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1 Introduction

The Mechanical Engineering Level 5 group project focuses on the design, prototyping, and refinement of a machine capable of ascending a vertical copper pipe, and executing a sequence of instructions autonomously. According to the event organizers, the project emulates real life applications of autonomous, or at the least unmanned, machines purposed for the inspection of industrial equipment in otherwise difficult to reach environments (Xu, F. et al., 2021). Traditionally, manual inspection of suspension bridge ropes or ground lines can be hazardous, costly, and labour intensive. A relatively inexpensive robot, capable of operating in hazardous situations with little risk to persons, not only improves the safety in these tasks, but by reducing costs ensures maintenance can be done more frequently, preventing catastrophic failures from a lack of predictive maintenance.

The project requires deliberate effort into mechanical design, sensor selection and integration, electrical systems, programming, and prototype testing, all aspects that must be considered in a real-world application. Further, the success criteria for the robot, that being that the robot follows a set of instructions and stops at a target that is a known distance away from the ground in a repeatable fashion, mirrors real life applications, where accuracy and repeatability are paramount.

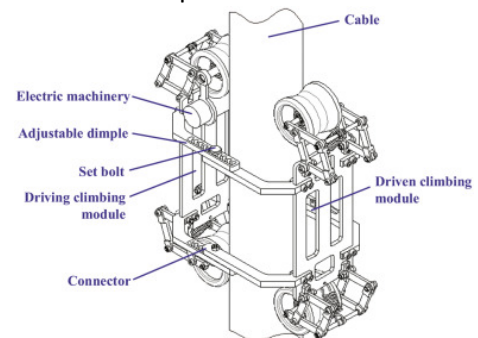


Figure 1, Industry Example of Cable Climbing Robot, Xu, F. et al. (2021)

2 Team Roles and Responsibilities

The division of labour for a project requires a balance of assigning workloads to those whose skills compliment the work needed, and ensuring no person has a disproportionately large workload.

The idea with dividing the labour in such a way is that, once the project is underway, work can be done in parallel threads by each team member with minimal bottlenecking, in theory.

2.1 Assigned Roles

The team consists of four members, the responsibilities are outlined below:

Mechanical Design – Callum Williams

- Designing chassis, mechanisms, and climbing system
- Model Slicing
- 3D Printing

Electronics Design – Jonatas Fernandes

- Sensor & Motor Selection
- Microcontroller & Sensor Programming for automated task sequence
- Integration of electronics and power distribution

Testing & Integration – Thab Moyo

- Troubleshooting Climber
- Testing of prototypes on test rig
- Developing testing scenarios for Climber mechanisms

Project Lead – Ali Mostafa

- Noting down meeting minutes
- Scheduling and timeframes
- Procuring materials and pricing
- Collating report of design process

2.2 Required Skills for Personal Role

The Electronics Design role necessitates a strong knowledge of electrical engineering and programming. Often, a large portion of the development time can revolve around fixing erratic behaviour or finding more elegant or reliable solutions to various systems, as such, a methodical and patient approach to problem solving is paramount.

The devices most commonly used for prototype autonomous applications tend to be easy to use microcontrollers, often in the form of an all-in-one package featuring a printed circuit board housing the microcontroller, and direct connections to input/output (I/O) pins for interfacing. The team chose to use an Arduino for this project, usually coded in C, or a C derivative language such as C++.

The responsibilities of this role require, amongst others, the following traits:

- Strong understanding of C/C++ and implementation of sensors and control logic
- Logic driven problem solving for debugging
- High attention to detail, meticulous commenting to prevent confusion when re-analysing code

2.3 Belbin Role Analysis

Belbin's model highlights tendencies towards different behaviours in individuals, specifically in regards to working in a team. With alignments towards "Completer-Finisher" and "Resource Investigator", the role of Electronics Design seems a good fit. Completer-Finishers excel at following through, maintaining a high standard of work and ensuring no cut corners. In a project where cut corners can lead to exponential increases in lead time, should issues arise as a result, the guarantee that work has been done to the highest standard possible offers reassurance. Resource Investigator's openness towards new ideas and approaches is advantageous for tackling programming with an outside of the box perspective.

Acknowledging limitations and drawbacks is important to reduce blind spots in planning, and account for weaknesses. For example, Resource-Investigators struggle to remain enthusiastic for a project once it is well underway. Accounting for this includes keeping ideas fresh, to introduce novelty within each prototype cycle, and regular checks with the team to ensure productivity is not dipping due to lack of interest. Further, Completer-Finishers can have issues with letting go of features that aren't up to a certain standard, it is important to not allow one to get tunnel visioned as it can lead to an improper use of time on unimportant features.

3 Overall Group Tasks and Timings

The initial plan for the group tasks involves a starting period of concurrent research, where all members contribute towards the early concept ideas, and as the design refines the responsibilities branch into parallel sequential and concurrent activities. This early overlap allows for multiple concepts generation, as each member contributes a design idea, and with all members researching prior examples in industry not only are there fewer blind spots in available research, but all members will earn a deep understanding of the requirements and real-life applications that are relevant to the competition.

This approach mirrors industry standard practices (Camburn, B. et al., 2017), allowing for easy iterating of designs whilst reducing rework due to misunderstandings from varying departments. As some tasks, such as programming the microcontroller and testing the climber cannot be accomplished until the project is well underway, some roles necessitated a flexible working ethos, providing assistance in picking up the slack. The scheduling illustrates an awareness of dependency chains, tasks that depend on previous tasks are planned for to prevent delays in minimum requirements being met for prototyping.

Task	Description	Week Start	Week End
Initial Research	Combined Research into concepts present in industry.	1	2
Concept Generation	Collating of ideas and generating one viable concept to go through with.	2	3
Initial Design	Creating a concept in CAD, adhering to constrictions present in competition brief.	3	4
Material Selection	Selecting desired materials, based on early pricing information and material requirements. Selecting	4	7
Prototype	Development of a finalized prototype, based on selected materials, motors and sensors.	7	9
Bill of Materials	Collating materials and finalizing an early revision of a BoM.	9	10
3D Printing	Slicing models, preparing them for printing and assembly.	10	12
Testing & Iterating	Testing of robot and implementing iterative changes.	12	14
Final Design	Final design, ready for en vivo.	14	15

Table 1, Group Project Timeline, Fernandes, J. (2025)

4 In-Depth Analysis of Personal Tasks

The methods to program a device, or any relatively complex program in general, is a highly cyclical process, requiring implementation, testing and iteration until the desired specifications are reached, or it becomes unwise to invest more time into it. Breaking the autonomous program down into separate threads allows a clearer distinguishing of the surprisingly linear thought process present in each individual action. The autonomous machine runs through a set list of instructions, every instruction activating a linear series of events, and the role of a programmer is to tweak the variables, timings, and order of these until the desired effect is reached. A modified variable can have a cascading effect on later processes, requiring exponential fine tuning, as such, it can be assumed a majority of the programmer's time is spent tweaking variables and troubleshooting, rather than writing novel code.

The sensor and motor selection is relatively quick to obtain, only totalling a few hours of work. The vast majority of the total time spent working on this project for this specific role is assigned to the programming itself.

4.1 Detailed Task List

Task	Hours	Week Start	Week End	Notes
Initial Research	2	1	2	All members
Concept Generation	2	2	3	All members
Initial Electronic Design	2	3	4	Drafting wiring in Proteus 8, adhering to design brief.
Material Selection	4	3	5	All members
Sensor Selection	2	3	4	Resarching sensors based on useability for test scenario.
Motor Selection	2	4	5	Researching motors based on price, torque, and dimensions.
Prototype CAD Design	4	6	8	Collating all design choices into one prototype, all members.
Initial Programming	8	9	10	Familiarizing with ArduinoIDE, and preliminary programming for sequence.
3D Printer Setup	2	9	10	All members.
Troubleshooting	12 (estimated)	13	14	Testing sequence on prototype, iterating until satisfied.
Final Design	8 (estimated)	14	15	Final touches.

Table 2, Electrical Design Task List, Fernandes, J. (2025)

4.2 Bill of Materials

Component	Description	Price	Lead Time
Arduino Nano R4	Small form factor budget Arduino	£ 14.06	3-5 days
iMetrx 1.5-3.8V Stepper Motor	Stepper Motors, low power	£ 16.66	0 days
HC-SR04	Ultrasonic Distance Sensor	£ 5.99	3-5 days
FSR-400	Force Sensitive Resistor, for detecting "ceiling"	£ 0.78	3-5 days
Buzzer	Sound wave emitting device	£ 0.40	3-5 days
4x AA Battery Holder	4x AA Battery Holder	£ 1.00	0 days
Wires	Assorted wires		0 days
LED	LED, required for challenge	£ 0.03	0 days
3D Printing Filament	Filament for additive manufacturing	£ 6.30	3-5 days
Total:		£ 45.22	

Table 3, Bill of Materials, Fernandes, J. (2025)

5 Significant Milestones

The projects pacing is centred around milestones, as they provide a straightforward method of measuring progress and encouraging reflection on next steps after big changes. Conversely, gateways are a part of these periods of reflection, where as a team the viability of the current approach must be considered, and, depending on the decision, changes in plans can be implemented. From a project management perspective, milestones ensure the project is where it needs to be before moving on to further developments, this prevents adjustments being made later. As touched on previously, a change made to an earlier part of the process can have a cascading effect, where multiple variables must be modified down the line, so keeping these changes minimal is key to avoiding massive run off costs and time sinks.

Milestone 1 – Initial Design that adheres to the brief specifications

The first milestone confirms whether the selected design conforms with the design specs, and is feasible for manufactory. Any concerns or hold ups over other designs must be addressed, and the team must be positive that this design is the most advantageous choice, at least on paper. To quantify this, the cost of components, design complexity, and examples in industry must all be assessed.

Milestone 2 – Prototype

Once the initial design has been refined, and altered to hold all the components deemed necessary, and selected in the materials selection section, it must be greenlit by all members. Once again comparing to examples available in industry, and balancing based on weight, cost of materials, and ease of iteration for refinement.

Milestone 3 – Automation

The device must be able to complete the sequence in a test bench without failure before further improvements can be considered. This assessment should be conducted by stress testing the prototype, ensuring it can complete the sequence repeatedly, and accurately, without fail.

Milestone 4 – Final Revision

Testing for this milestone involves stress testing the final revision with different variables, to simulate unknown issues that could present themselves. This could involve slicker contact surfaces for the wheels, testing fall back mechanisms, such as multiple sensor types, chain position on the chain holder, uneven loads, motor failures or underpowering. Once the device can complete the sequence without fail in any tested circumstance within reason, the revision can be considered to be final.

5.1 Criteria of Measurable Aspects

Category	Unit/Type	Target	Method
Weight Reduction	% of mass	>10%	Finite element analysis of cad model + topology optimisation
Structural Integrity	Safety Factor	> 1.25	Finite element analysis of cad model
Interchangeability	# of identical parts	>0	Consolidating design elements to allow for identical parts in similar applications
Printing Time	Time	Decrease	Lowering infill, bigger print layers, printing multiple components concurrently

Table 4, Criteria of Measurable Aspects, Fernandes, J. (2025)

The table above shows targets present within the gateway for milestone 2. To ensure proper conditions for rapid iterating in further prototypes.

6 Risk Identification and Mitigation

The risks identified below are selected both for their likelihood, and their ability to disrupt the robot's ability to complete its sequence.

6.1 Technical Risks

Insufficient Torque

Should the motors be unable to support the weight of the robot and ascend the robot would automatically fail its objective. As such, insufficient torque is a high impact risk. To mitigate this, motor torques should be calculated, and selected motors should have a good safety margin. By utilizing two motors, there is some fallback, in case one loses power intermittently or completely. A conservative gear ratio, whilst harming max velocity, improves the motors torque.

Stepper motor inaccuracy from wheel slip

Stepper motors were chosen for this design, due to their ability to move with extreme precision. The idea is that as, once the robot has ascended to the top of the climbing rig, it will "count" how many steps it must travel down to reach the target, based on the radius of the wheels, the gear ratio between the motor and the wheels, and the angular distance between the steps in the motor. Should the robot slip on the copper pipe whilst traversing down, the readings it is taking would become wildly inaccurate. Due to the low friction of the metal pipe, this is considered a high-probability and high impact risk. To counteract this, an inexpensive ultrasonic distance sensor is used concurrently. If the readings from the stepper motor are too misaligned with the readings from the sensor, the sensor data will be used as a fallback. Otherwise, the stepper motor's more accurate readings will be used.

Sensor inaccuracy

In unforeseen circumstances the ultrasonic sensor could take false readings that would be highly inaccurate. One mitigation is to include a minimum and maximum tolerance, as the height of the testing rig is known, if the sensor submits a reading outside of these parameters, the robot will ignore the sensor for the remainder of the run and continue based on the stepper motors readings. The low likelihood of this happening, and the small impact makes it a low risk.

Insufficient Friction

Should the robot not apply enough force through the wheels to the copper pipe, it could be unable to adhere to the surface. As the pipe is thin and made of metal, the risk of this happening is quite

high. To mitigate this, the climber robot will have an adjustable frame, ensuring a tight fit on every installation.

6.2 Organisational Risks

Limited Experience

As programming lead, learning a new system is time consuming, and there can be a lot of easy mistakes to make early on with potentially huge ramifications later. To mitigate issues, meticulous commenting can ensure following the path of the program during debugging is as straightforward as possible.

Insufficient Testing Time

Testing the prototype on a rig is time consuming, with each run being up to 120 seconds long. The number of tests necessary can be reduced by selecting essential variables that only for rig testing, such as the chain hold's capacity, the driving mechanisms, and sensor accuracy. Other factors, such as sequence, LEDs and buzzers activating, buttons pressing successfully, can be tested either virtually or without the need for a rig.

Uneven work distribution

In a design task, careful care must be taken to ensure the workload isn't done mainly by one or two parties. All members must maintain vigilance of their own workloads, and offer to help if their own responsibilities are lighter than expected during a time period.

7 Gantt Chart

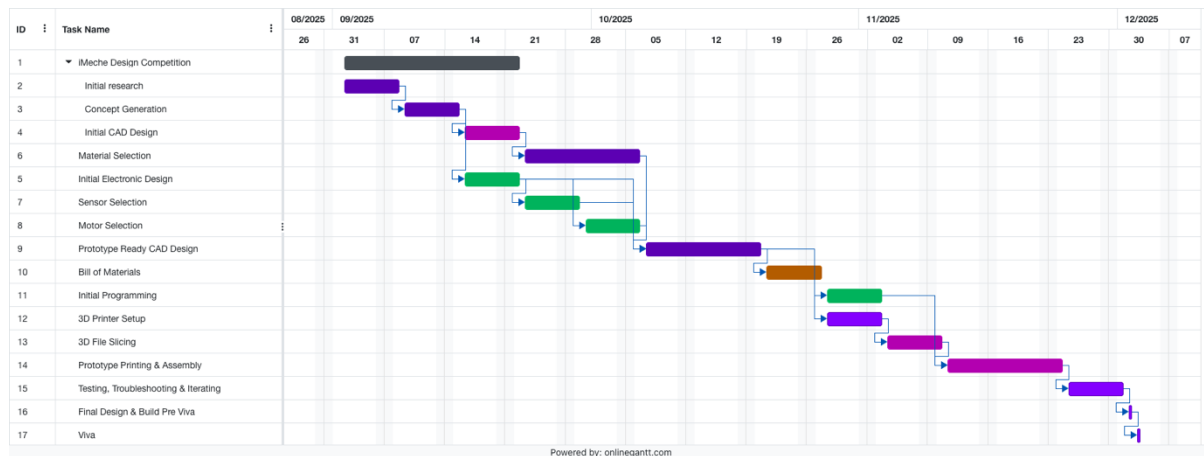


Figure 2, Group Wide Gantt Chart, Fernandes, J. (2025)

The project begins with a combined research and concept phase, and splits into threads running concurrently, over the lifecycle of the project, all team members will come back to work on bottleneck tasks.

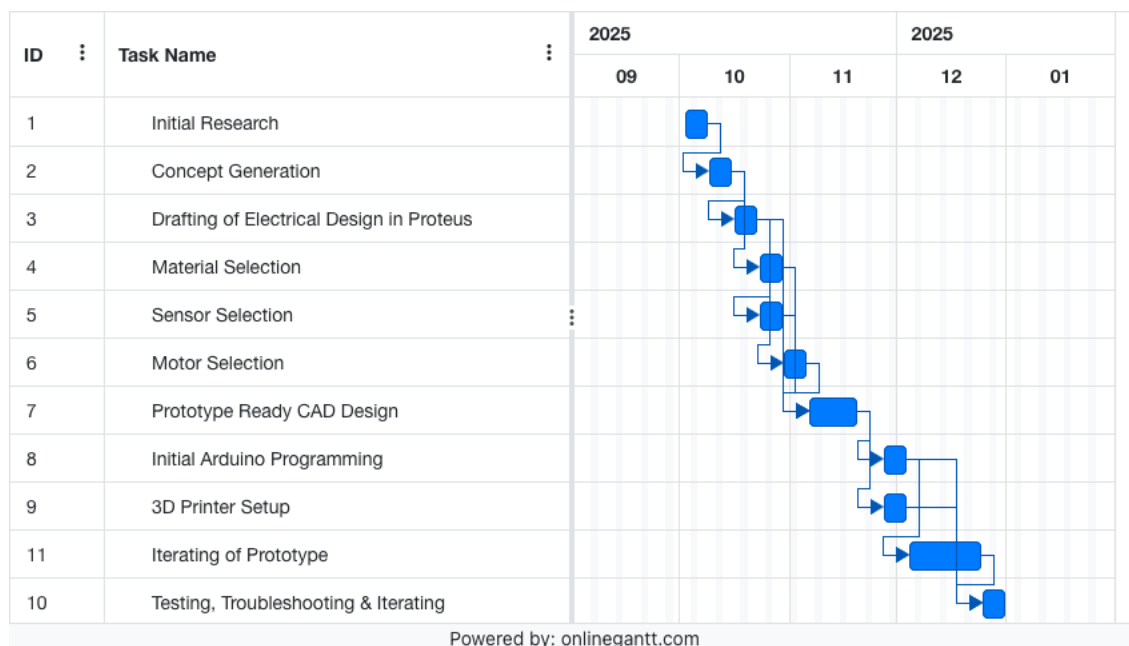


Figure 3, Electrical Design Role Specific Gantt Chart, Fernandes, J. (2025)

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Xu, F. *et al.* (2021) *Figure 1*