# Integrated Design Project: Final Report

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(formerly known as Comic Sans MS)

## Contents

# 1. Overview

## 1.1. Mechanical Design

The basis of our design was a modular robot that layers could be easily added to to give more space for electrical components or sensors. To pick up and move blocks we wanted a claw attached to the front. This would also provide a place to attach the relevant electrical parts (e.g. coil) for metal detection. The claw ended up not being used to due time constraints.

The chassis was originally made of aluminium but we ended up having to convert to using a mix of MDF and aluminium to avoid interfering with the circuitry. The mechanical performance of the robot could’ve been massively improved by taking more care with our original design to prevent further problems. We could have then focused more time on getting the structure of the claw completed sooner to give the other sub-teams time to integrate it.

## 1.2. Electrical Design

The electrical system design consists of a line follower, a metal detector, an ultrasonic distance sensor, a switch (to start the robot) and a LED system (an amber flashing light).

The Line follower used 2 OPB704 sensors and resistors and was very effective in guiding the robot to follow the line over the ramp to the collection ramp and back. The 2 sensors were positioned either side of the white line and were programmed to detect white or black and feedback a voltage. If a sensor detected white, it was programmed to rotate the wheel on the side of the white line detection more to get back on track. This design was much more accurate than the initial IR sensor design.

The pulse induction metal detector used a single coil as both transmitter and receiver. The arduino was programmed to send powerful, short pulses of current through a coil of wire, which generated a brief magnetic field. When the pulse ended, the magnetic field reversed polarity and collapsed very suddenly, causing another current (reflected pulse) to run through the coil. If a piece of metal came inside the range of the magnetic field lines, a change in both amplitude and phase of the received signal was detected. But this was not powerful enough to detect the metal blocks. So, the value of capacitance was reduced on the breadboard, but was not effective when soldered onto the stripboard as there may have been some stray capacitances that were not taken account of. The number of turns on the coil could have also been increased in retrospect.

The ultrasonic sensor worked well to accurately measure distance and was initially planned to be used for block detection, but due to positioning issues, it was used to help the robot stop at a wall. The initial metal chassis also short circuited circuits on the breadboard, so there were some integration issues.

## 1.3 Software Design

The software was developed with the electronics team to ensure reliable operation. The main algorithms made were for the line follower and an ultrasonic distance detector. Plans were also made to include a magnetic loop sensor and claw closing/opening mechanism, however limitations on our efficiency prevented this. Deviations from plans made during the first two weeks made conceptualisation difficult. However, after rejecting the possibility of applying wireless communications, we were able to coordinate better with the electrical team to develop the sensor interfaces, using solely the Arduino.

# 2. Project Management

## 2.1. Organisational Structure

We decided on having a project lead and two sub-leaders to try and maintain organisation. Michaela was project leader, while Tungsten oversaw the mechanical decisions and Lorcan oversaw the electrical and software side of things.

We used our Gantt chart to show what tasks we were aiming to complete for each deadline or progress meeting, however we did not use this effectively. We ended up with very broad, open-ended tasks that made it hard to track progress. Ideally, we should have compiled lists of specific tasks that could be easily monitored and checked off as completed. This would have made our Gantt chart a much more useful tool for monitoring progress and may have prevented us from ending up so far behind where we should've been.

## 2.2. Team Management

We could have benefitted from having some more decisive mindsets, but used a bit more forethought in these decisions. Better team management would have avoided a lot of the problems we had. For example:

- Ensuring we set realistic aims: we should have aimed for a more simple original design and built up from there with any spare time.
- Ensuring everyone was communicating progress: when we got behind schedule, it was hard to reallocate team members to other tasks as no one was completely sure what the other sub-teams were doing. This problem was especially noticeable when we had no members from particular sub-teams in attendance on some days, meaning no progress could be made on their elements of the robot.
- Avoiding sticking to ideas we would later backtrack on: if we hadn't stuck so stubbornly to the completely metal chassis, it likely would have made the progress beyond that a lot easier. The metal chassis ended up causing problems with the electrical circuits and had to be altered.

# 3. Initial Ideas and Testing

## 3.1 Mechanical

### 3.1.1 Chassis and Wheels

Our original plan for the chassis was just a box shape that everything could be placed inside. We planned on being able to add layers to this to create more space in what we termed a 'lasagne structure'. We originally went with a metal chassis due to its structural rigidity, ease of manufacturing and stability in holding all the components of the robot. This appears to be an issue from an integration standpoint, see section 5.2.1.

In terms of wheels, we tested them, according to the original plan, as soon as the metal chassis was produced. RPM imbalances are significant where one is 70% speed of the other, possibly due to friction, hence the original plan of in-place rotation (the whole robot rotating about axle) required additional calibration of motor speeds in software. It is fortunate that we picked up the issues of both insufficient torque and traction (surface friction), even with an empty chassis, when going up the ramp. While this also depends on weight distribution, we realistically wish to prioritise reliability (torque), especially in light of uncertainties with electronics, over speed, hence switching to the smaller VEX wheels.

#### 3.1.2 Block Movement Method

We wanted to remove as many possibilities in the movement of the block so as to increase the chances of scoring highly even if the robot went wrong. We looked at either pushing the blocks to the desired areas or picking them up. Although picking the blocks up would be more mechanically complex, pushing them would encompass too many places where the robot could dramatically fail. This includes the block potentially catching on lips on the surface of the ramp. Especially at the start and end inclines. We landed on the idea of picking up the blocks to eliminate those potential downfalls.

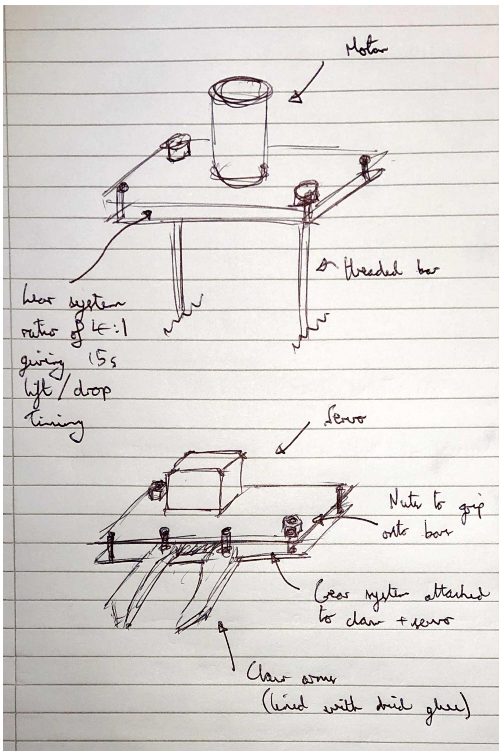


**Fig. 1.** First drawn concepts of the claw and elevator levels

The design consisted of two different levels. One which housed the claw gear system including the servo integration. The other housing the Elevator gear system and motor in order to be able to lift the claw level. The idea being that the claw would grab the block and the elevator would lift it high enough that it wouldn't collide with the ramp elevation or any lips on the flooring of the test area. The claw would have increased grip utilising the grip of a bead of glue on the cut out claws. The best way to manufacture the levels was identified as laser cutting. Prototypes could rapidly be altered and printed out to test.

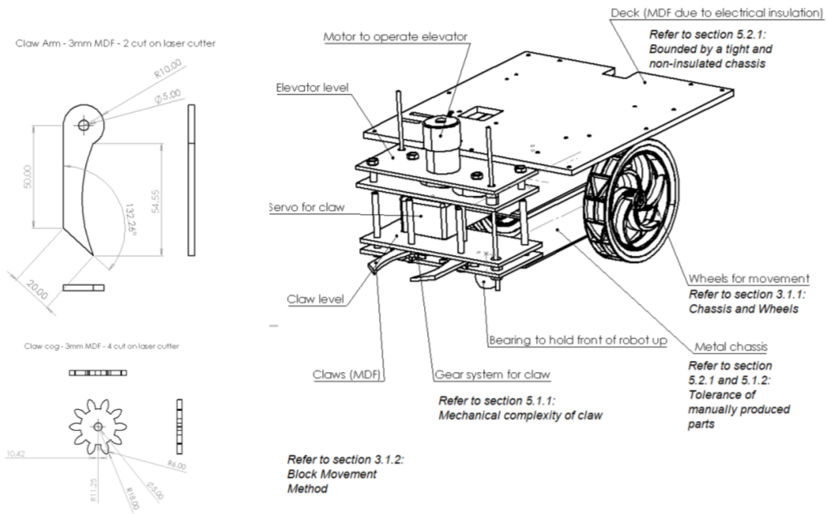


**Fig. 2.** a) CAD drawings of claw components b) CAD drawing of constructed claw on robot

The gears could easily be manufactured on the laser cutter or by using the pre-made available gears. It was decided to use cut gears for the claws to allow for more precision and then the pre-made gears for the elevator system in order to accurately move the levels up and down. The way the elevator level worked was by using the gear system directly connected to the motor to turn 2 vertically oriented threaded bars. These were connected to fixed nuts within the claw level. The turning of these bars would subsequently cause the claw level to rise or lower depending on the direction of rotation. Although the fastest motor we could use was rated at 40rpm, if we used a 4:1 ratio then the time to fully raise the claw level so that it would not impede with the ramp was approximately 15s or less. This would still allow for the successful transportation of all the blocks within the specified time. A rough approximation was that the threaded bars would move up or down by 1mm per full rotation at most. So at a motor speed of 40rpm, a gear ratio of 4:1 and a requirement to lift vertically by 35mm then an exact time of 13.2s could be achieved. In the end the claw integration with the servo proved to be successfully and reliably performed but the pre-made gears in the MDF layer had too much friction involved with them so it was difficult to make work. The concept did work in testing with slow rotation of the bars but when the motor was added, the gears failed to keep up resulting in the motor firing without turning the shaft.

## 3.2 Electrical & Software

### 3.2.1 Navigation Algorithm

Initially, the idea was to use the computer vision library OpenCV by running a Python script which would identify features on the table from the overhead camera, with wireless communications enabling the Arduino and computer to send and receive data. However, this approach proved to be deceptively difficult due to a variety of issues (see Section 6.2). During the second week, the software sub-team decided to change the fundamental approach to a system comprising the Arduino and its sensor circuitry alone.

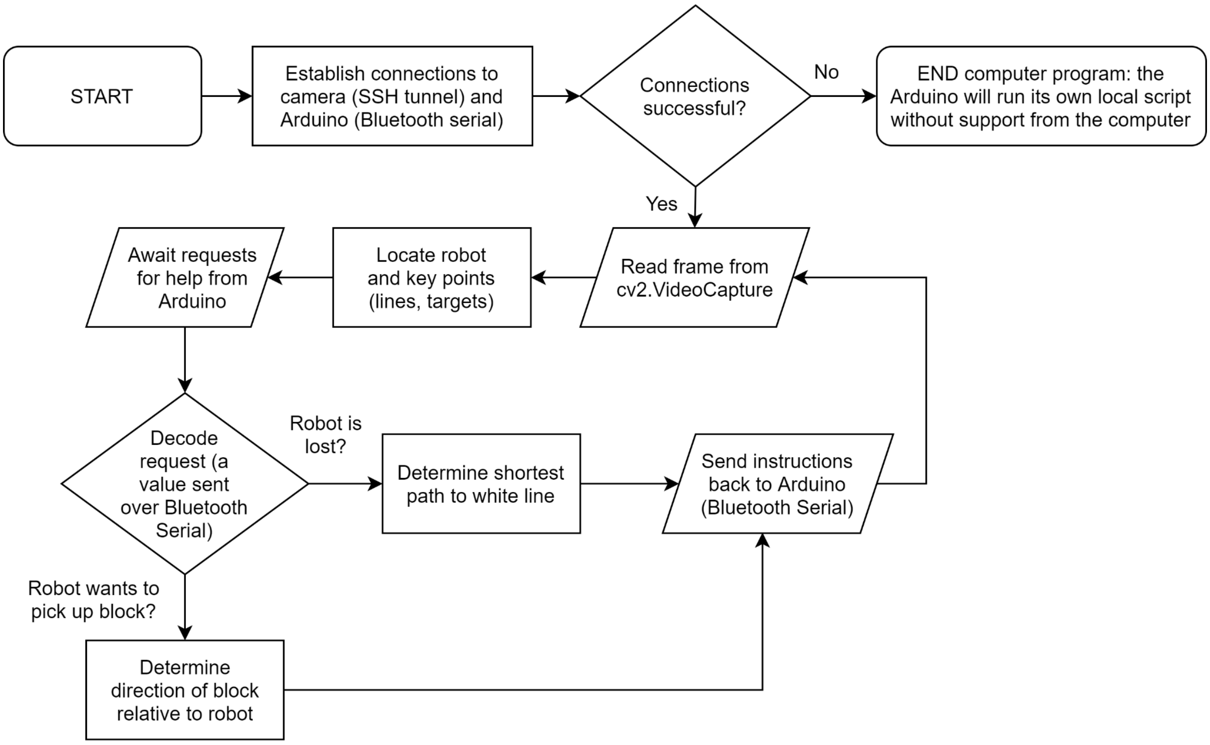


**Fig. 3.** Initial concept helper algorithm, to be run on a computer in Python.

Our aim was to run the Arduino's movement script (using line following with IR sensors) until a change in behaviour is required. This could be because the robot has reached its destination area, the robot has got stuck or strayed too far from the white lines, or when it was time to return. The algorithm shown in Fig. 3 would then execute, communicating data over a serial Bluetooth connection between the computer and the Arduino. The computer would therefore act as a helper device, doing the more computationally intensive task of image processing and passing instructions to the Arduino to continue in the correct manner.

### 3.2.2 Metal Detector

During the conceptualisation phase of our project, an agreement was made between the electrical and software teams to use the Hall effect sensor to distinguish between the metallic and non-metallic blocks. This was mainly due to the availability of a high-quality magnetic field sensor, the AD22151 - an integrated circuit featuring a built-in amplifier and temperature stabilisation - in our ADALP2000 electronics kit, which proved to be very capable during initial testing.

However, upon further testing by the electrical team, we discovered a significant amount of noise from the environment, which complicated the metal classification as a simple binary threshold could not be identified. Another unforeseen caveat to this approach was that the deployment of an aluminum chassis had undesirable interference effects on our sensor which made the Hall effect sensor overall an uneconomical approach for the task. Therefore, we decided to use a coil as it worked a lot better and gave clearer output signals with metal objects. We also thought it would be better to detect the blocks as it would integrate better with the picking up mechanism. This is shown in figure 5.

As mentioned in the overview, the metal detector was sensitive enough to detect large amounts of exposed metal, but could not detect the small amount of metal  in the insulated lego block. To attempt to make it more sensitive, we reduced the value of the capacitance from 100nF to 100 pF so that it would charge and discharge quicker to allow the software to be more sensitive to signals from the reflected pulses for smaller amounts of metal. This worked on the breadboard but did not work when soldered onto the stripboard, so there may have been some stray capacitances that were not taken account of on the breadboard.  The number of turns on the coil could have also been increased, or the signal could have been amplified using an op amp in retrospect to make the detector more sensitive. This metal detector, although it detected metal, did not meet the specifications to detect the metal blocks. It also did not incorporate an LED system to distinguish between metal and non-metal.

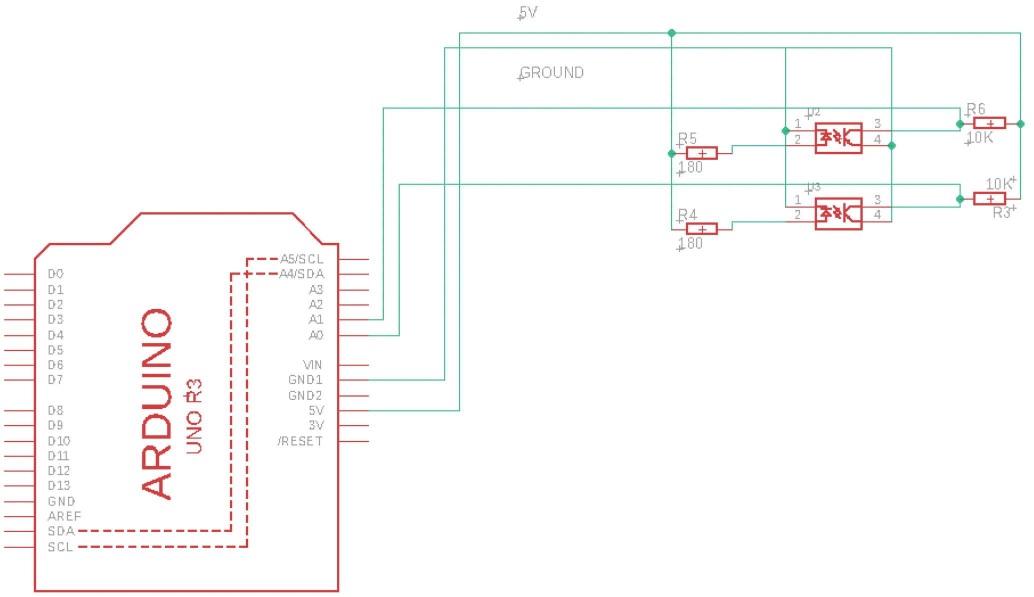


**Fig. 4.** Schematic for line sensor

### 3.2.3 Robot navigation

Initially, we thought of using the IR sensors to follow the lines, but the signals were very unreliable and the sensors themselves were very sensitive. So, as the chassis also struggled to go up the ramp initially, we contemplated using an ultrasonic sensor to follow the walls of the arena. However, we realised that integrating this with software would be very unreliable and complicated, especially since the cameras were not going to be used, and therefore would be hard to get to the collection area. So finally, we decided to use the OPB sensors to create a line follower with 2 resistors (shown in figure 4). It took a whole to find the right resistor values and required some experimentation to see which ones would make the sensors sensitive enough. The spacing between the OPB sensors was also a bit unreliable as the robot turned more than the spacing between the sensors meaning that it completely went off track sometimes. So that was adjusted before the final competition. Initially, a Schmitt trigger was going to be used to convert analogue signals to digital. But due to time limitations and issues with altering the limits of the threshold voltages, we decided against using this. However, we met the specifications for the robot to accurately follow the line to the over the ramp to the collection area and back.

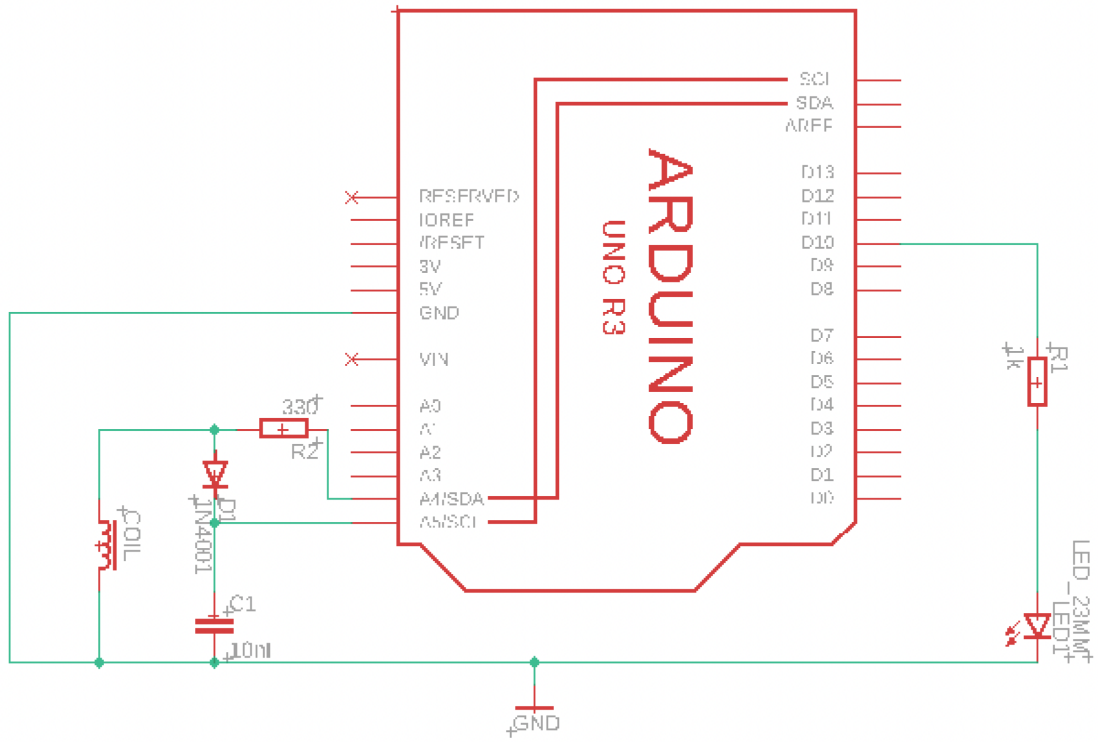


**Fig. 5.** Schematic for metal detector

### 3.3.4 Block detection

The ultrasonic sensor was tested and it worked well to accurately measure distances. It was initially planned to be used for block detection, but due to positioning issues, it was used to help the robot stop at a wall. The initial metal chassis also short circuited circuits on the breadboard, so there were some integration issues. Due to not having any system to detect the cubes, the robot failed to meet the specification to deliver and sort the cubes to the right square.

### 3.3.5 Integration of electrical system

We decided to mount the line sensor circuit, metal detector, the amber LED and the switch on one strip board with connections going to the arduino. We had mounted the ultrasonic sensor separately on a smaller strip board so that it can be moved and positioned easily. We made the connections as neat as possible, avoiding crossing wires and grouping wires using the insulation tubes. The final schematic is shown in figure 6.

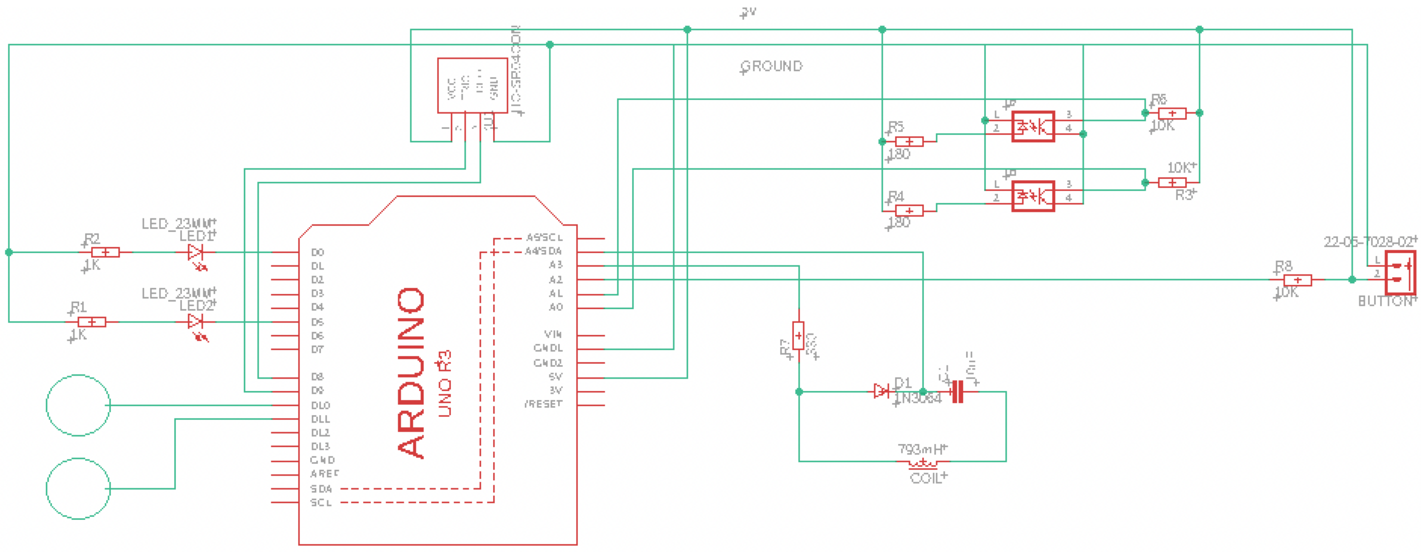


**Fig. 6.** Schematic for electrical system

## 3.3. First Competition

We tested the button in the first competition, but this was not very successful as the robot did not start or move. This was because there were some issues with software and sub-team communication that we needed to sort out.

Therefore, after the first competition, we prioritised the features of our robot which would maximise points gained while reducing focus on the overall objectives of the task. This involved making adjustments to our line following and navigation algorithms, as well as ensuring our robot met the standard specifications set (blinking LED when in motion; pausing before approaching block etc). An ultrasound transducer was also mounted on the robot in order to sense distances and interrupt motion - a primitive version of our initial idea of using computer vision to fulfill this role. This enabled the robot to continuously loop back and forth across the table, which was deemed acceptable behaviour for the final competition.

We altered the chassis by adding an MDF plate to the base layer to insulate it. We took the top layer and cut it down to form two side pieces that a larger MDF board could be attached to. The larger board homed all of the circuitry while the battery was moved to the middle layer. While it meant that all of the cables and circuits would be exposed, it meant that we were able to get the robot to a position where all of the circuits necessary for its movement and detection could be attached and used.

# 4. Successes

## 4.1 Team View Of Successes

It feels as though we had very few successes in this project but the progress made between the first and final competition was success compared to the previous performance. In the space of a few days, we managed to take a robot that couldn't leave the starting box or reliably follow a line to a robot that managed to cross the ramp, reach the collection box and turn around.

### 4.2 Successes In Respect To Task Specifications

Our failure to be able to pick up any blocks or check for metal means that the only part of the task specific specifications we met is our ability to use the ramp to travel past the obstacle to the collection area and back. Our coil for metal detection could not be mounted properly as our claw was not attached or working.

In terms of the standard specification, we meet quite a few points. These include:

- Modular design and mainly using standard components
- Button to push to start
- Cable colours conform to set regulations
- Robot fits entirely inside start/finish area
- Robot travelled accurately over the ramp to collection area and back
- Had an amber light to signify robot motion

However, we failed to ensure good construction. Some parts are not attached or only attached with glue. Our wires and circuit boards are all on the top plate with very little support or protection.

## 5. Failures

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### 5.1. Design Challenges

#### 5.1.1 Mechanical complexity of claw

The gear system integration with the elevator level proved to house a lot more friction than previously anticipated. It was thought that the pre-made gears with their plastic composition along with the washers and a not too tight a level structure would allow the gears to run smoothly. It was the positioning of the holes that maintained the positions of the bolts that resulted in this complication. The bolts could sometimes rub too hard against the edge of the holes cut. Also, because there was some leniency in the positioning of the holes, the gears could move meaning that the gear teeth sometimes wouldn't properly fit together resulting in not the correct torque being applied to each gear. Sometimes the gears could move far apart enough that they could skip each other which would be a problem when moving the level up a certain amount. If the motor was programmed to turn for a certain length of time to achieve a certain vertical lift then skips in the gears would result in different heights. This error compounded over multiple cycles could result in the claw level being too high to pick up a block or too high that it could collide with the ramp.

#### 5.1.2 Tolerance of manually produced parts

By approximate inspection, there is a tolerance of 10% of any manually produced aluminum parts. This results in issues with fitting (bolting) structural parts together, where there is a lack of symmetry and hence all parts must always be oriented in a specific way. This resulted in problems for the electrical and mechanical subteams as it affected their ability to be able to find ways to install sensors and circuits without making the robot impossible to reconstruct correctly.

Hence, despite not being best practice, we resorted to using a tracing of the realistically produced dimensions in the last stages of production, then making the insulated MDF base plates for electronics, where real dimensions are used in lieu of the theoretical (CAD) dimensions.

### 5.1.3 Sensitivity of metal detection through self inductance

As mentioned in the previous section, the lack of sensitivity of the metal detector led to us not being able to meet the task specifications for blog collection and sorting. Our tests gave different results when it was soldered to the stripboard. This could have been due to unknown stray capacitances in the breadboard, aiding the test results and also maybe loose connections when soldering.

## 5.2. Integration Challenges

### 5.2.1 Bounded by a tight and non-insulated chassis

The mechanical team started work with limited knowledge in how the electronic components, especially sensors, will be mounted. A reasonable course of action would be to allow flexible and versatile space for the electrical team to utilise as amendments are made.

While the ‘lasagne’ structure, stacked upon a compact metal chassis, allows more layers to be added to accommodate more components, if they were to be added, it does not factor in the position and dimension of components attached, especially with regards to the spacing wires. Hence much of the electrical testing happened with components, including the arduino and battery, placed on top of the structure, rather than inside (between the shelf and chassis) as intended, as it is difficult to alter wires when they all pass through the centre hole conduit. This is in addition to the problem that aluminium is a conductor, and hence makes the components prone to faults and even possibly safety hazards (short circuits), making electrical testing inconsistent and difficult.

In hindsight, a ‘lasagne’ structure would be effective as a final prototype or finalised product to retain planar compactness, but not in a short production cycle with rapid prototyping where a single plane construction would be preferable. But even so, the issue of weight distribution when the robot is tilted longitudinally remains a major issue, see 5.2.3.

### 5.2.2 Incompatibilities of Bluetooth and Arduino

The first two weeks were spent attempting to incorporate wireless communications between the Arduino and the computer. While connections to the overhead camera with WiFi were achieved successfully, establishing Bluetooth serial communication proved much more difficult. A variety of challenges were encountered, including:

- The firmware for the ESP32 module onboard the Arduino was out of date and required downgrading to a previous version of a particular library (the WiFiNINA package). This was especially difficult to debug as our knowledge of such low-level systems was extremely limited.
- Apparent issues in serial connections, including faulty USB cables and inconsistent COM port allocation made testing and verification of communications very difficult.
- The firmata protocol we were using, PyFirmata, is poorly documented. We were able to deduce the point of failure within the source code but unable to do anything about it as the errors similarly pointed to very low-level features such as the semaphores of the serial communication system.

### 5.2.3 Weight distribution

As we were using a caster ball for one wheel, we needed to try to keep weight off of it as too much would cause problems with its movement. Shown in figure 7 are early calculations of moments to minimise reaction force on the caster ball, with unknown weight distribution of the claw, where an estimated allowable moment is calculated for the team member designing the claw, which is 215 N mm about the driving wheel. Over iterative testing, we discovered that if too much weight was on it, it would get caught on any slight depression or lip on the table surface, causing the robot to be unable to travel up the ramp. However this weight distribution led to a rather unbalanced robot, especially as we did not have the claw attached which would've provided a necessary counterbalance. This meant our robot had a tendency to tip backwards when it went up the ramp. We would likely not have had such a problem with this if we had not had to change our chassis near the end due to a lack of space and the metal affecting the circuits.

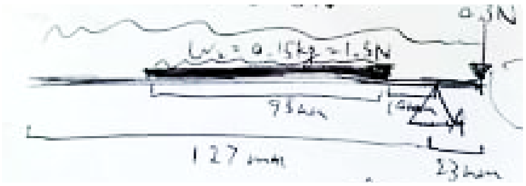


**Fig. 7.** Moment calculations to estimate allowable weight distribution of the claw extension

## 5.3. Avoiding Future Issues

If we were to do this again, we would need to ensure that we set out with a sensible and more disciplined focus. In some areas we started too broad, e.g the variety of sensors, which wasted time that could've been spent improving a concept. In other areas e.g. our chassis, we quickly followed one plan and did not consider adjusting it until far too late and this hindered our progress. If we'd started with a focus at the midpoint of these two behaviours, we could have achieved a lot more and this is something to keep in mind for any future projects.

Another way we could have avoided some of our issues is if we'd had the electrical and mechanical teams working more closely at the beginning. Aiming to ensure easy integration earlier on would've meant that we could have a better understanding of where sensors needed to be placed, where the battery and arduino would need to sit, and how cables could be passed along the robot. This could have allowed us to create a better suited chassis from the start, rather than having to backtrack near the final deadline. Having a sensibly designed chassis at the start would likely have made the electrical and software teams' jobs much easier as they could have tested the robot with components in situ rather than sitting on top of the robot without a designated place.

Laser cutting was a very reliable and repeatable process of manufacture so could have been utilised more. It is a lot more accurate and the designs can be easily manipulated based on how printed prototypes performed in testing. If we didn;t use metal for the entire structure then the need for insulation around the electronics wouldn't have been needed and the structure would have been much lighter so less traction would have been needed to get over the ramp. Thus putting less pressure on the motors to pull the robot over the incline.

Another potential source of failure elimination would be to travel around the ramp and the walls. This would completely eliminate the complexity of going over the ramp and avoiding the lips in the testing area. This would mean the entire claw and elevator mechanism would not be needed and a pushing system could be used reliably. This would be a lot less complex. Although it is unknown to us how easy or hard it would be to follow the wall structure around the walls protruding from either side of the ramp.

We could have also tested the metal detector sooner and worked closer with the software to potentially experiment with the strength of the pulses sent to the coil to make it more sensitive. Taking time to do some research to understand in depth how the metal detector worked would have also aided in helping us decide what adjustments were needed to make it sensitive. To satisfy another specification, we could have also added the LED system for metal detection. The software and electrical teams should have worked closer from the start so that all the coding was not left to the end to debug.

# 6. Conclusions

## 6.1 Technical approaches: learning from fellow student teams

From observing other teams at the competitions and during testing, we realised that they had done extensive testing with integrated components from the start rather than just testing individual electrical or individual mechanical components until the last minute. This would have made our test more effective and would have helped us progress quicker and satisfy more of the specifications. Testing earlier would have allowed us to focus on a specific design earlier and helped us to identify which exact approach was easiest to design and implement within the given timescale.

## 6.2 General Conclusion

Through completing IDP, we have realised the importance of communication and integration between subgroups and the importance of testing and research throughout the project. This is especially important within the preliminary design period. There is also a necessity to have a big emphasis on constantly analysing ideas and considering trade-offs, whilst also having clear goals by constantly referring to the specifications and tasks required for success within the project.