be big enough and therefore could not be used. To remedy this, two non-standard longer keys were created, and shown on the left-hand side of *Figure 4.11*. The longer keys were then inserted to connect the shaft to the motor allowing the output gear to easily slide over and be held in place with a grub screw, as shown within *Figure 4.11*.

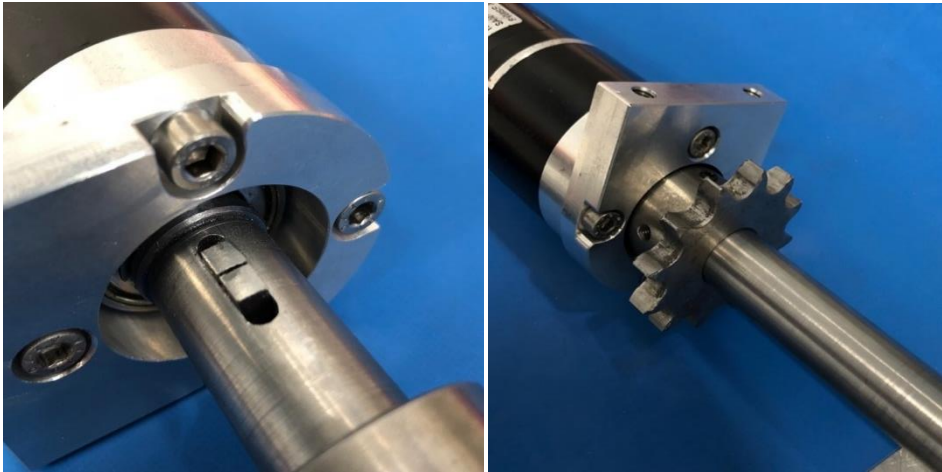


Figure 4.11: Custom keys connecting the output shaft to the motor (left) and the output gear attached to the assembly (right)

Aside from this small complication, the rest of the powertrain assembly was successful first time. The full sub-assembly of the powertrain can be seen below in *Figure 4.12*.

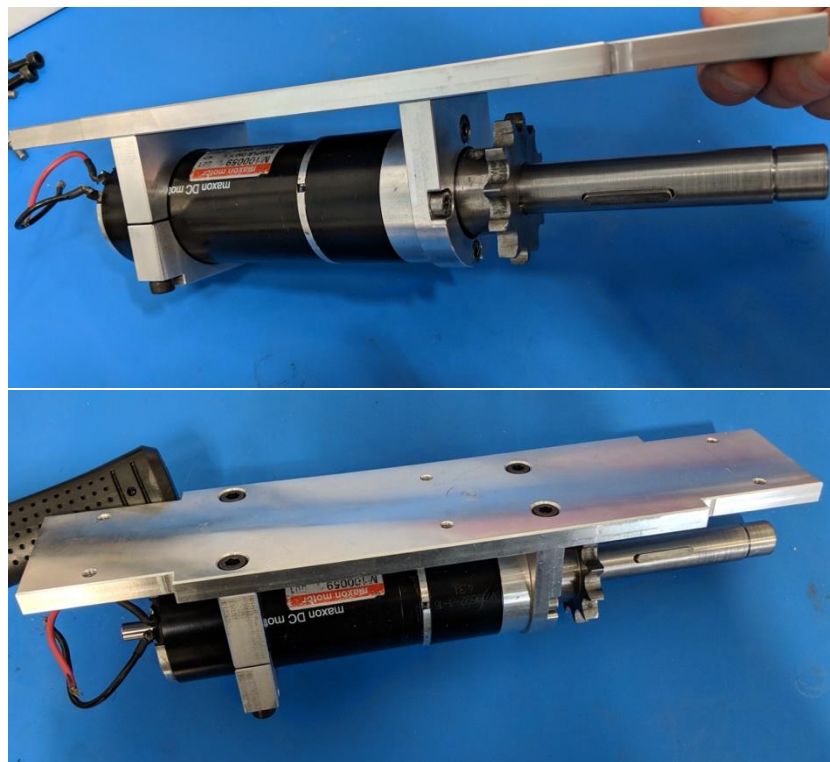


Figure 4.12: Full powertrain sub-assembly

From here the next step was to connect this sub-assembly into the assembly of the whole robot. The powertrain was connected using bolts through the top plate of the sub-assembly onto the middle honeycomb plate of the robot, as is shown below in *Figure 4.13*.

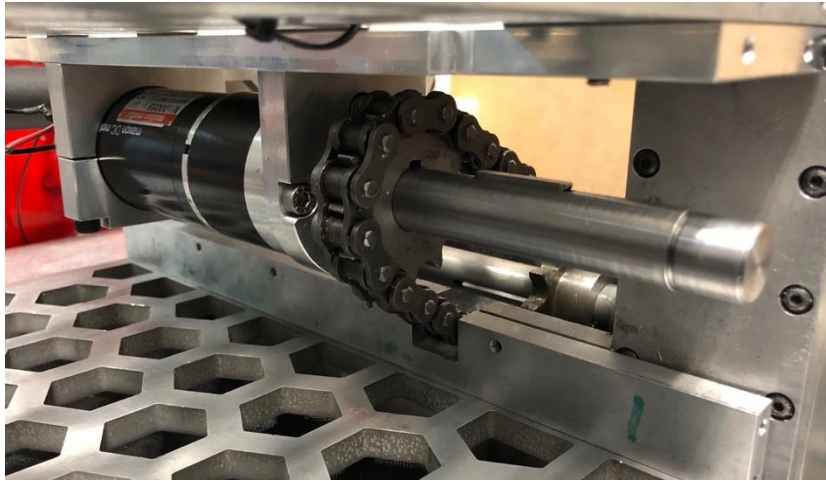


Figure 4.13: Powertrain sub-assembly connected to the robot

The drive chain was attached to the powertrain's output gear, to connect to the axle that powers the tracks. Overall, this connected successfully as the two gears were aligned in the same plane meaning that there were no misalignment issues. The separation distances were correct as the chain was held taught; ensuring that it will transmit torque efficiently without slipping. The chain connecting the powertrain and the drive axle can be seen below in *Figure 4.14*.

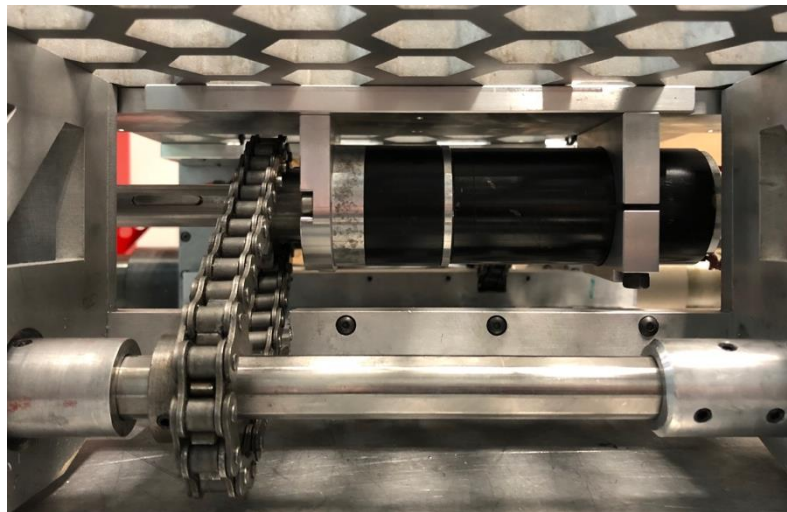


Figure 4.14: Chain connecting the powertrain and the drive axle

This assembly process was repeated for the second drive axle, located at the front of the robot. Because of symmetry the process taken was exactly the same as for the first one. As seen in *Figure 4.15*, both powertrain systems were successfully connected to the robot, ready for testing.

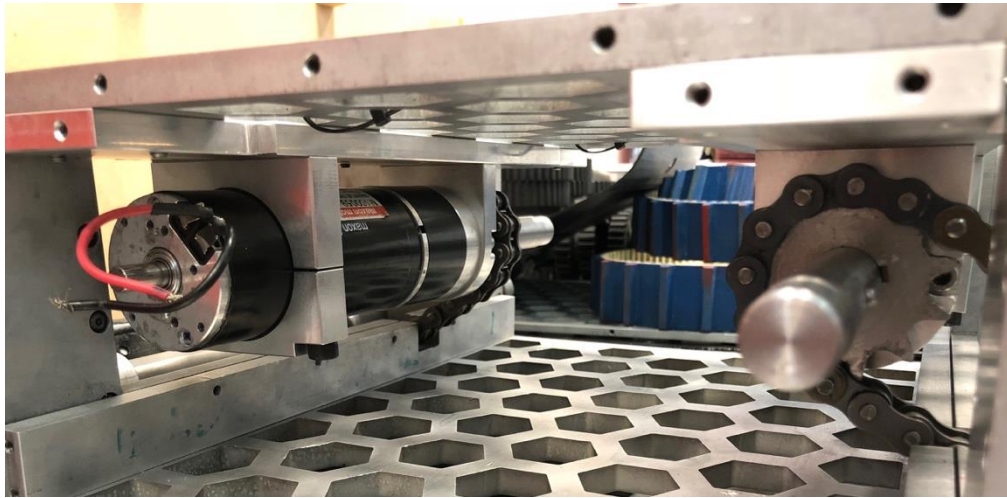


Figure 4.15: Both powertrain sub-assemblies attached to the robot

4.5 Cladding

The final design specification of the robot cladding consisted of two elements; research and investigation into the potential use of prototype recycled carbon fibre cladding, and a modified version of the original cladding to allow for the alterations made to the rest of the robot. The research into the utilisation of composite materials can be seen as follows and the modifications made to the original cladding can be seen in Section 4.3.

4.5.1 Prototype Carbon Fibre Cladding

The preliminary prototype carbon fibre cladding consisted of manufacturing a new updated version of the cladding of the robot. However, as using carbon fibre within the robot is novel to this project, along with the cost of raw materials and the manufacturing process, it was deemed sensible to first create a test piece of cladding before making a final decision. This process involved using the old cladding parts as a mould, and then layering resin and precursor to create the new cladding on top of this. The process can be seen in *Figure 4.16*, the first step being cutting the correctly sized piece of carbon fibre matrix and the second applying the resin evenly to this matrix.



Figure 4.16: Cutting the carbon fibre matrix (left) and applying the resin (right)

Once appropriately layered, this was then placed inside a vacuum bag and the vacuum was turned on for twenty-four hours to allow the carbon fibre to set correctly. This led to the final part being produced. As seen in *Figure 4.17*, the appearance of the component is not that of typical carbon fibre, because of it being made from recycled carbon fibre, causing the cosmetic difference. The WMR team was proud to be able to investigate the use of a recycled material because of the environmental impacts in a project such as this one.



Figure 4.17: Manufactured Carbon Fibre Part

Upon inspection and testing of the carbon fibre, it was deemed that manufacturing the entire cladding assembly out of carbon fibre would be effective. However, at that stage in the project it was deemed inappropriate to do so for two reasons.

Firstly, by the time this test piece had been designed, manufactured and tested there would not be enough time to fully manufacture the whole cladding assembly. The designs are created are however available for future years to use. More importantly, the second reason was because of the success of the manufacture of the test piece, it was suggested that rather than just the cladding the entire chassis shell could be made from carbon fibre with steel inserts for increased strength.

Producing a chassis in such a way would be incredibly beneficial as it would remove significant weight as there would be no need for the heavy aluminium chassis components. This is clearly something that would take a prospective team an entire year to implement and is therefore something that is advised within the recommendations in Section 7.2.

Because of this development it was clear that it would be a better use of time to modify the current cladding for the purposes of this year instead of making brand new cladding that would be scrapped almost immediately by the next team. Future WMR project teams can build on the preparatory research and development that has been conducted by this year's team in investigating carbon fibre utilisation for the chassis of the robot.

4.6 Electrical System

4.6.1. Power Distribution and Battery Monitoring

Figure 4.18 below shows the power distribution board on the right and the bus bar connection system inside the black box on the left.

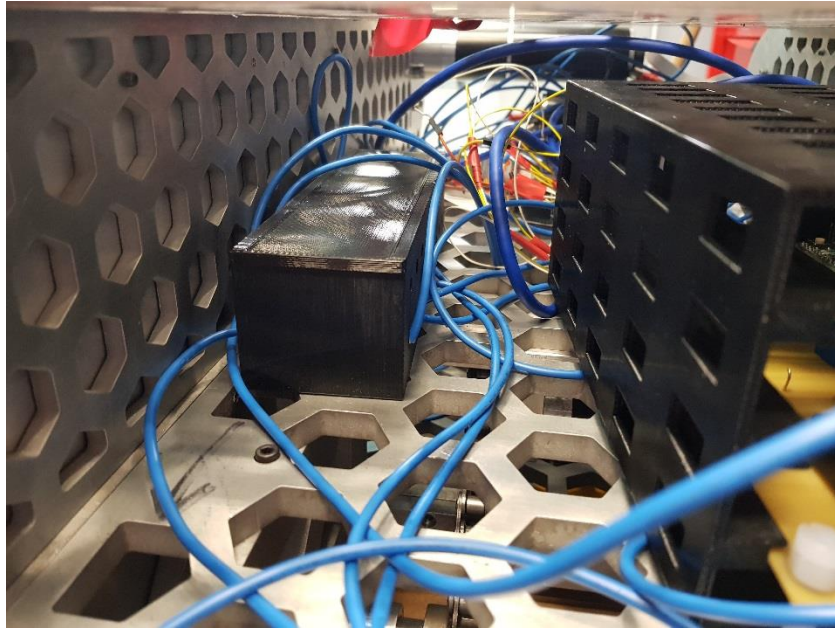


Figure 4.18: Bus bar Connection System

Figure 4.19 below shows the printed circuit boards made to monitor voltages of six cells in each battery. This is done through the Analog-to-digital converter in an Arduino and multiple voltage dividers. The Arduino further controls the signal to a MOSFET that connects or disconnects the batteries from the robot's electronic peripherals. Please refer to the design portfolio for more information.

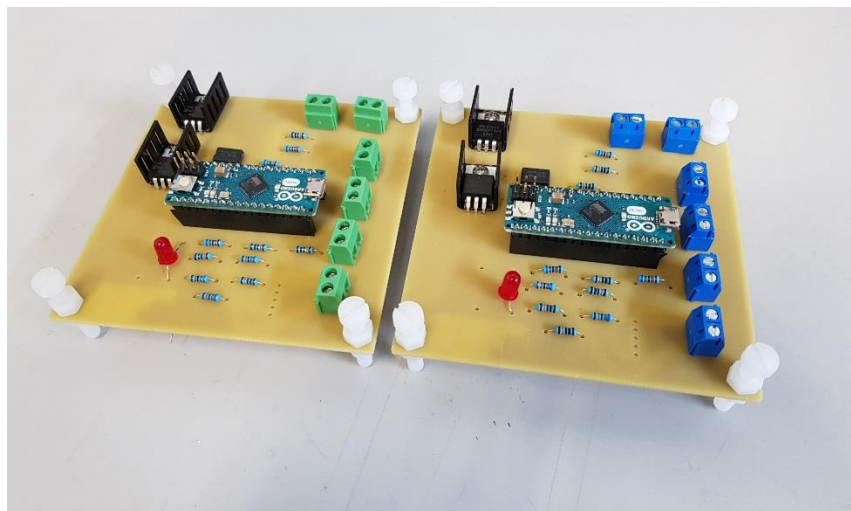


Figure 4.19: Battery Monitoring System

4.6.2. Electronics Trays & Bus Bar Box

To prevent any movement of electronics boards internally when traversing rough terrain or up inclines, electronics boxes were created to hold these in place. The electronics boards that need to be encased have set sizes shown in the *Table 5*.

Table 5: Box specifications

Battery Management System x 2	100 x 100 mm	Internal
FPGA	180 x 150 mm	Internal
Power Regulation Board x 2	150 x 180 mm	Internal
Sensor Board	150 x 100 mm	External

Each board needs 30mm clearance to allow for wires and fixings to be attached. This accompanied by the different sizes of the boards meant that two trays were required internally and one externally. The same design with cut outs along each edge will be implemented into both internal boxes to allow for the boards to be easily accessible with wiring from components elsewhere in the chassis. *Figure 4.20* shows the trays to be closed at one end only, allowing for quick access if needed. A slot along each shelf output was added, for the placement of the boards. This will limit any vertical movement that may occur as the robot moves. A lid was found to be impractical because of the limited space, therefore a turning pin was added at the end to prevent the boards from sliding out; saving space.

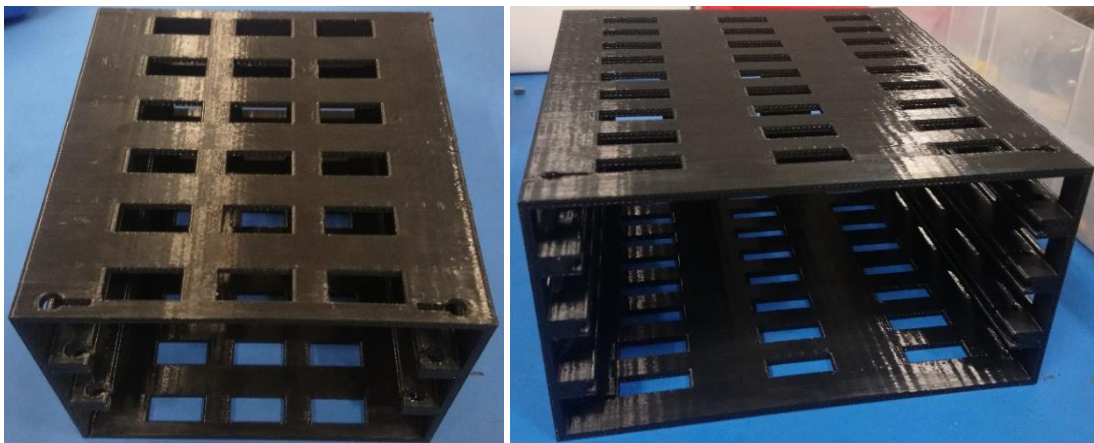


Figure 4.20 The 100x100 (left) and 150x180 electronics boxes (right)

4.6.2.1 Sensor Box

ATLAS's main functionality is that of a search and rescue robot, which requires sensors to relay data back to the base computer. The sensors, including a CO₂ sensor, microphone and camera, all need to be controlled, and because of their position on the outside of the robots shell the PCB board controlling these is to be placed externally.

The sensor board is 100 x 150 mm but will also require clearance to allow for wiring of 30 mm. The tray also needs to be enclosed as it will be exposed to the elements which is provided by the sliding cover, as shown in *Figure 4.21*. The design allows for the selected CO₂ sensor to protrude from the top of the box, from the circular hole on the roof. The holes are only cut out of the base of the box not all sides as in the internal boxes, to allow for connections to the internal circuitry without causing any unnecessary exposure to the elements.



Figure 4.21: Sensor Electronic Box

4.6.2.2. Bus Bar Box

A bus bar, made from copper has been procured and will be placed along the centre of the robot. The purpose of this is to conduct high current and to be connected to other electronic parts. Because of the nature of this it should be encased to protect it from discharging onto the chassis. A bus bar box has been created, with a removable lid for access and holes on each side to allow for connections to be made, see *Figure 4.22*.

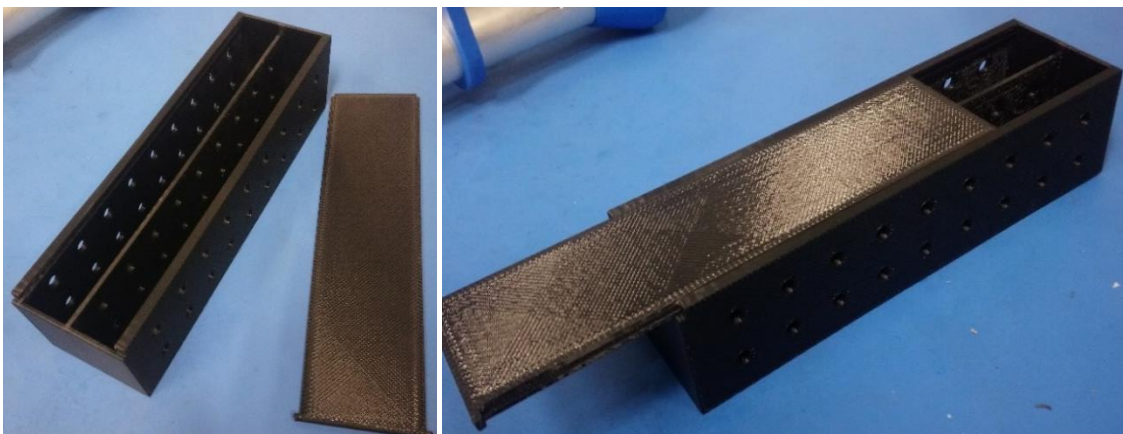


Figure 4.22: Bus Bar Box and Lid Assembly

All of the trays and boxes have been 3D printed in WMG. 3D printing was chosen as the parts can be made quickly and robustly in house, whilst the material has been tested for strength and shown to be light and sturdy.

4.7. Communications

An important specification for Atlas was that the robot uses a wireless, high bandwidth communications system that can allow Atlas to communicate with the base station with small latency and to allow it to transmit data intensive video and data streams. Wireless communications were chosen for Atlas as it increases its mobility and robustness. In real life deployments of USAR robots, tethers are common source of mission failure, therefore these were discarded in the Atlas design at a cost of higher complexity (Murphy, 2014).

The communications network of Atlas was realized using the D-Link DWR 118 high performance wireless router. The router was placed inside the body of Atlas and was powered from the on-board power management system. The router created a wireless local area network (WLAN) around the robot using the IEEE 802.11n communications protocol using both 2.4 GHz and 5 GHz signals. The WLAN could be accessed by operators using the correct network password. This allowed multiple operators to monitor the operation of Atlas from multiple devices in a secure manor, not just the base station operator. Devices on the body of the robot were networked to the WLAN router using Ethernet cables.

The communications network was tested in a controlled environment where the base station was no more than 10m away from Atlas. In these conditions the network provided a stable data link that efficiently streamed video, LIDAR-SLAM map and IMU (inertial measuring unit) data, while also providing high speed control to the robot motors at an approximate latency of command to motor motion start of ~200ms.

4.7.1. Onboard data acquisition and motor control system

The central control system of Atlas consisted of an Axiomtek Pico-842 pico-computer. The computer handled communications with the base station, interfaced sensors and motor controllers. Originally the Atlas Legacy design included an FPGA control system that would have operated in parallel to the pico-computer. However this was excluded in the final build because of time constraints.

The primary software running on the pico-computer was the Robot Operating System (ROS) which is a middleware software that allows different applications to efficiently communicate within a device as well as across a WLAN network. The base station, running LabVIEW, was interfaced using the ROS-LabVIEW toolkit developed by Tufts University (Crooks, 2012). Open source ROS code libraries as well as bespoke code was used to achieve the operational requirements of the Atlas control system. *Figure 4.23* shows a network diagram of the Atlas control system devices. Overall the pico-computer successfully completed all of its sensing, communications and control tasks without any performance issues.

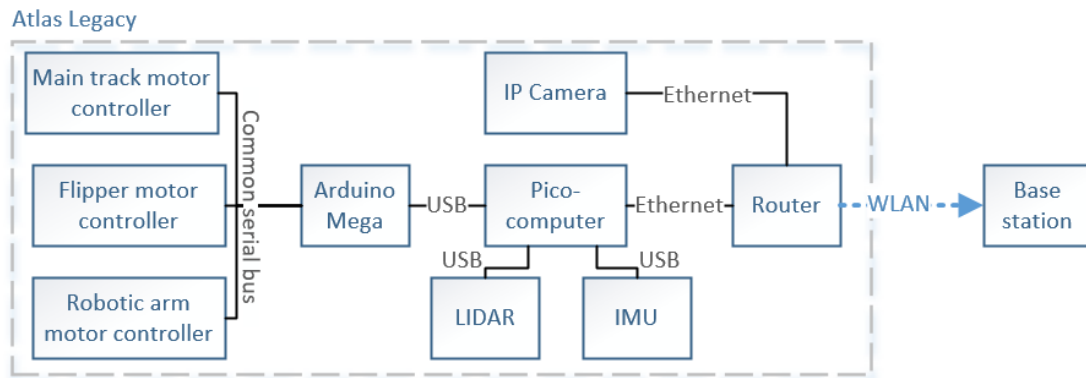


Figure 4.23: Network diagram of the final implementation of the Atlas Legacy control system.

4.8 Processes Controlled by Pico-Computer

4.8.1. Motor control

The 3 RoboClaw motor controllers aboard Atlas control 6 motors, 2 for the primary tracks, 2 for the robot flippers and 2 for the robotic arm. The motor controllers were interfaced to the pico-computer using an Arduino Mega microcontroller and the *rosserial_arduino* ROS software library (Bouchier, 2017). The motor controllers interface the Arduino using a common serial bus shared between all three devices. The controllers were uniquely instructed using an address system. The Arduino interfaced the pico-computer via a USB cable.

Bespoke code was written using the *Arduino ROS.h* (Bouchier, 2017) and the *Roboclaw.h* (Ion Motion Control, 2015) library to create a ROS node on the Arduino responsible for motor control. This allowed the pico-computer and the base station to interface the motor controllers over the ROS platform. The software on the Arduino decoded ROS messages into motor commands which it then sent to the appropriate motors. *Appendix 2* shows the Arduino sketch file.

The motor controllers have a feature whereby they continue executing the last command they received indefinitely until they receive a new command or are powered off. This causes the risk of the robot to enter a runaway condition if it loses contact with the base station; therefore a timeout functionality was created whereby the Arduino sends a stop command to all motors if it has not received a command from the base station for a whole second. To ensure this function is capable of executing whenever the motor controllers are on, the Arduino was powered from a 5V output coming from the motor controllers i.e. if the motor controllers are on so will the Arduino. The motor control system was successfully tested on Atlas along with the other safety features. Future work on motor control should focus on installing and utilising motor encoders to provide odometry and to enable precise PID control of the robot motors.

4.8.2. Sensors

In the final implementation of Atlas Legacy, 3 primary sensors are included. These were a camera, LIDAR and an Inertial measuring unit (IMU).

4.8.3. Camera

The camera utilised was the Axis M1054 IP camera. The benefits of using an IP camera were that the base station could interface the camera directly over the WLAN without requiring processing from the pico-computer. The camera could produce video streams using various video compression codecs, of which the most efficient was the H.264 codec. However LabVIEW is only capable of accepting streams of this format using the Vision Acquisition Software package costing approximately £400. This cost was deemed too large therefore a work around was implemented: Using the Axis Media Control plugin, Windows Media Player is capable of processing a live H.264 stream from the Axis camera. Next Windows Media Player was embedded into LabVIEW using an ActiveX container. This solution provided a free and efficient way of directly streaming video from the camera to LabVIEW with an approximate latency of ~400ms. The camera was mounted on-top of the robotic arm allowing Atlas to peak into narrow spaces and to vary its vantage point.

According to (Murphy, 2014) one of the most common modes of mission failure, during real life deployment of USAR robots, is operator error. This error can be reduced by providing operators an intuitive and immersive control interface that provides them with good situational awareness. This could be achieved using a 360 camera and Virtual Reality (VR) Headset which would offer the operator a wide-angle view of the robot's surroundings and allow the operator to look around the robot intuitively, using natural head movements. WMR is already in possession of a VR headset therefore it is recommended future teams look into this option.

4.8.4. LIDAR and SLAM

The final incarnation of Atlas Legacy also featured a Hokuyo UTM-30LX LIDAR which provided data to the *hector_mapping* simultaneous localisation and mapping (SLAM) ROS package (Kohlbrecher, 2016)(Rockey, 2016). The SLAM algorithm was used to create a 2D map of Atlas' surroundings which can be used by an operator for navigation and mission planning. The *hector_mapping* SLAM package does not require odometry data to function which made it quick to implement independently of other sensor systems. The ROS-LabVIEW interface was used to send a SLAM map of the ROS *occupancy_grid* format to the base station. Appendix 3 shows the LabVIEW code that received the SLAM data and Figure 4.24 shows the custom message parser that decoded the ROS message into a data format useable in the LabVIEW environment.

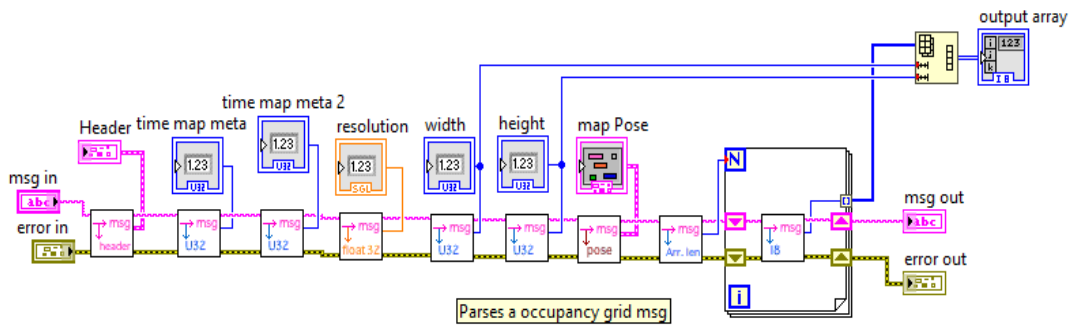


Figure 4.24 Message parser responsible for decoding the ROS occupancy_grid format SLAM map. Created using libraries from (Crooks, 2012).

The SLAM functionality of Atlas was successfully tested by mapping a region of the WMG IMC building. Figure 4.25 shows the output of the SLAM algorithm as seen on the base station control GUI. In these conditions (robot on flat surface) the SLAM algorithm performed excellently with high dimensional accuracy; for example, a cupboard that was measured to be 74cm long on one axis was measured to be 75cm on the SLAM map. One drawback using LabVIEW to visualise the SLAM outputs, and not a Linux based ROS package, was that the SLAM map was processed rather slowly at an approximate rate of once every 10 seconds.

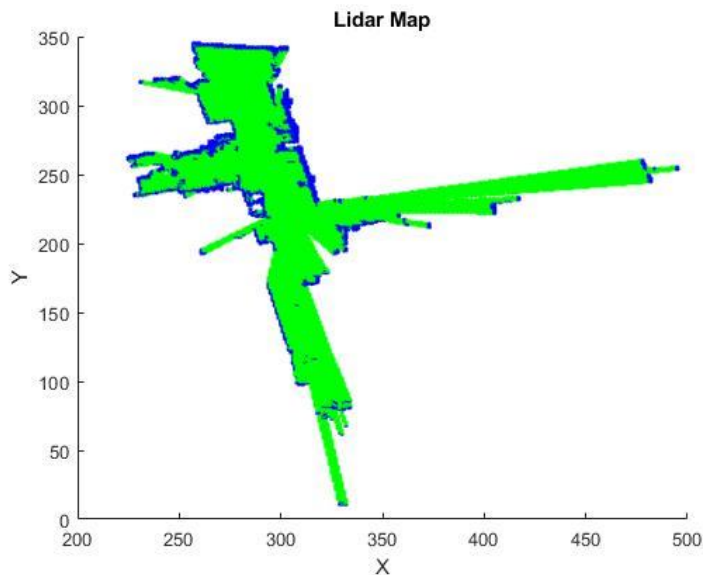


Figure 4.25 2D SLAM map constructed from LIDAR scans of WMR workshop area in IMC building. Data created with aid of hector_slam package created by (Kohlbrecher, 2016), plotted by WMR.

4.8.5. Inertial Measuring Unit

Atlas was also equipped with an IMU that could sense the orientation of the robot. This data can be used by an operator to assess how the robot is positioned and also by other instruments. The IMU used was the Xsens MTi which was connected to the pico-computer via USB and driven using the *xsens_driver* ROS package. The data from the ROS node was processed at the base station using the ROS-LabVIEW interface; the block diagram of this is shown in *Figure 4.26*. During live testing of Atlas, the IMU system provided fast and stable readings to the base station.

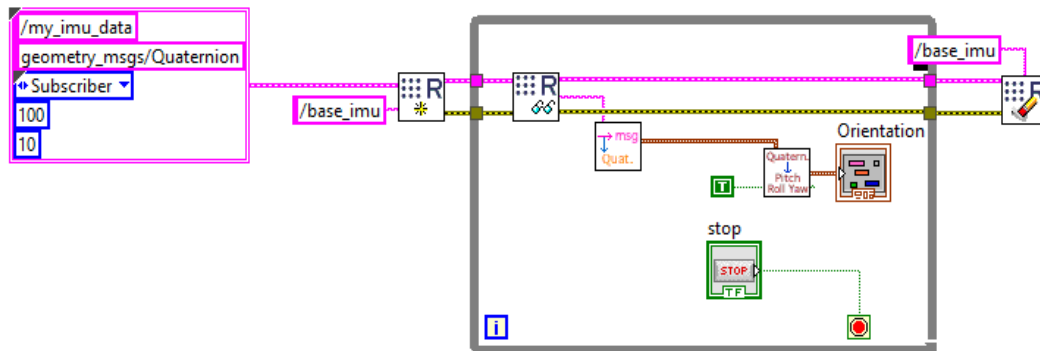


Figure 4.26 LabVIEW block diagram of the IMU data receiver for the base station. Created using libraries from (Crooks, 2012).

The current SLAM package used on Atlas generates a 2D map of the robot's surroundings; therefore, if the robot is tilted, an erroneous map maybe generated because the LIDAR is scanning in a non-horizontal plane. In future, the IMU could be used to filter the LIDAR data if a certain threshold tilt is exceeded.

4.9 Base computer controlling software

4.9.1 Base computer Block Diagram

Figure 4.27 shows how all incoming and outgoing data will be processed. Table 5 shows the breakdown of each system, where multiple steps can be done in the code. Figure 4.27 shows the GUI that can be used as a display and interface for the robot. Each section of code was run through a timing simulation to check the speed it can achieve. This was to ensure smooth control of the robot from the base computer interface used.

Red	User input
Green	Process for output
Orange	Process for input
Blue	Movement for information

Table 5: Info for Block Diagram

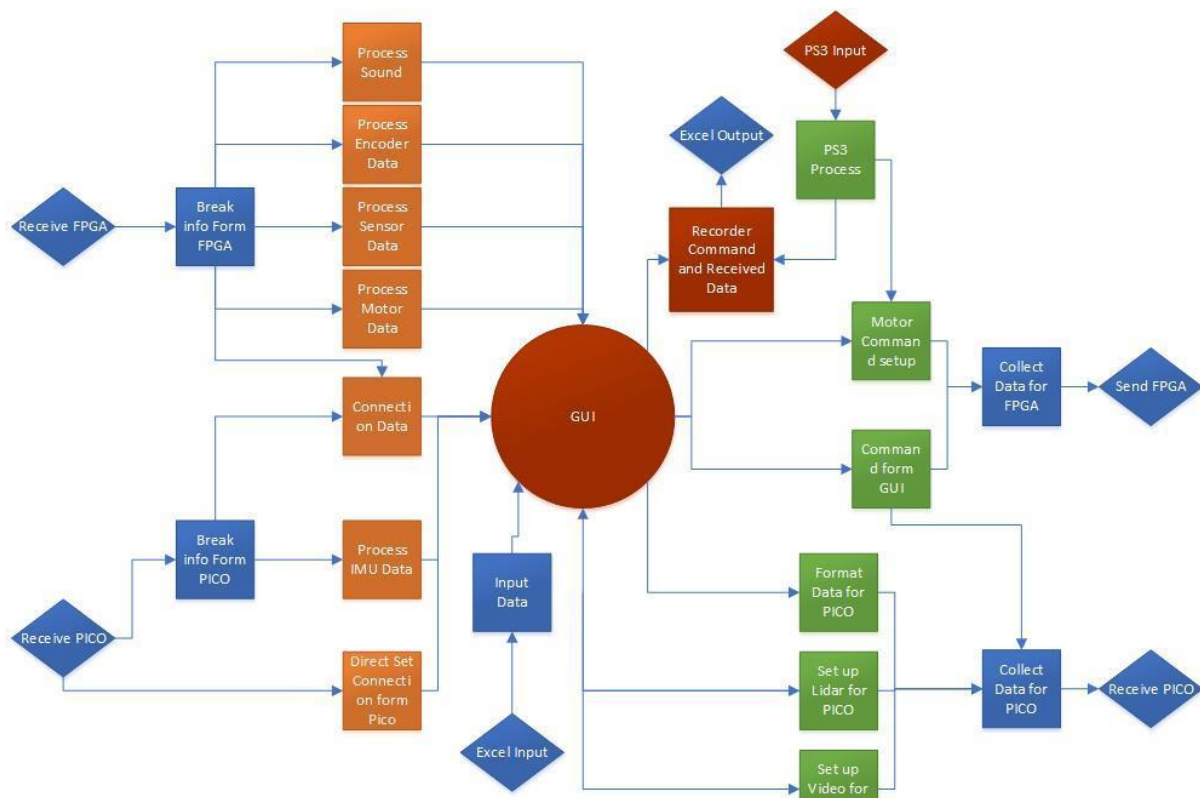


Figure 4.27: Block Diagram

4.9.2 Basic Control System

This code is for the basic control of the robot, specifically for the use of the main tracks and motor control through a local GUI.

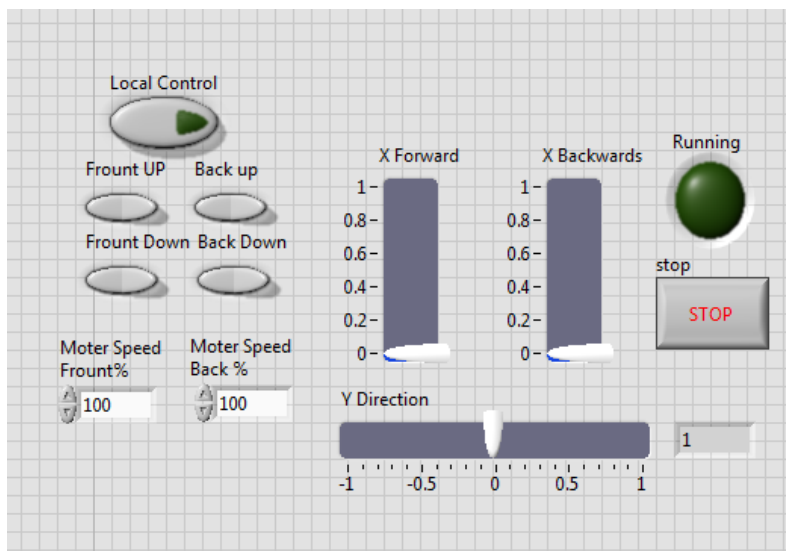
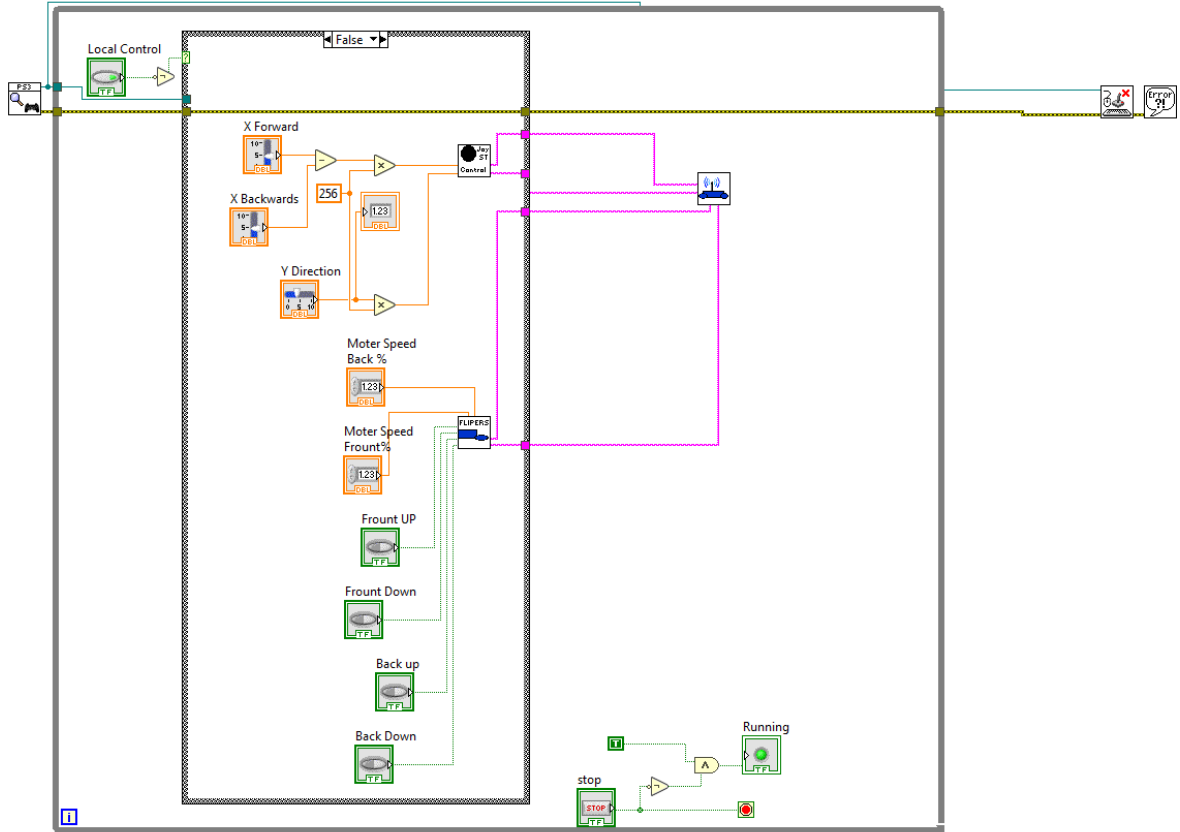


Figure 4.28: Basic Control Code

4.9.3 Full GUI controller

This is the basic function for the control of system. Each block controls how often each code will be run. Additionally, it prioritises the important functions of the robot, e.g. the motor control is deemed the most important part of the system and will therefore refresh 100 times a second. This is shown on the screen when controlling the robot.

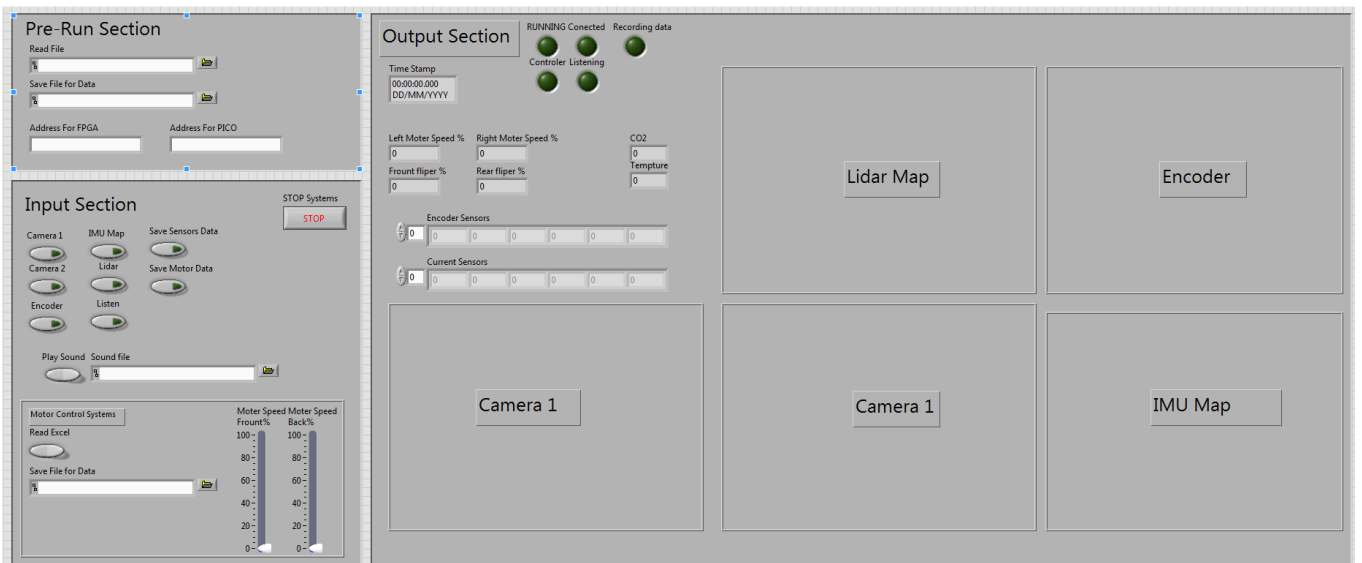
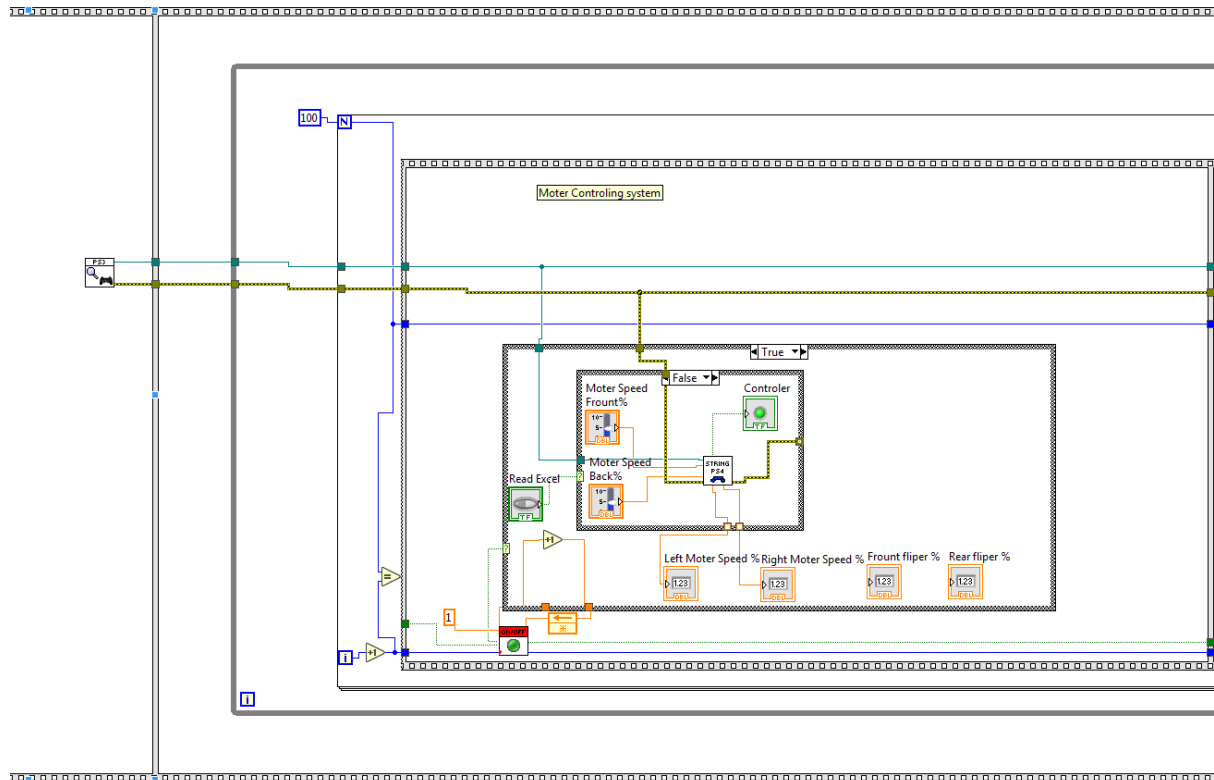


Figure 4.29: Full GUI Controllers

4.9.4 Motor Control Systems

These are the maps that take the input commands and transfer them into motor control signals. They also have basic control to check inputs will not cause errors.

4.9.4.1 Main Motor Control

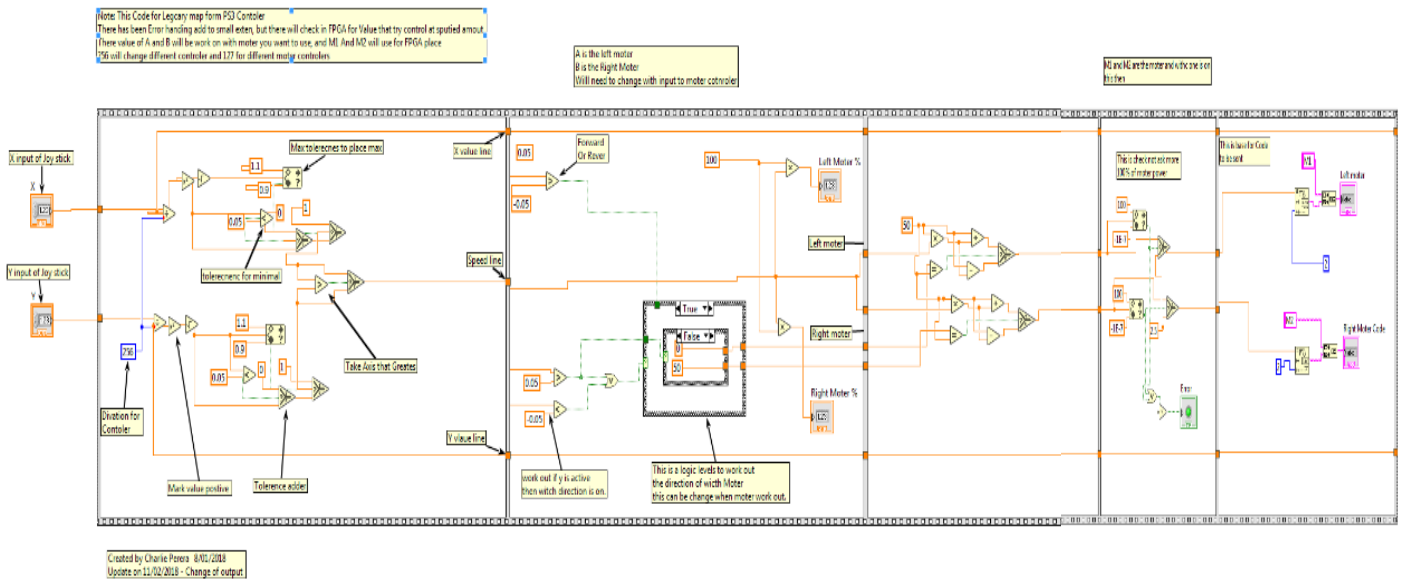


Figure 4.30: Main Motor Control Code

4.9.4.2 Flipper Motor Control

The basic flipper control code is shown below, this is not controlled by set input speed but by an on/off switch.

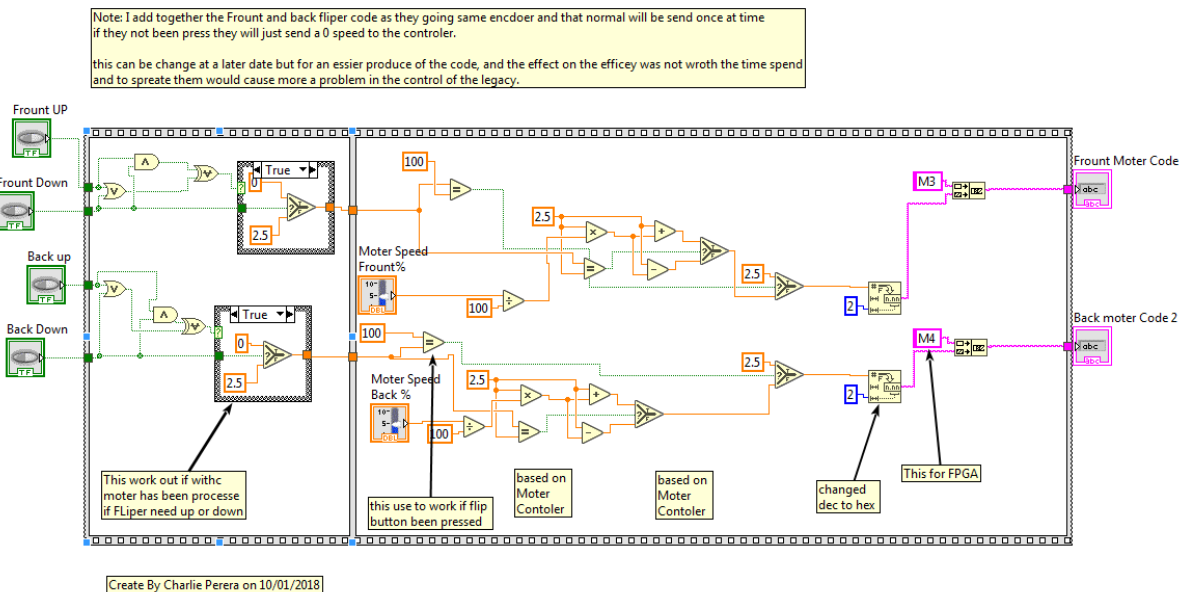


Figure 4.31: Flipper Motor Control code

4.9.4.3 Robotic Arm

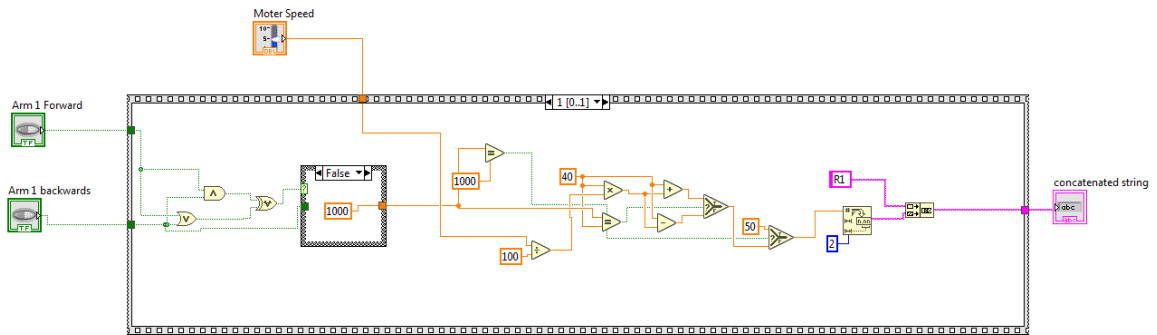


Figure 4.32: Robotic Arm Code

This has a loop function for the robotic arm where each function of the arm has a loop controlled through a stacked loop.

4.9.4.4 Read form Excel

This code reads from excel. It can be used to receive and send the input control from the reading of the data. This enables basic robot automation.

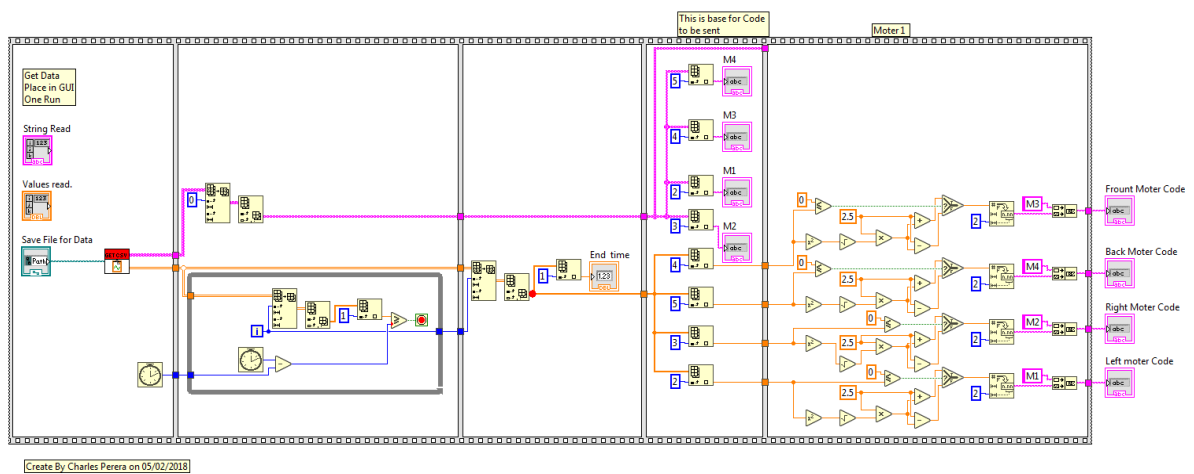


Figure 4.33: Read Form Excel Code

4.9.4.5 PS3 Control

The ability to control the robot from a PlayStation controller, is very useful for piloting of the robot. The left joy stick was enabled to control the main direction and speed of the robot, the triggers control movement of robot flippers and the right joy stick and arrow button control the Arm.



Figure 4.34: PS3 Controller

These take the control values from the controls, then take PS4 control input and are then used for the output of the motor controls. (Ben Clark 2013)

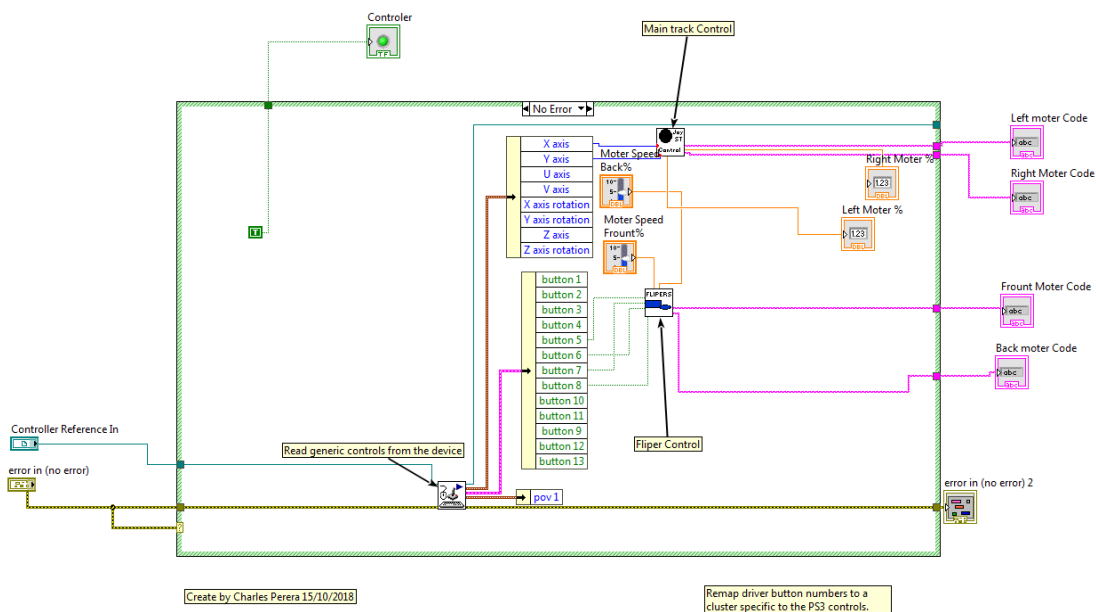
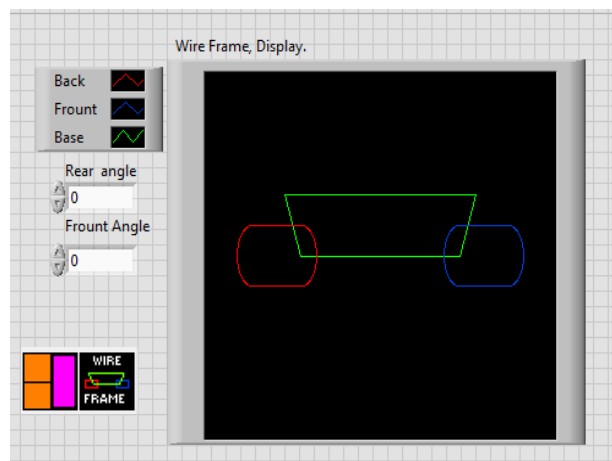
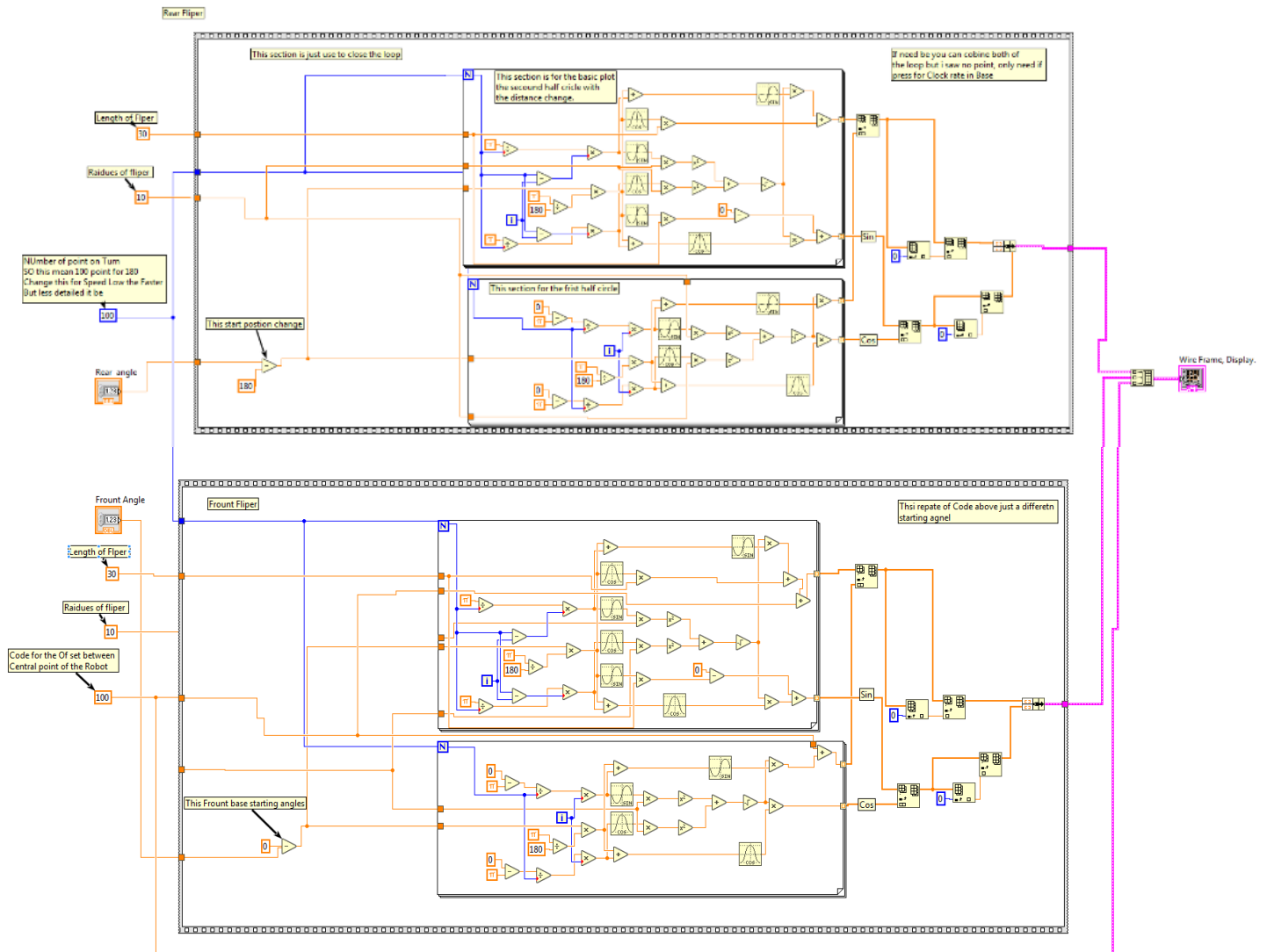


Figure 4.35: PS4 Control Code

4.9.5 Encoder data and map

This takes input data from motor encoders and creates an encoder map and displays it on the GUI. This is an example code similar to the LIDAR, camera, sound system, IMU and sensor map. The Encoder display is an example of what the display on the GUI looks like whilst



running.

Figure 4.36: Encoder Data and Map code

5. Testing and Verification

In order to test and verify needed to create a system that will be able simulate and test the conditions the robot will go through during the RoboCup. Tests have also been designed to ensure all systems run as expected, and that any faults in design can be identified and resolved as soon as possible.

Testing will be done during the construction and operation phase of the project. The following plan remains ongoing, however large parts have been completed.

Test - Checking connections.

Steps	Inputs	Expected output	Achieved
1	Power robot up	All power lights come on.	Yes
2	Send test signal to FPGA	Correct return signal value.	N/a
3	Send test signal to Pico computer	Correct return signal value.	Yes
4	Send test signal for motor control check	Correct return signal value.	Yes
5	Send test signal for encoder	Correct return signal value.	Yes
8	Send test signal for camera check	Correct return signal value.	Yes
9	Send test signal for Lidar check	Correct return signal value.	Yes
10	Send test signal for IMU check	Correct return signal value.	Yes
11	Send test signal for sound check	Correct return signal value.	Yes
12	Power robot down	All power lights turn off.	Yes

Table 6: Connection Test

Test - Motor movements.

Steps	Inputs	Expected output	Achieved
1	Power robot up	Power lights come on.	Yes
2	Send test signal for motor control check.	Correct return signal value.	Yes
3	Left motor 25%, Right motor 25%	Movement of both tracks forward, both tracks at same speed.	Yes
4	Left motor -25%, Right motor -25%	Movement of both tracks backwards, both tracks at same speed.	Yes
5	Left motor 75%, Right motor 75%	Movement of both tracks forward, both tracks at same speed, faster than step 3.	Yes
6	Left motor -75%, Right motor -75%	Movement of both tracks backwards, both tracks at same speed, faster than step 4.	Yes
7	Send forward movement requirement at 100% reverse	Movement of both tracks forward, both tracks at same speed, faster than step 5.	Yes
8	Left motor -100%, Right motor -100%	Movement of both tracks backwards, both tracks at same speed, faster than step 6.	Yes
9	Left motor 75%, Right motor 0%	Robot turns clockwise.	Yes
10	Left motor 0%, Right motor 75%	Robot turns anticlockwise.	Yes
11	Left motor 100%, Right motor -100%	Robot rotates clockwise on spot.	Yes
12	Left motor -100%, Right motor 100%	Robot rotates anticlockwise on spot.	Yes
13	Power robot down	All power lights turn off.	Yes

Table 7: Main Motor Test

Test - Movement of flippers

Steps	Inputs	Expected output	Achieved
1	Power robot up	All power light come on	Yes
2	Send test signal for motor control check	Return of correct signal value	Yes
3	Front flippers up for 1 second	Movement of front flippers up	Yes
4	Back flippers up for 1 second	Movement of front flippers up	Yes
5	Front flipper down 1 second	Front flipper returns to start position, encoder gives same value as start of step 3.	Yes
6	Back flipper down 1 second	Front flipper returns to start position, encoder gives same value as start of step 3.	Yes
7	Both flipper up 1 second	Movement of both flippers up	Yes
8	Both flipper down for 1 second	Both flippers returns to start position, encoder gives same value as start of step 7.	Yes
9	Power robot down	All power lights turn off	Yes

Table 8: Flippers Test

Test - Robotic arm movement

Steps	Inputs	Expected output	Achieved
1	Power robot up	All power lights come on	Yes
2	Send test signal for motor control check	Return of correct signal value	TBC
3	Movement of rotating base through 360 degrees and then back to start position.	Arm rotates through full range and returns to original position.	TBC
4	Movement of base joint from horizontal through 180 degrees and back to start position.	Arm can be moved through full 180 degrees of motion and returns to start position.	TBC
5	Movement of elbow joint through 180 degrees and back to start position.	Elbow can be moved through full 180 degrees of motion and returns to start position.	TBC
6	Rotation of head joint through 360 degrees and back to start position.	Head rotates through full 360 degrees of motion and returns to start position.	TBC
7	Tipping head forward 90 degrees, backwards 180 degrees and then return to start position.	Head can be moved through full range and returns to original position.	TBC
8	Open and close input to end effector.	Gripper closes and opens as required.	TBC
9	Power robot down	All power lights turn off	TBC

Table 9: Arm Movement Test

Test – Recording movement

Steps	Inputs	Expected output	Achieved
1	Power robot up	All power lights come on	Yes
2	Send test signal for motor control check	Return of correct signal value	Yes
3	Turn on movement recording	Light showing the movement is being recorded.	Yes
4	Start basic movement set, flippers and arm movements.	Basic movement is carried out as requested.	Yes
5	Save data in excel format.	Check correct data has been recorded through time.	Yes
6	Power robot down	All power lights turn off	Yes

Table 10: Recording Test

Test – Reading recorded movement

Steps	Inputs	Expected output	Achieved
1	Power robot up	All power lights come on	Yes
2	Send test signal for motor control check	Return of correct signal value	Yes
3	Turn on read movement recording of previously performed motions.	Light showing and robot performs requested movements.	Failed
6	Power robot down	All power lights turn off	Yes

Table 11: Reading recording test

Test – Pico computer sensors

Steps	Inputs	Expected output	Achieved
1	Power robot up	All power lights come on	Yes
2	Send test signal to PICO	Return of correct signal value	Yes
3	Send test signal for camera check	Return of correct signal value	Yes
4	Send test signal for Lidar check	Return of correct signal value	Yes
5	Send test signal for IMU check	Return of correct signal value	Yes
6	Turn on camera	Video feed displayed on base computer.	Yes
7	Turn on Lidar	Visual feed displayed on base computer.	Yes
8	Turn on IMU	Display on base computer, check data produced to ensure it is correct.	Yes
9	Export Lidar and IMU data to excel.	Data file with outputs over time.	Yes
10	Power robot down	All power lights turn off.	Yes

Table 12: PICO sensors Test

Test – the IMU and check the SLAM recording system

Steps	Inputs	Expected output	Achieved
1	Power robot up	All power lights come on	Yes
2	Send test signal to PICO	Return of correct signal value	Yes
3	Send test signal for IMU	Return of correct signal value	Yes
4	Turn on IMU	IMU data being received.	Yes
5	Turn on SLAM recoding system.	Check data is being record	Yes
7	Control inputs to the robot.	Robot will start to move.	Yes
8	Save data to Excel	Data file is produced with output to time.	Yes
9	Power robot down	All power lights turn off.	Yes
10	Look at the recorded data	Check data corresponds to reality.	Yes

Table 13: IMU and SLAM Test

Test – Lidar System and outputs.

Steps	Inputs	Expected output	Achieved
1	Power robot up	All power lights come on	Yes
2	Send test signal to Pico computer	Return of correct signal value	Yes
3	Send test signal for Lidar	Return of correct signal value	Yes
4	Turn on Lidar	Lidar data being received.	Yes
5	Movement inputs to robot along test course.	Lidar output displayed on base computer, data logged.	Yes
6	Save data to Excel	Data file is produced with output to time.	Yes
7	Power robot down	All power lights turn off.	Yes
8	Look at the record data	Check data corresponds to reality.	Yes

Table 14: Lidar Test

15.4 Testing for Competition

These are high level test to ensure that the robot meets the RoboCup competition requirements.

Testing Mobility

Steps	Inputs	Expected output	Achieved
1	Power robot up	All power lights come on	Yes
2	Send test signal to all items in robot	Return of correct signal values	Yes
3	Run the robot over a flat smooth terrain	Successful	TBC
4	Turn on point left and right	Successful through 360 degrees in both directions.	TBC
5	Run the robot over carpet	Successful	TBC
6	Run the robot over gravel	Successful	TBC
7	Go up flight of stairs	Successful	TBC
8	Go down flight of stairs	Successful	TBC
9	Power robot down	All power lights turn off.	TBC

Table 15: Mobility Test

Testing Sensing

Steps	Inputs	Expected output	Achieved
1	Power robot up	All power lights come on	Yes
2	Send test signal to all item in robot	Return of correct signal values	Yes
3	Turn on Lidar, camera, IMU	Display of all items on base computer.	Yes
4	Produce static map of test area	Successful	TBC
5	Test course to produce moving map	Produced successfully from Lidar	TBC
6	Scan a QR code.	Successful reading of QR code.	TBC
7	Listen to verbal input.	Sound wave produced and audio output from base computer.	TBC
8	Recreate verbal input through speaker.	Sound output from robot speaker.	TBC
9	CO ₂ input to sensor.	Successful recording of data.	TBC
10	Power down robot	All power lights turn off.	TBC

Table 16: Full Sensing Test

Testing Dexterity

Steps	Inputs	Expected output	Achieved
1	Power robot up	All power lights come on	Yes
2	Send test signal to all Item in robot	Return of correct signal values	Yes
3	Test all movements of arm through full range of motions.	All motions successfully performed.	Yes
4	Open a push door with a robotic arm	Arm can open door.	TBC
5	Open a handled door with a robotic arm.	End effector can move handle and arm can open door.	TBC
6	Pick up a small wooden block and manipulate	Pick up, move and then replace in box	TBC
7	Power down robot	All power lights turn off.	TBC

Table 17: Dexterity Test

6. Battery State-of-Charge Management and Monitoring

The Groups Technical Academic Paper was submitted separately. The following details a brief introduction to this and the models that follow.

Urban Search and Rescue (USAR) Robots are required to operate in extreme conditions, for example in reconnaissance missions after structure fires or natural disasters. Because of this, the design of USAR robot on-board power supplies requires special focus on ambient temperature variations. Lithium batteries are energy dense, with densities up to 620Wh kg^{-1} , thus are employed widely in mobile applications, however their cycle life and State-of-Charge (SOC) is highly temperature dependent.

Battery-powered USAR robots often employ brushed permanent magnet direct current motors (BPMDC). To operate at a specific torque, these require a current that varies with temperature. The aim of the group was to model the effect of ambient temperature variations on the SOC of Lithium Polymer batteries powering the electronic system of a USAR robot employing BPMDC motors under varying load torques. Existing battery models have been considered and combined with dynamic modelling techniques for DC motors.

The results have then been used to develop an algorithm for robot power management in different ambient temperature conditions to allow improved on-board battery monitoring and for computationally inexpensive SOC estimations, increased robot mission reliability, in addition to extended battery life.

Both the battery and the motor are described in terms of their equivalent circuits and then simulated at different load and temperature conditions. Variation of internal battery resistance with battery state-of-charge and ambient temperature was shown. Temperature effects on direct current motor winding resistance and inductance are estimated as linear functions. A practical test of the described model has been carried out and potential causes of arising discrepancies have been identified.

It has been shown that a reduction in current draw extends battery life and may increase the reliability of search and rescue missions. The opportunity to decrease temperature dependence of battery life without extensive temperature compensation presents itself here. The general discharge behaviour of Lithium batteries consisting of fast initial cell voltage drop and a following cell voltage plateau region was verified and it is expected that extensive iterative system testing and results evaluation with consequent model adjustments may allow the development of a highly accurate algorithm for battery state-of-charge estimation in Urban Search and Rescue Robots. Its reliability should be unaffected by ambient temperature.

Simulation results and more detail on the dynamic model are given in through *Section 6*.

6.1 Simulink Models

6.1.1. DC Motor Control model

The model shown in *Figure 6.1* is of the DC motor control. The base model for the motor is shown in *Appendix 4*. The input of this model is ambient temperature and voltage input, the output will be the current, torque, the RPM and position.

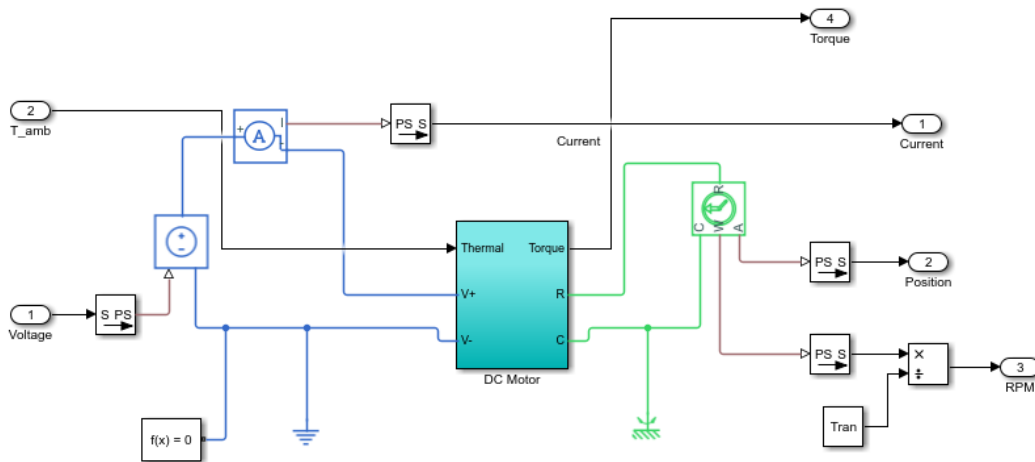


Figure 6.1 DC Motor Model

6.1.2. Battery Cell Model

Figure 6.2 shows the base model for each of the cells in the battery, with the V_{load} and input current. These have the input of the current load on the battery and the ambient temperature around the battery, outputting the terminal voltage, SOC and temperature of the battery cell. Each of these are then connected together in series, shown in *Appendix 5*.

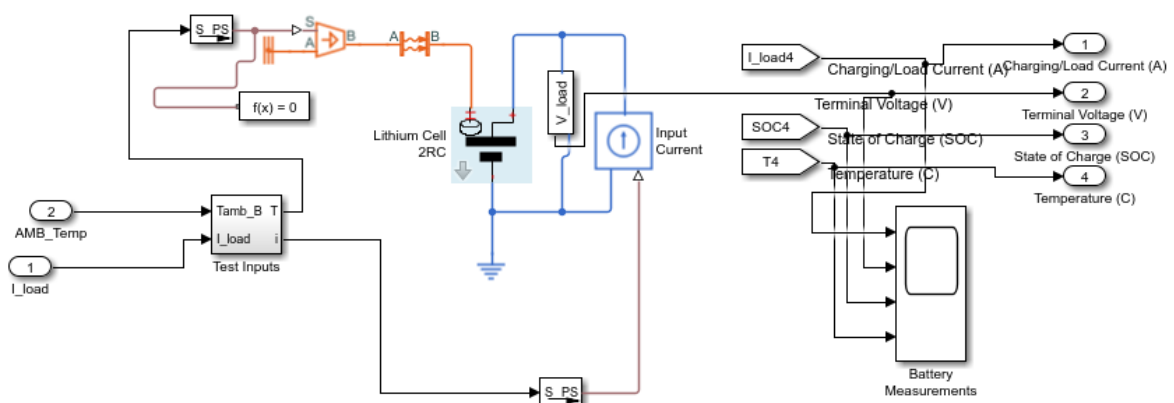


Figure 6.2: Battery cell model

6.1.3. Full Model

Figure 6.3 shows the full model, which has 2 motors and one battery. This is for simulation of the robot's main tracks with the addition of ambient temperature, the input to the model is the ambient temperature and a pulse voltage input to the motors to simulate normal operation of the robot. There is a range of main outputs, but SOC and battery temperature were the main two that were focused on.

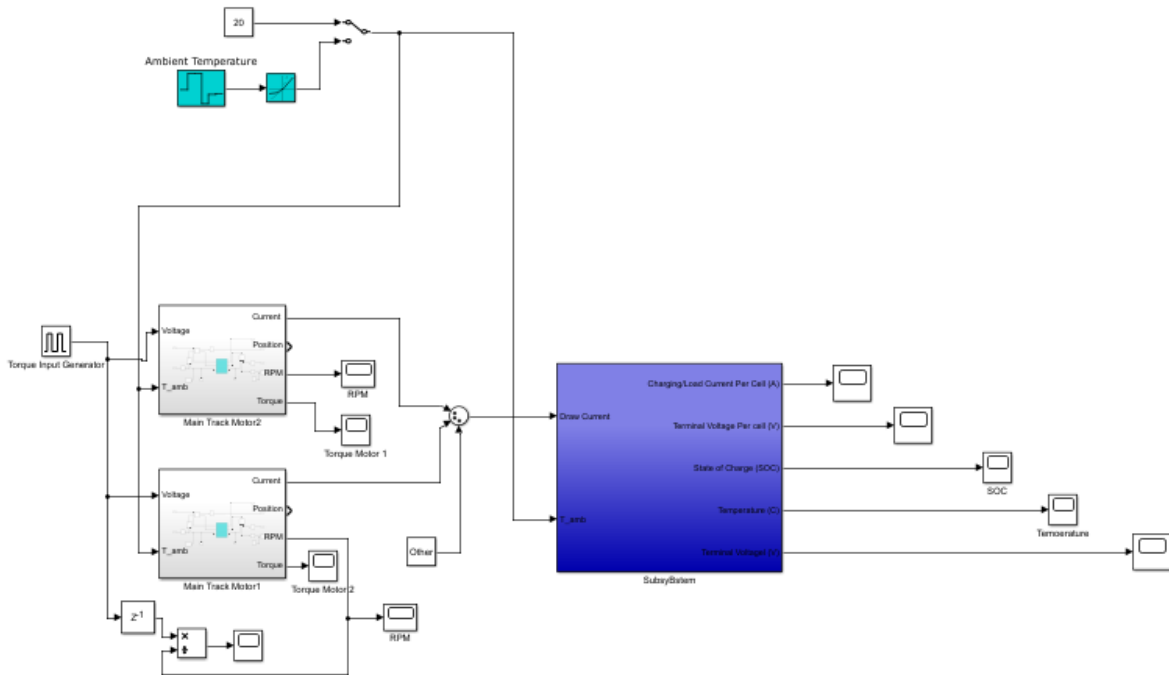


Figure 6.3: Full model

6.1.4. Controlling Code

This code was done to look at the change of ambient temperatures and torque on the model and to produce the relevant figures. All code produced is shown in *Appendices 5 to 7*.

6.2. Result of the Models

The input to these models are pulse inputs to simulate the movement of the robot, with periods of 10 seconds on and off. The robotic motors and sensors were assumed to be a constant drain.

6.2.1. SOC plot with Temperature Change

Figure 6.4 shows the decay of the model and the effect temperature has, also indicating that the model has worked successfully. At the lower temperatures, the battery can be seen to drain quicker

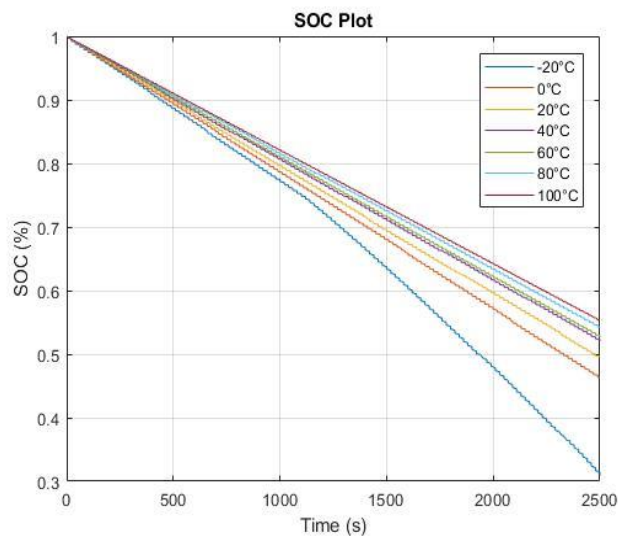


Figure 6.4: SOC plot with temperature change

6.2.2. Internal Temperature with Varying External Temperature

Figure 6.5 shows the internal temperature against the change in ambient temperature, with the internal model starting at 20°C. This shows that the model is working with incremental increases in temperature.

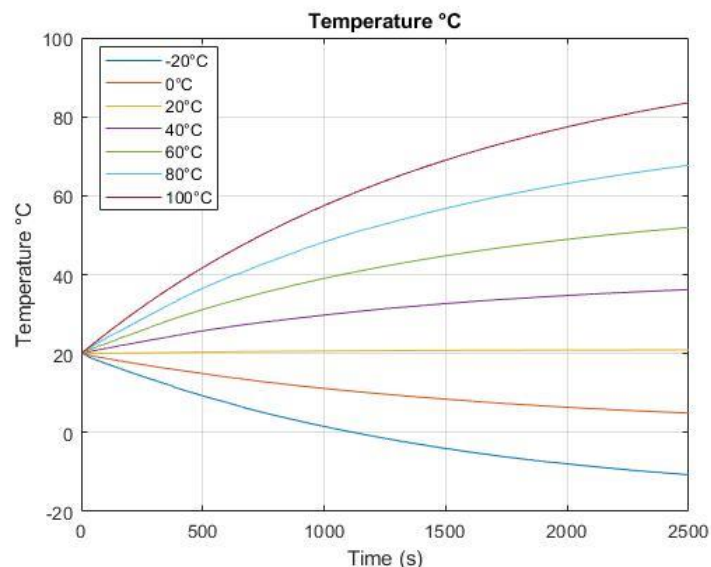


Figure 6.5: Cell temperature with change of ambient temperature

6.2.3. SOC with Varying Torque

Figure 6.6 shows that at higher torque loads, will drain the battery quicker. This is as expected, as a higher load will draw more current from the batteries.

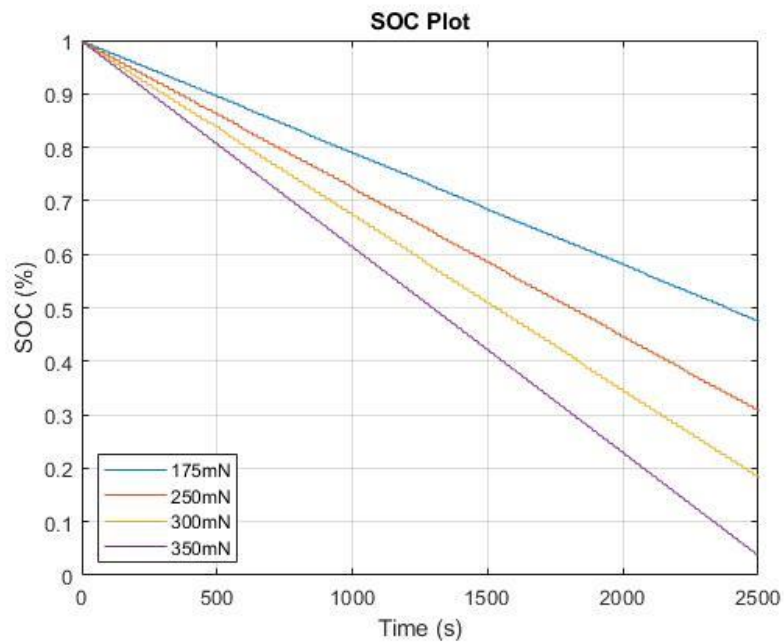


Figure 6.6 SOC Plot with Torque Change

6.2.4 Temperature the Torque Change

Figure 6.7 shows that with the general increase of torque, the internal temperature increases, to simulation the condition of the robot during operation.

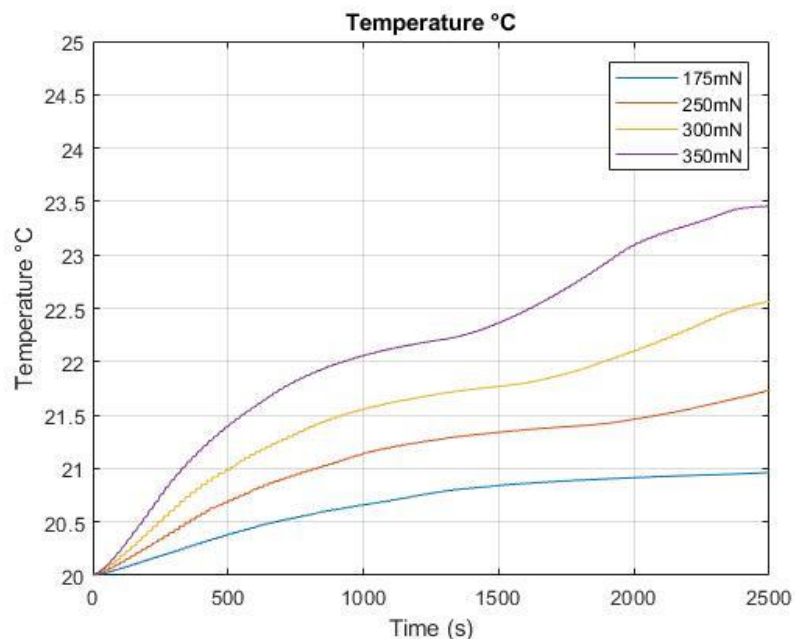


Figure 6.7 Temperature with Torque Change

7. Reflection and Recommendations for Further Work

7.1 Project Reflection

To conclude it can be said that the Urban Search and Rescue Robot project has largely met the objectives it set out to achieve, since the robot ultimately functioned as required. Nevertheless, some choices made throughout the project were not optimal. For example, the group spent a substantial amount of time attempting to reduce the robot's weight by redesigning many of the aluminium chassis parts. After contact was made with potential sponsors, the opportunity to redesign large parts of the chassis in carbon fibre presented itself, however, beyond the completion of some initial part designs, time was already in too short supply for the production of a full carbon fibre chassis at that point.

Another aspect the group overcomplicated somewhat was the initial concept for motor control. Because of budgetary constraints at project initiation the available motor controllers were not easily interfaceable, it was decided to implement an FPGA communication system that sends commands to the controllers via a digital-to-analogue converter. On top of the complete redesign of the electronic system and the undertaken battery research this was a rather ambitious plan to begin with and was ultimately abandoned somewhat unfinished when the funds for the purchase of more recent motor controllers became available.

It can be said that the project plan functioned well as a whole, occurring delays could be mitigated as a result of thorough initial risk analysis with the appropriate contingency plans put in place early on.

An example of a sensible design choice was that of the LabVIEW-ROS interface created to control the robot wirelessly, since this could be troubleshooted and implemented seamlessly once the robot was constructed, which allowed the mitigation of delays that had occurred in robot manufacturing beforehand.

As was outlined previously in Section B the successful fulfilment of project learning outcomes could thus be ensured.

7.2 Summary of Recommendations

The packaging of parts within the robot is a key aspect to investigate further, specifically to improve the battery packaging. Further development in this area could allow easier hinge access to a mounting system equipped with cooling fans. Additional packaging considerations include the redesign of the single layered PCB to multiple copper layers for better space utilization.

Alongside packaging, light weighting is an area important to the success of robot in the future. Using the tried and tested production of carbon fibre cladding, it is strongly recommended that this should be taken much further by building upon the preliminary research and development that has been conducted. To fully utilise the potential of the composite materials it is recommended that the entire chassis should be made from carbon fibre reinforced with steel or aluminium inserts to maximise the light weighting potential.

This year battery systems have been investigated in depth leading to various recommendations for future development. Findings revealed issues with the switching delay of the comparator controlled emergency power supply, implemented to overcome the control system's power cut recovery time; this is an area for further development.

Furthermore, the Arduino microcontroller used to monitor cells could be replaced with a single board design to monitor multiple batteries. Additionally, the battery drainage and the battery control code internal for the robot can be considered further. Finally, an algorithm to estimate battery state-of-charge was created and tested. More accurate results can be obtained by further evaluation of this model.

For ease of manufacturing the power distribution and battery monitoring system were designed on single-layered PCBs and it is desirable to decrease their size, for example through utilization of multiple copper layers.

An attempt of Field-Programmable-Gate-Array control of motors to free up pico-computer memory was initiated, however time constraints led to this not being fully implemented with enabled wireless communications. The existing hardware designs could be taken further.

Lastly, from input to output, several aspects of software can be further developed and explored. Improvements can be made to the GUI and input of information, data transfer rates between the Pico and base computer and finally data fusion for the output of the robot.

A full trouble shoot of the LabVIEW code could be done and data fusion for the robot control could be investigated.

It is suggested that future teams upgrade the router to an IEEE 802.11ac protocol router with beam forming capabilities.

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Appendix

Appendix 1 – Breakdown of the Various Parts and Mouser Electronics Expenses

Item	Number	Cost (£)
Hinge for side cladding panel	2	11.43
Shoulder bolt	10	17.10
Ball bearings	500	8.99
Compression springs	10	15.40
Latch	2	3.08
Microphone	1	7.00
Speaker	1	12.99
Plastic washer	100	4.00
USB Mini breakout	1	1.50
Battery pack	1	22.00
Micro-SD card	1	8.99
Bus bar	2	15.77
Bus bar connector	20	20.00
DC Plug	10	5.07
DC Plug 2	2	10.60
PCB socket	10+	0.54
Pin	10+	0.69
Solder	1	8.90
Wire	100m	8.00
Tension springs	10	12.00
Soldering stand	1	7.71
Solder cleaner	1	5.95
Battery holder	1	1.06
Battery connector socket	10	31.60
battery connector plug	10	18.40
banana plug	20	26.80
20 Amp wire m	1	68.99
Anti-Static wristband	1	5.52
Red LED	10	2.00
Green LED	10	2.10
White LED	10	7.40
Total		371.53

Item	Part number	Number	Cost (£)
N-Type MOSFET 1	942-IRFI530NPBF	10	7.46
N-Type MOSFET 2	942-IRLB3034PBF	5	10.85
Through Hole Comparator	512-LM2903N	4	2.60
Diode	863-MUR405G	10	2.83
Resistor 7.5 Ohm	588-20J7R5E	10	19.60
Resistor 10 Ohm	588-20J10RE	10	16.6
Resistor 0 Ohm	1623934-1	100	2.30
4 Channel OpAmp	595-LM324N	10	3.02
TO220 Heat Sink	567-274-2AB	10	2.01
T220 Insulator and Screw	532-4880M	8	14.72
Zener Diode	78-TZX5V1B	10	1.29
Hall Effect Encoder	985-AS5048A-TS_EK_AB	5	62.65
Gate Drive IC	863-MC34152PG	5	4.95
OpAmp	512-LM358N	20	6.40
DB15 cable	651-1656275	5	47.85
ADC	579-MCP3202-BI/P	2	4.64
Voltage Converter	595-TL7660CP	10	9.72
1.5 μ F Capacitor	598-155CKR050M	20	0.60
470 nF Capacitor	80-C317C474K3N9170TR	20	8.36
Temperature sensors	595-TMP100AQDBVRQ1	3	5.82
Current Sensors	726-TLI4970-D050T4	10	70.70
D-Sub Standard Connectors D15	806-K22X-A15P-N30	10	53.60
Microphone	485-3421	1	5.32
Speaker	424-SPEAKER	2	19.88
MOSFET 100V	942-IRFI530NPBF	10	7.46
DC Fan 12V	978-9GA1212P4G001	2	77.40
MENS Microphones	721-SPH0641LU4H-1	5	7.55
IMU- 9 axis	512-MTI-1-8A7G6	1	115.36
Total Cost			591.54

Appendix 2 - Arduino motor control sketch

Created using libraries from: (Ion Motion Control, 2015) and (Bouchier, 2017)

```
/*
 *Motor control for Atlas Legacy Robot
 *Motors controlled: 2x main track, 2x flippers, 2x arm
 *Created by: Balint Vidos
 *Email: vidos.balint@gmail.com
 */

#include <SoftwareSerial.h>
#include "RoboClaw.h"
#include <ros.h>
// Twist message is used temporarily so no new type of message file needs to be
created...
// use UInt8 array in future
#include <geometry_msgs/Twist.h>

unsigned long cur_time,cmd_time; //time variables for fail safe operation

SoftwareSerial serial(10,11);

RoboClaw roboclaw(&serial,10000);
#define address_track 0x80
#define address_flipper 0x81
#define address_arm 0x82

ros::NodeHandle nh;

void servo_cb( const geometry_msgs::Twist& cmd_msg){
  byte Ma1= (byte) cmd_msg.linear.x;
  byte Ma2= (byte) cmd_msg.angular.x;
  byte Mb1= (byte) cmd_msg.linear.y;
  byte Mb2= (byte) cmd_msg.angular.y;
  byte Mc1= (byte) cmd_msg.linear.z;
  byte Mc2= (byte) cmd_msg.angular.z;

  roboclaw.ForwardBackwardM1(address_track,Ma1); //control motor a 1 speed
  roboclaw.ForwardBackwardM2(address_track,Ma2);
  roboclaw.ForwardBackwardM1(address_flipper,Mb1);
  roboclaw.ForwardBackwardM2(address_flipper,Mb2);
  roboclaw.ForwardBackwardM1(address_arm,Mc1);
  roboclaw.ForwardBackwardM2(address_arm,Mc2);

  cmd_time=millis(); // record time of callback
  digitalWrite(13, HIGH-digitalRead(13)); //toggle led
}

ros::Subscriber<geometry_msgs::Twist> sub("servo", servo_cb);

void setup(){
  pinMode(13, OUTPUT);

  nh.initNode();
  nh.subscribe(sub);

  //Open roboclaw serial ports
  roboclaw.begin(38400);
}

void loop(){
  nh.spinOnce();

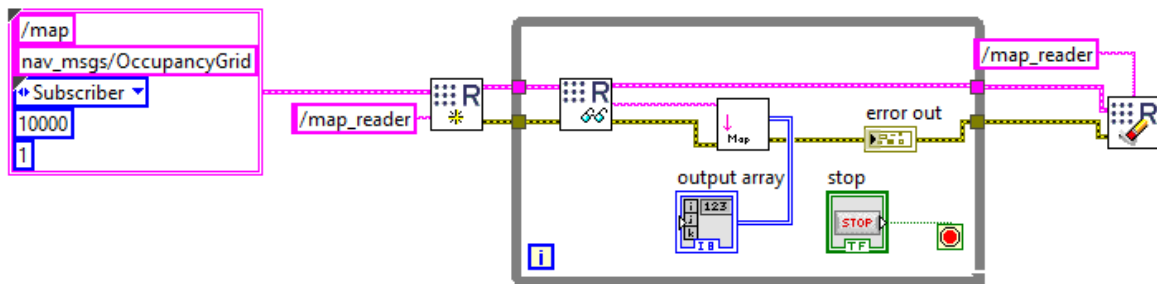
  cur_time=millis();
  if ((cur_time-cmd_time)>1000){
```

```

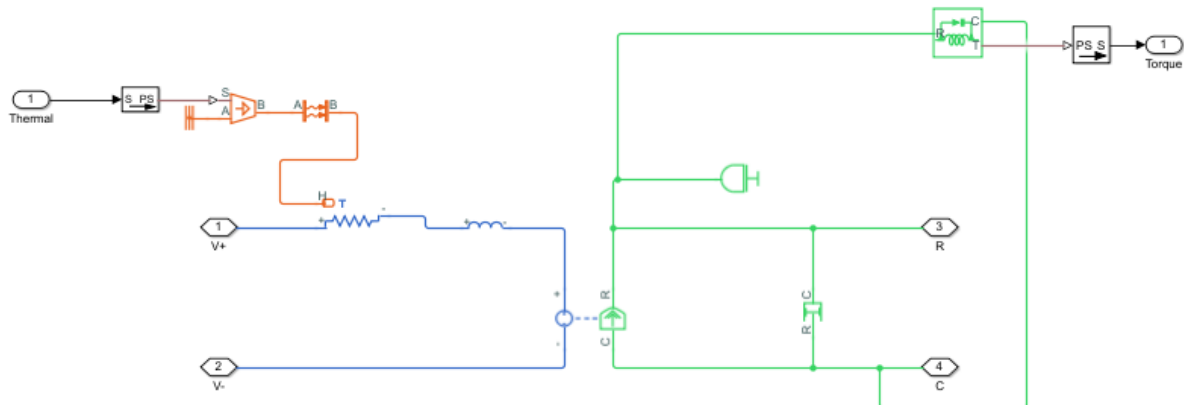
    roboclaw.ForwardBackwardM1(address_track,64); //if no command in ls --> stop mo-
tors
    roboclaw.ForwardBackwardM2(address_track,64);
    roboclaw.ForwardBackwardM1(address_flipper,64);
    roboclaw.ForwardBackwardM2(address_flipper,64);
    roboclaw.ForwardBackwardM1(address_arm,64);
    roboclaw.ForwardBackwardM2(address_arm,64);
}
delay(1);
}

```

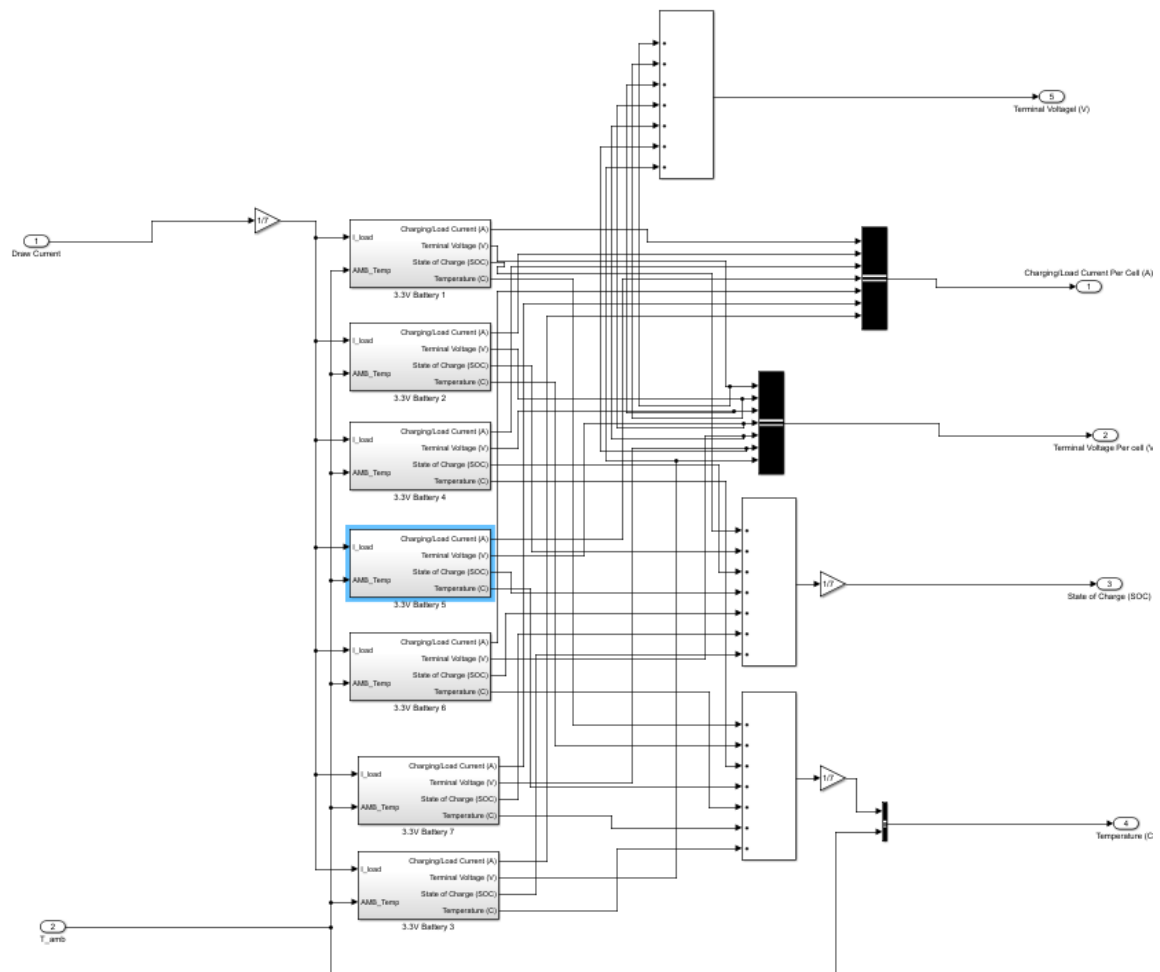
Appendix 3 - LabView Occupancy Grid reader



Appendix 4 - Basic DC Motor Model



Appendix 5 - Battery Connection Model



Appendix 6 - Internal condition for the models

```
% this is setting the Input
TimerR = 3;
SFV = 240;
Slope = SFV/TimerR;
Tran = 2*pi()*0.001;
Other = (1.3 + 0.9 + 0.7 + 1.5 + 0.35)*1.1;
```

```
%Condition of input
J = 112.5;
b = 0.1;
K = 2.3;
Kref = 2.3;
L = 0.01;
R = 0.46;
RValue = [0.46 0.231 0.15 0.1];
TAIM = [175 250 300 350];
Tamb = 20;
%3.08 , 0.01
%resistor model
Alp = 0.004041;
Tref = 20;
Rref = 0.46;
```

```

Kalp = 0.0012;
Kref = 0.072;

%tempture range
Tmin = -50;
Tmax = 50;
Number = Tmax-Tmin;
step = 5;

%Conoters
i = 1;

% Battery Values

C1_LUT =
[619,493,873,1941,860,22842;351,221,19,1115,2072,74025;10435,2209,3895,5088
,6814,298857;25987,24765,40020,71649,89099,665892;4779,1001,4522,4008,5591,
53143;663,15,45,1128,1935,6313;148,10,12,512,541,108];
C2_LUT =
[14,78,21,115,27539,13861;44695,212996,143644,361717,346974,362745;1268,414
,216,3876,3623,75454;208,103,222,847,886,39630;36,163,492,1921,5320,58952;3
156,14964,29348,68274,68279,256576;16210,99517,242065,140296,140437,331497]
;
Capacity_LUT =
[2.741000000000000,2.903000000000000,3.333000000000000,4.059000000000000,4.1800
0000000000,4.178000000000000];
cell_area = [0.1019080000000000];
cell_Cp_heat = [810.5328000000000];
cell_height = [0.2200000000000000];
cell_mass = 1;
cell_rho_Cp = [2040000];
cell_thickness = [0.00840000000000000];
cell_volume = [0.0003973200000000000];
cell_width = [0.2150000000000000];
Em_LUT =
[3.238000000000000,3.199000000000000,3.189000000000000,3.101000000000000,3.0290
0000000000,3.142000000000000;3.309000000000000,3.363000000000000,3.34400000000
000,3.245000000000000,3.230000000000000,3.235000000000000;3.350000000000000,3.2
5200000000000,3.256000000000000,3.268000000000000,3.295000000000000,3.29700000
000000,3.267000000000000,3.271000000000000,3.276000000000000,3.287000000000000,
3.343000000000000,3.316000000000000;3.303000000000000,3.279000000000000,3.28900
00000000,3.308000000000000,3.345000000000000,3.338000000000000;3.3150000000000
00,3.314000000000000,3.317000000000000,3.340000000000000,3.367000000000000,3.33
800000000000;3.343000000000000,3.330000000000000,3.331000000000000,3.504000000
00000,3.483000000000000,3.585000000000000];
h_conv = [5];
Qe_init = 0;
R0_LUT =
[0.0475000000000000,0.0304000000000000,0.0276000000000000,0.0148000000000000
0,0.0124000000000000,0.0019000000000000;0.0539000000000000,0.045000000000000
000,0.0280000000000000,0.0121000000000000,0.0116000000000000,0.0023000000000
00000;0.0655000000000000,0.0400000000000000,0.0254000000000000,0.0171000000
000000,0.0243000000000000,0.0075000000000000;0.0439000000000000,0.02760000
00000000,0.0256000000000000,0.0116000000000000,0.0062000000000000,0.003800
0000000000;0.0537000000000000,0.0389000000000000,0.0252000000000000,0.0116
000000000000,0.0214000000000000,0.0055000000000000;0.0471000000000000,0.04
430000000000000,0.0245000000000000,0.0123000000000000,0.0389000000000000,0.0
0100000000000000;0.0425000000000000,0.0270000000000000,0.0182000000000000,0
.0130000000000000,0.0095000000000000,0.0211000000000000];

```

```

R1_LUT =
[0.1124000000000000,0.0893000000000000,0.0963000000000000,0.0762000000000000
,0.0686000000000000,0.0103000000000000;0.0792000000000000,0.0851000000000000
0,0.0727000000000000,0.0386000000000000,0.0346000000000000,0.0030000000000000
000;0.7022000000000000,0.0420000000000000,0.0543000000000000,0.0217000000000000
000,0.0737000000000000,0.0987000000000000;0.0025000000000000,0.0136000000000000
00000,0.0170000000000000,0.0249000000000000,0.1033000000000000,0.2771000000000000
0000;0.0254000000000000,0.0189000000000000,0.0086000000000000,0.0068000000000000
0000000,0.0325000000000000,0.0025000000000000;0.0283000000000000,0.0230000
000000000,0.0265000000000000,0.0137000000000000,0.0225000000000000,0.003300
00000000000;0.0523000000000000,0.0510000000000000,0.0298000000000000,0.0427
000000000000,0.0497000000000000,0.0291000000000000];

R2_LUT =
[0.0941000000000000,0.0137000000000000,0.0432000000000000,0.3822000000000000
,0.3938000000000000,0.4072000000000000;0.0966000000000000,0.1342000000000000,0
.0773000000000000,0.0591000000000000,0.0930000000000000,0.1976000000000000;0
.0569000000000000,0.0275000000000000,0.0303000000000000,0.0061000000000000
,0.0293000000000000,0.0067000000000000;0.0475000000000000,0.0483000000000000
00,0.0284000000000000,0.0143000000000000,0.0405000000000000,0.0027000000000000
0000;0.0193000000000000,0.0144000000000000,0.0160000000000000,0.007100000000
000000,0.0132000000000000,0.0056000000000000;0.0386000000000000,0.03540000
00000000,0.0397000000000000,0.0348000000000000,0.1296000000000000,0.00520000
00000000;0.2546000000000000,0.3326000000000000,0.6113000000000000,0.956500000
000000,0.9837000000000000,0.9115000000000000];

SOC_LUT =
[0;0.1000000000000000;0.2500000000000000;0.5000000000000000;0.7500000000000000;
0.9000000000000000;1];

T_init = [293.150000000000];

Temperature_LUT =
[253.150000000000,258.150000000000,263.150000000000,273.150000000000,293.15
0000000000,313.150000000000];

```

Appendix 7 - Torque Control

Controlling code for change the input torque

```

clear all %Clear the date
close all %close the fingure
run Motor_con %Run the Constant that load
for i= 1:4
% these set the torque input that
Tin = TAIM(i);
R = RValue(i);
Out = sim('Battery_24V_Lith_full_systeam'); %this run model
%this section code standized the size for messurements
for j = 1:20000
SOCtemp(j) = SOC(j,1);
end
SOCsave(:,i) = SOCtemp;

for k = 1:20000
Temptemp(k) = TempOut(k,1);
end
Tempsave(:,i) = Temptemp;

```



```

end
%these produce of statzation of time.
for j= 1:20000
Time(j) = Out(j,1);
end
% these take the data then the different torque for the output.
%these take the SOC
figure (1)
plot(Time,SOCsave)
title('SOC Plot')
xlabel('Time (s)')
ylabel('SOC (%)')
xlim([0 2500])
ylim([0 1])
legend( '175N', '250N', '300N', '350N')
grid on
% this take different tempture.
figure (2)
plot(Time,Tempsave)
title('Temperature °C')
xlabel('Time (s)')
ylabel('Temperature °C')
xlim([0 2500])
ylim([20 25])
legend( '175mN', '250mN', '300mN', '350mN')
grid on

```

Appendix 8 - Temperature Change

```

clear all %Clear the date
close all %close the fingure

run Motor_con %Run the Constant that load
% these set the torque input that
Tvalue = [-20 0 20 40 60 80 100];
for i= 1:7
% these set the different
Tamb = Tvalue(i);
% these set input of Change movements
K = Kref*(1+Kalp*(Tvalue(i)-Tref));
R = Rref*(1+ Alp*(Tvalue(i) - Tref));

Out = sim('Battery_24V_Lith_full_systeam'); % run the model
%this section code standized the size for measurements
for j = 1:20000
SOCtemp(j) = SOC(j,1);
end
SOCsave(:,i) = SOCtemp;

for k = 1:20000
Temptemp(k) = TempOut(k,1);
end
Tempsave(:,i) = Temptemp;

end
%these produce of statzation of time.
for j= 1:20000
Time(j) = Out(j,1);
end
%these take the SOC
figure (1)

```

```
plot(Time,SOCsave)
title('SOC Plot')
xlabel('Time (s)')
ylabel('SOC (%)')
xlim([0 2500])
ylim([0.3 1])
legend( '-20°C', '0°C', '20°C', '40°C', '60°C', '80°C', '100°C')
grid on
% this take different tempture.
figure (2)
plot(Time,Tempsave)
title('Temperature °C')
xlabel('Time (s)')
ylabel('Temperature °C')
xlim([0 2500])
ylim([-20 100])
legend( '-20°C', '0°C', '20°C', '40°C', '60°C', '80°C', '100°C')
grid on
```