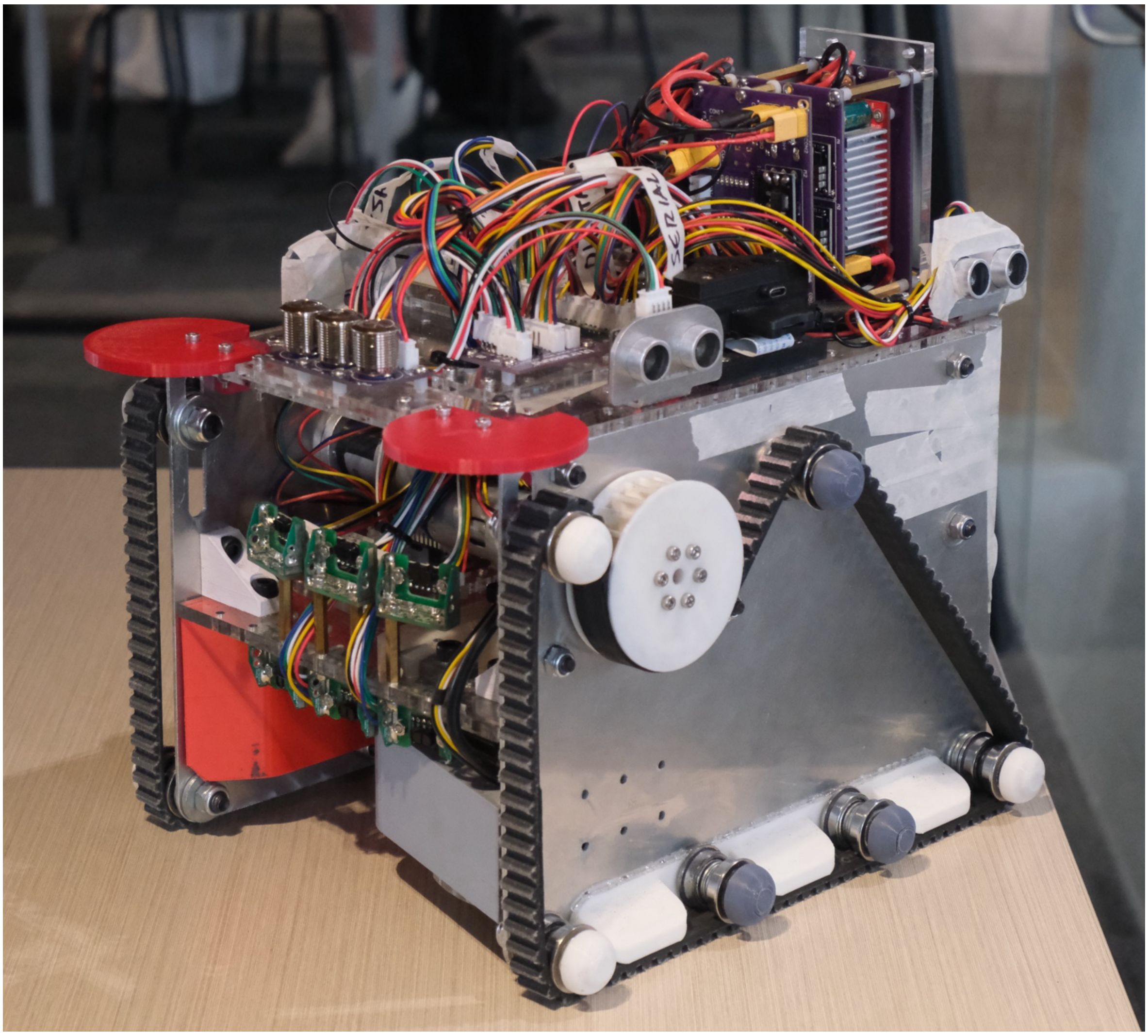
ENMT301 Group 10 Robocup Evaluation Report



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Digby Eele, Eric Kleiner, Jack Edwards

Executive Summary

A sensor-driven robot utilising a Teensy 4.0 was constructed to compete in a competition to pick up turned cylindrical metal weights. Rounds consisted of competing against another robot for two minutes, with the goal of collecting or returning the most weights to the starting location of the match. We placed 6th overall in the competition, collecting 11 weights and returning 5 to our home base. Our robot performed as intended in all but our first round; no parts failed during the competition. We met all but one of our requirements specified in previous reports. The failed requirement specified that our robot should be able to return home in 20 seconds. Being unable to do this ultimately contributed to our elimination, in combination with facing an incredibly competitive robot that favoured the arena and trapped our robot for over a quarter of the round. Improvements were made to our robot, such as enhancing its ability to navigate over bumps, sensor accuracy, and range. These changes were vital to the success of our robot. Our group is satisfied with the performance of our robot, completing many tasks over and above our specification while maintaining a unique and interesting design. Our small footprint required innovation and thinking outside of the box, leading to our incredibly effective weight collection system.

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1. Introduction

The goal of this project is to create a robot to compete in the 2024 Robocup challenge. The competition is constructed in rounds where two robots go head-to-head to collect as many target weights as possible and/or the snitch. After two minutes, the robot with the greatest score wins the round. The competition occurs within an arena containing obstacles, target weights, fake target weights and the snitch. The score is calculated based on the weight of target weights on the robot, twice the weight of any target weights returned to the robot's home base, 3 points per snitch and 0.25 points for any fake weights removed from your score. The design of the robot is constrained by the competition rules, such as the robot being autonomous, running on the supplied Teensy 4.0 and having a budget of $50 over the provided parts.

This report provides a detailed account of our chosen design, justifying and explaining design choices for any changes compared to the robot described in the Detailed Design report [1]. Each system will describe the changes made to the system compared to the robot described by the Detailed Design Report.

The report will also provide an evaluation of the robot in terms of competition performance and compare it to three robots against which it competed in rounds 33, 41, and 60 of the competition, designed by Groups 19, 25, and 27, respectively. Any features that could have improved our robot will also be discussed after comparing the robot to other robots.

2. Design Description

Our final competition-ready robot is depicted on the title page. This robot can search the arena for weights, navigate to weights, determine if they are a target or fake weight and then collect the weight accordingly. If our robot came across its home base while wall following, it would drop off any collected weights in the cover of the home base. To complete this task, our robot largely appears the same as the one presented in our DDR [1]. Using a belt system and servo-actuated door to collect weights controlled by a Teensy 4.0, sensors and timers are used to decide the robots' actions. The first significant change is the addition of more sensors, three more long-range time-of-flight (TOF, VL53L1) sensors, and four ultrasonic sensors (HC-SR04). The second significant change is the addition of two bearing rollers and a track brace at the bottom of each track drive, as well as 3D printing custom drive wheels to match the supplied drive belt.

2.1. Drive Method and Chassis Design

From the initial design concept, our robot has had a low ground clearance. This was to maintain its small size and low centre of gravity, which proved vital to our successful ramp navigation. Our initial design had difficulty navigating the bumps located around the home bases. This was due to the large distance between our two lower bearing rollers. When the bump was between these points, the belt would deflect, placing the robot on its low chassis. The issue could have been fixed by creating larger wheels to place on the bearings, which would have increased the clearance for our chassis. However, due to the design of our collection mechanism, we would have to move the system down to be at the same height so our collection rails would still line up with the weights. As well as this, raising the total height of our robot would affect the sensor position and increase the robot's centre of gravity. For these reasons, we attempted to fix this issue by increasing belt tension, which led to chassis rigidity issues, reducing drive control and speed. Instead, we opted to add two more bearing rollers to each side of the track. Reducing the distance between the rollers lowered the maximum defection. This allowed us to easily navigate the bumps at the home bases, except when we had three weights on board; when this happened, the increased weight deflected the belts too much again, and the chassis would contact the bump, leaving the robot stuck. To fix this issue, a track brace was developed, as shown in Figure 1, to prevent the belt from deflecting between the bearing rollers.

Another change to the drive system was replacing the supplied drive pulleys with 3D printed ones that had matching teeth to the provided belt. The supplied pulleys worked best with the flat side of the belt contacting them, as the teeth were meant to grip the belt's teeth. Using the belt this way worked effectively for testing, as it was reliable due to the strong aluminium pulleys. However, as our robot became heavier with added parts and combined with when it had weights on board, the belts would slip significantly, reducing the top speed and control of the robot. As discussed above, we increased belt tension to try to fix the robot bottoming out. This did improve the belt slip issue but was not worth the trade-off of chassis flex issues and lower speeds. Instead, we designed pulleys to use the provided aluminium shaft collars to ensure a durable rotational interface and concentric, straight rotation while having the correct teeth to grip the belt, as shown in Figure 1.

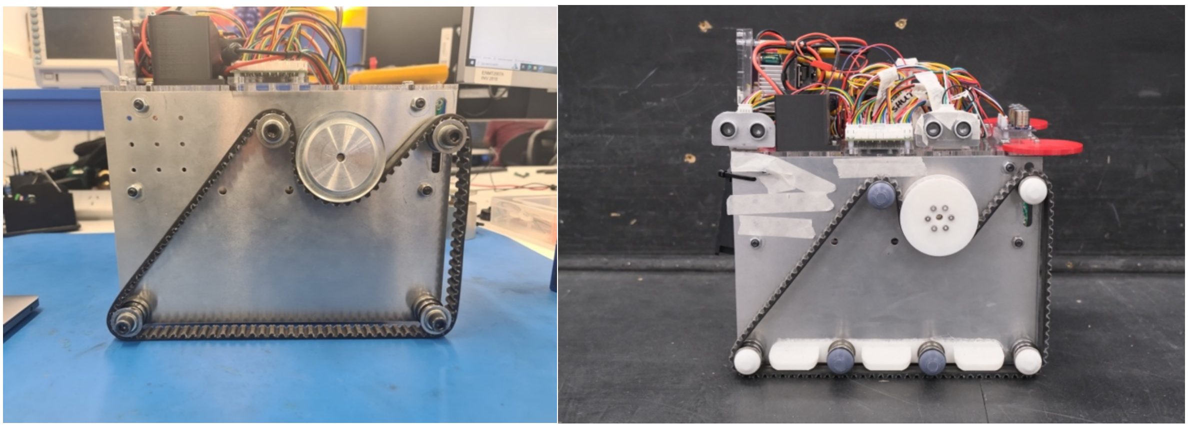

Figure 1 Improvements to Drive System (left before & right after)

2.2. Weight Detection and Navigation

Initially, we planned to use three long-range TOF sensors in a horizontal line and alternate the SPAD arrays between the top and bottom halves of each sensor. This would allow the weight detection to be triggered if the lower half read a distance some tolerance shorter than the top sensor. This works as the weights and the ramp are the only short objects in the arena; all walls and obstacles are orthogonal to the floor and at a specified height. We encountered issues using this strategy as the SPAD arrays do not effectively isolate the region of interest, causing the top SPAD array to detect the weight at closer distances, which prevented the weight from being detected. To resolve this issue, we changed to using six long-range TOF sensors, three horizontally and two vertically; this allowed for more precise positioning of the vertical field of view, as shown in Figure 2. This improved the weight detection up close and improved the consistency of rejecting edges of walls and weights, an issue that used to occur.

Another improvement made to the weight detection sensors was the addition of sensor value filtering by strength. TOF sensors return the distance of the object with the greatest signal strength. For example, when a wall is out of range, the floor is detected with a weak signal strength. A status register does return a different state if the sensor value is below a certain threshold strength, but this threshold is not adjustable in the Arduino library and still returns a short measurement distance. So, in our design, the raw strength value is read from registers, and if it falls below a custom threshold, the sensor distance reading is set to the maximum distance. This prevented the bottom sensor from detecting the floor when no wall was within 1.3 meters. This was a needed fix as it ensured no more false weight detections.

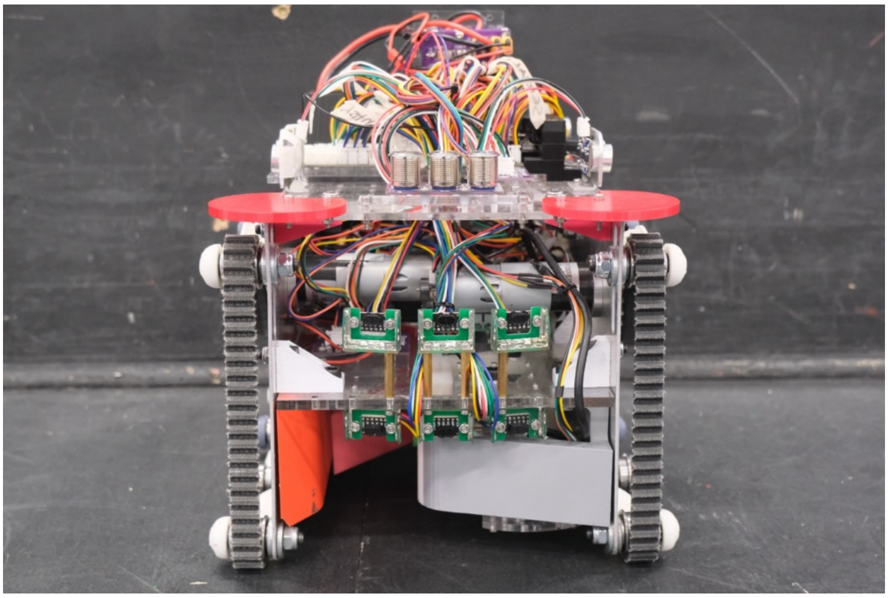

Figure 2 Changes to Weight Detection Sensor Array

2.3. Weight Collection and Drop-off

The method of weight collection and drop off discussed in the Detailed Design Report section 2.3 Weight Collection and Drop-off had only minor changes made to the specific software implementation and the length of the rails, as shown in Figure 3 [1]. The changes in software mainly involved editing the timing of actions and the speed at which the robot would operate when dropping off weights. The alteration to the length of the rails was cutting them a little short of the end to make the drop-off system more consistent, as testing found that it would be inconsistent with the final weight being dropped off at the original length. These changes made the robot faster and more reliable in drop off with no changes made to the weight collection system as it was thoroughly tested before the Detailed Design Report was written.

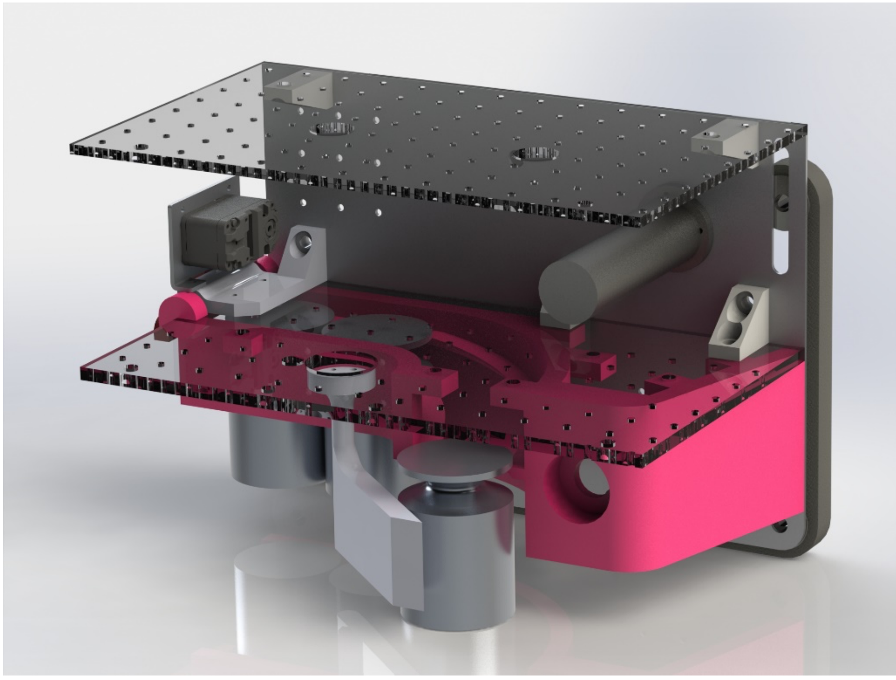

Figure 3 Collection System

2.4. General Navigation

In our last report, we did not yet implement a general navigation algorithm. Therefore, there has been a lot of development in this area. We decided to avoid developing a navigation system that relies on the robot knowing its location in the arena. Instead, for simplicity, general wall following navigation was chosen, with a weight drop off subroutine triggered if we encounter our home base. We did implement the ability to save the heading we started facing to point back towards after collecting three weights before wall following home. But we did not end up using these features in many rounds as depending on the arena it had the ability to get the robot stuck in a loop. Our general navigation process was a conditional priority system where the robot would check every logic cycle and complete the highest priority sub-routine if certain conditions were met, as shown in Figure 4. This system was effective as it assured the robot would only collect weights if it had capacity to do so and was within the arena but also assured weight collection was of high priority interrupt any normal arena navigation.

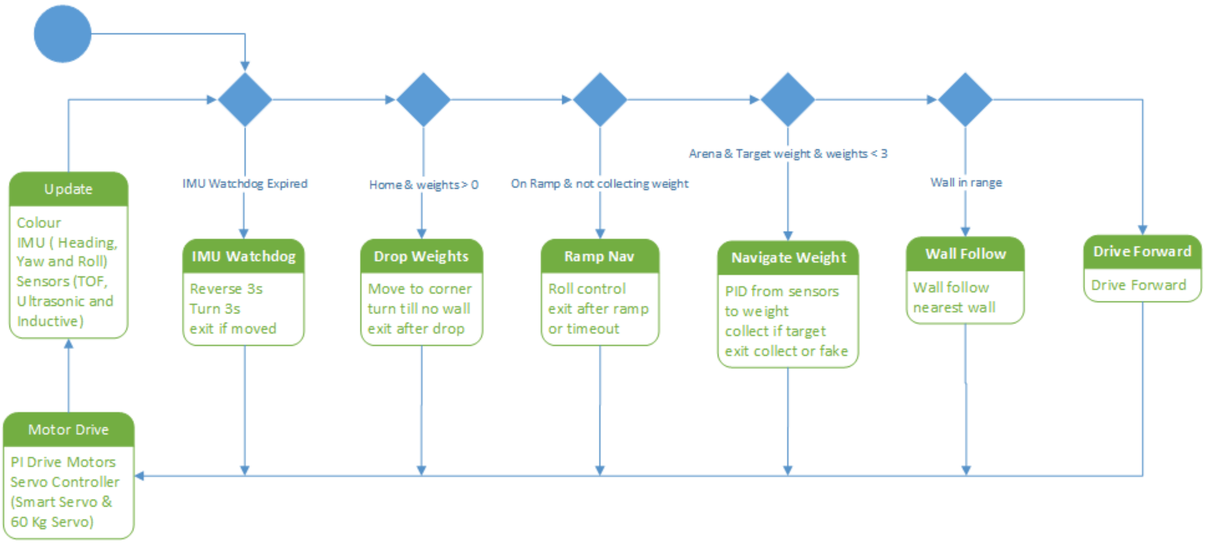

Figure 4 Simplified Navigation Finite State Machine

2.4.1. Wall Following

The implementation uses two PID controllers with a combined output to ensure that the angle and distance from the wall are maintained and corrected. The angle from the wall is calculated by taking the difference between a front and rear ultrasonic sensor that are perpendicular to the direction of travel; this allows for wall following to be consistent, as if only controlling for distance, oscillation is inevitable. Distance is controlled by taking the average of the front and back ultrasonics. Both corrective outputs are tuned and constrained to ensure effective control. When the robot encounters a wall below some threshold on its front sensors that are used for weight detection, it turns on the spot away from the direction of the wall it was last following. This system prevents the robot from getting stuck, as it should always turn until an open space is found. If no wall is detected within some distance on either side of the robot, it travels forward.

2.4.2. Watch Dog Timers

Four watchdog timers were implemented for our robot; the first checks every 150 milliseconds to see if our heading has changed by more than 3 degrees. If it has, the timer is reset to 8 seconds, and the robot's navigation is not interrupted. If the timer expires due to the heading not changing for 8 seconds, the robot will perform a full speed reverse for 3 seconds and then turn to attempt to recover from a stuck position. The watchdog is reset in certain states, such as at the start of weight collection and during weight drop off, to ensure it is not triggered, as the robot can be stationary during these times.

The second watchdog in use was for weight searching and occurred after wall following without seeing a weight for 6 seconds. The robot would complete a 180-degree turn away from the wall it is following, and a 180-degree turn back if it detects a weight. This time, it drives towards using the existing weight detection function. This watchdog proved effective in adding some random behaviour to our robot to ensure it does not get stuck in loops and was able to effectively spot weights in the middle of the arena, which was outside of its field of view when wall following.

Another watchdog timer in use was our return-to-home watchdog. This was a last-minute addition, using heading data to face back towards the home bases every 20 seconds when three weights are on board. This watchdog was supposed to ensure the robot does not spend a large amount of time traversing the back of the arena if it collects its last weight whilst facing away from home. This watchdog had the possibility to produce navigation loops if within a wall pocket facing away from the home base. For this reason, the timer was set to 20 seconds to allow the traversing of features that were blocking the path home.

The last watchdog in use was specifically for ramp navigation, if the robot ramp state, as discussed below, did not change for 5 seconds, the robot was presumed stuck and performed the heading-based watchdog reverse and turn. After this, the ramp state is reset to OFF. This watchdog, therefore, also prevented the ramp state from being stuck ON in the event of reversing down a ramp or falling off.

2.4.3. Ramp Navigation

We implemented the ramp navigation code between the first and second competition days. As we suspected, more use of the ramp after successfully collecting a weight on the ramp and getting stuck on our second traversal. This code relied on the roll data from the IMU to correct for approaching the ramp at an angle, and this worked in testing. Slowing the robot for more precise control. To ensure the IMU data was accurate enough for the 1 or 2-degree roll angles we were correcting for, a calibration process was completed. Including specific movements and angles for the robot to be placed at after achieving a level 3 calibration, this data was stored in EPROM and rewritten whenever the robot was initialised. To trigger the ramp navigation, the pitch angle of the robot was measured, allowing the position of the robot on the ramp to be determined as only certain state changes are allowed, such as OFF to UP, UP to FLAT, FLAT to DOWN and DOWN to OFF, as shown Figure 5.

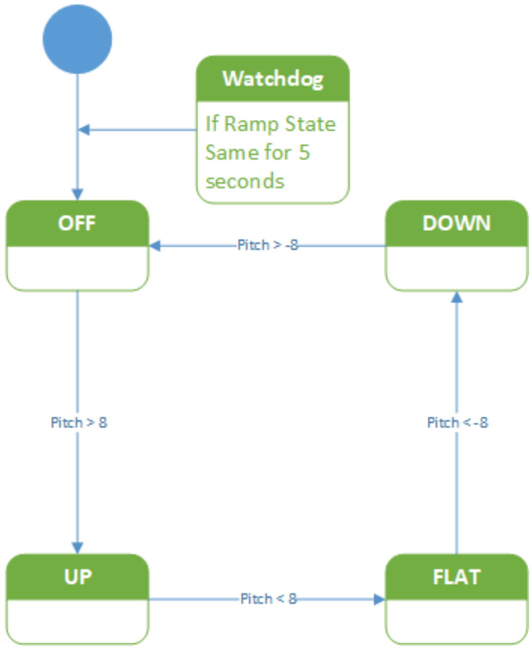

Figure 5 Ramp Finite State Machine

3. Results and Evaluation

3.1 Review and Evaluation

Overall, we came 6th place in the competition, competing in 6 rounds, 5 of which our robot performed well, including the round we got eliminated in. In total, we collected 11 weights and returned five home to our base. This is the same quantity of weights collected by the winner, but they only returned two weights home while competing in 1 more round than us. In our first round, our IMU watchdog failed, causing the robot to move erratically from the start of the round, getting stuck at home base and oscillating the entire round. If this did not occur, our robot would have likely performed much better, possibly winning the competition, as we would not have versed group 27 in the arena we did. When taking the average target weights collected per round, group 27 collected 2.43. This is the highest in the competition. Our robot collected an average of 1.83, including our first round. This is the 5th best of any robot in the competition and would be 3rd best when excluding our first round. As a group, we are satisfied with the performance of our robot.

From the requirements laid out in the Detailed Design report, requirement 1.1.2 required 80% accuracy on identifying metal target weights from plastic dummy weights [1]. This was achieved by using the side-mounted inductive proximity sensor, which allowed for a 100% rejection rate of plastic dummy weights, therefore meeting this requirement. To optimise simplicity and resource use via requirement 1.3, it was decided to totally abandon snitch capture method. This made requirement 1.2 rendered irrelevant. Despite interacting with the snitch in the competition, the robot could not be negatively impacted by catching the snitch, because the final design of the robot totally precluded this outcome. Requirement 1.6 which required the robot to be aware of its location in the arena had the more specific requirements 1.6.1 (To distinguish its home base for weight deposit) and 1.6.2 (To avoid picking up target weights from its own home base or opponent's base) met, we regarded this as sufficient for this requirement as to achieve exact positioning required a redesign of many working systems. These requirements were met using the colour sensor with weight collection being blocked when on either home base. The colour sensor was also able to distinguish between the two bases. Requirement 2.3 required the robot to travel at 0.3 m/s for 2 minutes, which was achieved in the final design, but during the competition, the robot would have achieved better results with a higher travel speed over the recorded 0.34 m/s. This could have been done by creating a different track design which allowed for larger drive track supports which would make the robot be able to travel at a faster speed. As discussed in section 2.1 of this report, improvements were made to the drive system, improving the navigation of the robot over bumps, including the entry to home bases, the ramp, and speed bumps. Requirement 2.1.2 states the successful navigation of these features; without the modifications to our robot, it would often get stuck travelling over the home base bump, especially when carrying weights. This is no longer an issue.

Design requirement 2.2 was not fully achieved. The original target of a 20 second maximum return time to home base could not be achieved. The final implemented return method was heading directed wall following triggered by a watchdog timer. The average return time to home base was found to be about 30 seconds. A future design of the robot could incorporate better arena mapping and return algorithms for a more optimized return path.

The robot achieved the requirements 2.4.2, and 2.4.3 in competition, as it was able to safely operate after various collision events, with no loss of parts.

The incorporation of the IMU into the robot's sensor package resulted in better navigational outcomes, but also created a minor software based "Sensor module fault" --> "branch trapped in loop" fault as shown in the FTA [1]. This fault manifested during the beginning of matches. While sitting on the base, a change in heading was not detected from the moment the unit was powered up, and the unit perceived that it was trapped. The robot's IMU heading watchdog timer never reset, and the robot was commanded to rotate at the home base. It was there for necessary to shake the unit to simulate heading changes before pressing the start button.

3.2 Competing Robot Comparison

3.2.1 Round 33

As shown in Figure 6, the area was configured with an initial horseshoe shaped trap. Both the trap's ends pointed towards the teams' bases with a pipe obstacle in the middle. A back wall divided the back half of the area. The perimeters of these constructions, and the edge of the area created open channels/voids for robot navigation and the placement of area weights. Two sets of fake weights were placed tangentially along the perimeter of the area for easy interception. 5 metal weights were distributed symmetrically around the rest of the arena. Our robot was situated on the green base, and group 19 on the blue.

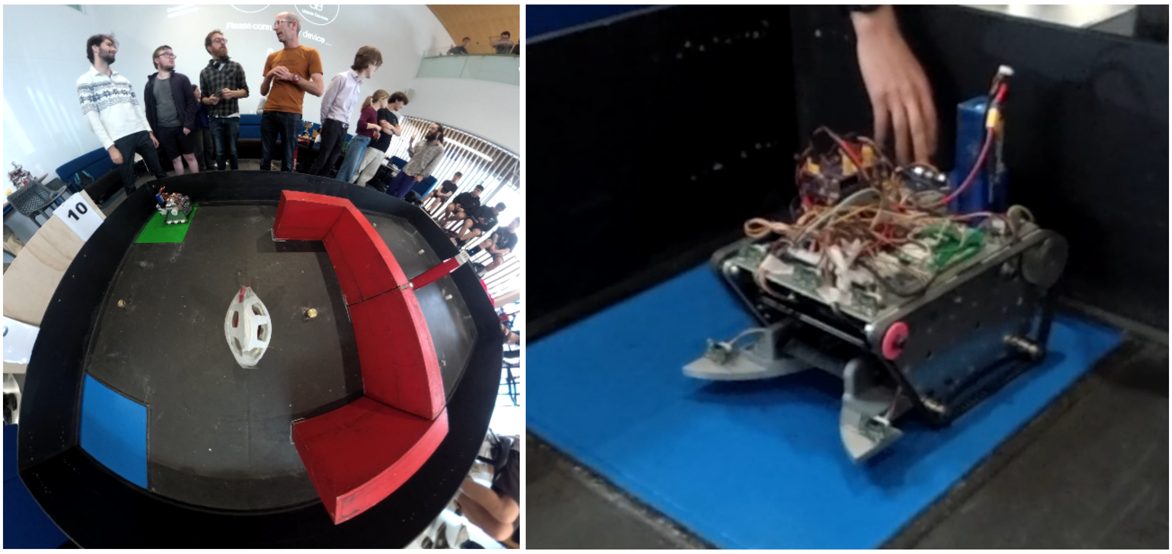

Figure 6 Round 33 arena layout overview and Group 19’s robot. [3]

Group 19’s robot utilized a similar drive train configuration; it could not be determined if tensioner pulleys were used for track tension. It had 3 straight facing top mounted TOF sensors with wide spacing as opposed to our more closely spaced dual layered angled arrangement. It had no rear facing sensors. It also had two forward facing TOF sensors on the front of the collection scoup intake, possibly as a form of weight detection. It didn’t appear to have any watchdog timer code to break it out of repeating navigational behaviour loops, as compared to our robot.

Round 33 was an ideal round for our robot’s performance. After the induced shake to keep the IMU/search watchdog timer from tripping due to lack of acceleration, the robot bolted out of the green home base at its full design speed [3]. After following the left wall, it passed over a fake weight. It then picked up its first weight after 17 s. Having turned right to follow the back wall, it passed over a second fake weight, then collected the second metal weight after 38 s in the far-right corner. Following the right-side wall back, it retrieved the third weight around 1 min 13 s. The weight collection function disabled, and the wall following algorithm and trajectory combination triggered the robot to follow the back of the horseshoe. After a left turn and a pass over the first fake weight, It dropped its contents at home base.

The robot went back out again, passing over the first fake weight. After a period of no weight detection, the robot’s search watchdog timer ran out triggered a left 180° spin/scan at time mark 1:30 seconds. It passed over the fake weight again.

Until this point, Group 19's robot never made it past the horseshoe structure. Its path oscillated between the two bases and the back wall in the form of left hand crescent shaped forward manoeuvres with a pre-planned reverse of the same arc path. Impacts with the wall mixed with forward sensor readings appeared to give variation to this oscillatory behaviour. The scoop TOF sensors were not used for wall detection, as these assemblies constantly hit the walls of the arena. It knocked over and collected one 0.75 Kg weight [2] about 45 seconds into the match [3].

On the return, our robot was blocked and repeatedly impacted for 12 seconds by the other robot at match time 1:44. The other robot backed up as ours initiated a left turn wall follow of the inside of the horseshoe, for the remainder of the match. A weight was missed in the last few seconds of the match. In total our robot retrieved two 0.5 kg weights and one 0.75 kg weight for a total weight score of 3.5 kg collected [2] and returned to the green home base. Basic performance measures are displayed in table 1.

Group 19's sensor spread, placement, and lack of diversity appears to have hindered situational awareness and navigation. Basic or non-implemented programming ensured that no usable arena navigation occurred, and weights were collected by chance. It was not possible to fully analyse the other group's performance characteristics. Neither did it collect a fake weight, nor did it drop any weights off during repeated return arcs to its home base. Despite these differences, Group 19's robot was able to collect weights faster than our unit. It appeared to knock them over and store them in a collection regardless of orientation, with no loss in forward speed due to not having to account for the complexity of a more complicated sorting/ storage mechanism.

3.2.2 Round 41 Against Group 25

The final score of this round was 2.25 to 1.25, with our robot picking up one additional 1kg weight compared to Group 25's robot [2]. The primary reason for our victory was the effective wall-following navigation logic implemented in our robot. Group 25's robot has been pictured in figure 7 in the middle of the round we competed against them.

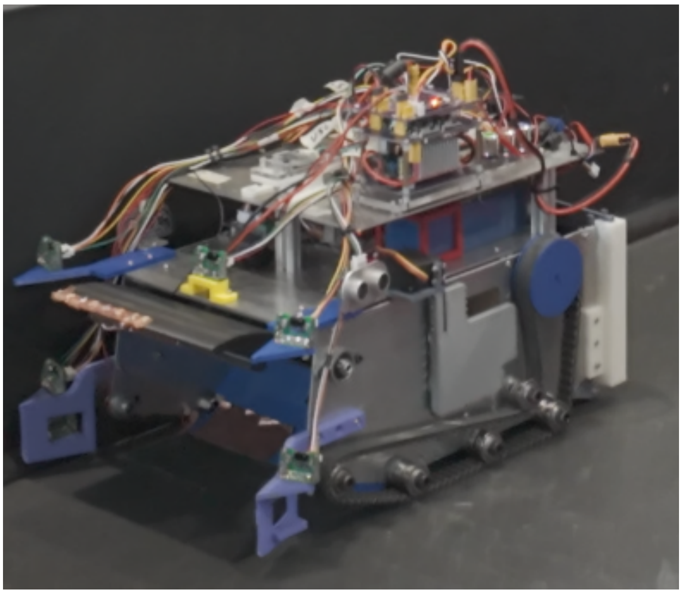

Figure 7 Group 25's Robot in round 41 [3].

The arena was designed to have a passageway along the walls for each robot to follow with 2 target weights for each robot to collect. These side passageways also created a central passageway which had a vertical pipe at each end and another 2 target weights inside. A ramp got place against the back wall of the arena which held 2 more target weights on top of the ramp. Fake weights were also placed on either side before the ramp with a third placed between each groups home base.

The round went as follows; an early tie occurred when both robots picked up the 2 target weights placed in their respective side passageways. This then proceeded with our robot advancing towards the back of the arena pushing a fake weight out of the way before climbing the ramp. This led to our robot partially riding 1 of the 2 weights on the ramp down the other side. Meanwhile Group 25’s robot had some navigational issues resulting in them turning around back through their side passageway and ramming into wall part way through the passageway. After dislodging the weight beneath it, our robot followed the wall through Group 25’s starting passageway. Both robots met near Group 25’s home base. At this point, our robot completed a search watchdog task, while Group 25’s robot struggled to leave its starting passageway. Group 25’s robot then proceeded to fail to detect their home base failing to drop off the weights it had collected. Then Group 25's robot eventually got stuck on the lip surrounding our home base and remained stuck for the rest of the round. Meanwhile our robot continued to follow the wall back to the ramp, where it found the remaining target weight. However, while collecting this weight, it became stuck on the side of the ramp for the remainder of the round.

Our Robot's Strengths included our reliable navigation which allowed it to encounter and collect more target weights, ultimately leading to its victory. Group 25's Robot was faster at picking up weights (3 seconds for us vs. 2 seconds for them), thanks to their claw mechanism. However, their navigational problems and failure to deliver weights to their base cost them the round.

In conclusion despite the faster weight collection mechanism of Group 25's robot, the superior navigation of our robot allowed us to pick up more weights and secure a victory. Both robots ended the round stuck, but the final score was 2.25 to 1.25 in our favour. For more detailed statistics on Round 41, refer to Table 1.

3.2.3 Round 60 vs Group 27

Our round against group 27 was our last. The primary reasons we lost were the lack of a proper return-to-home system and overall slower speed. This was particularly impactful as this arena layout had the most weight of any other arena, which played to the strengths of our opponent. In this round, our robot collected two weights earlier in the round and then was pushed by our opponent onto their home base, where they dropped weights home. Upon leaving the opponent's base, we pushed 2 of the 3 weights they had dropped home out of their base. The time spent trapped by the opponent consumed just enough time to inhibit the return of our robot to its base after collecting its 3rd weight.

Group 27's robot used an encoder on a wheel at the rear of their robot in combination with heading data from the IMU to follow a preconfigured path as shown in Figure 8. To do this, they pre-processed a photo of the arena and placed nodes on weights for the robot to navigate to. This allowed for an extremely fast accusation of weights and a direct return home but prevented it from avoiding our robot when we were on its pre-planned path. The use of the pre-planned navigation and faster drive system allowed their robot to be highly effective in the more open arenas with many weights, such as the one we versed in. I believe they could have won the competition if they did not occasionally over-collect weights. The TOF used to sense the number of weights could mistake 2 stood-up weights for a single flat weight in its collection shoot. This happened in a round before ours, but the robot was able to drop all four weights home, receiving no penalty. This issue led to their elimination one round later when a smaller gap prevented their return home, receiving a penalty for ending the round with four weights on board. If Group 27's robot was given an arena with the specified 400 mm minimum distance, they would have likely been unable to pass through a gap this size or even bigger due to their robot's large width of 360 mm compared to our robot 250 mm, especially when accounting for error in positional data and route planning. For the same reasons, their robot would struggle to navigate the ramp as effectively as ours. I believe in a different arena we could have moved on to further rounds instead of being eliminated. This is due to our ability to navigate more complex terrain.

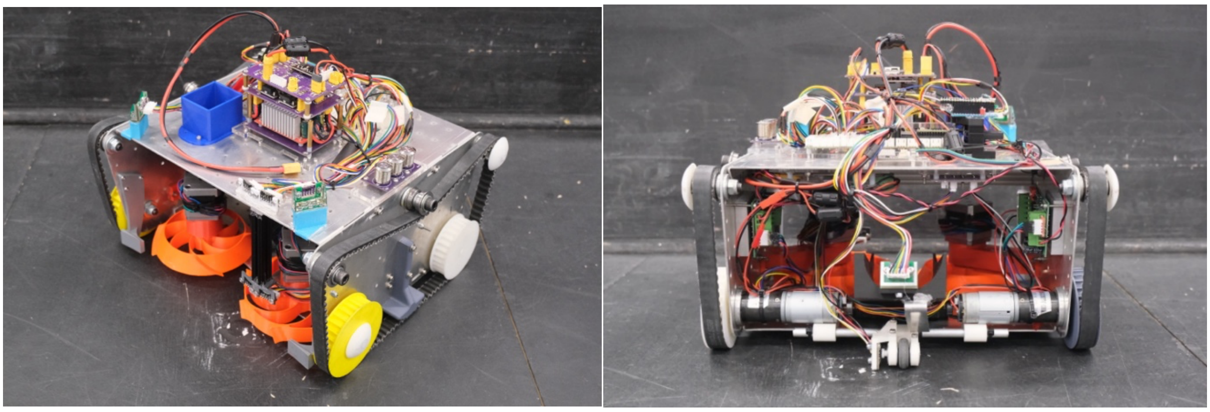

Figure 8 Group 27's Robot

Table 1 Round 33, 41, and 60 Statistics [2]

	Round 33		Round 41		Round 60	
Parameter	Team 10	Team19	Team 10	Team?	Team10	Team27
Ave Collection time [s]	3	0	3	2	3	1
Time Stuck/or in loop [s]	7	32	30	25	34	4
Time searching [s]	65	88	81	91	42	86
Weights collected	3	1	3	2	3	5 – 2 lost
Return to base [s]	31	N/A	N/A	N/A	35*	23
Weights drop off time [s]	8	N/A	N/A	N/A	N/A	2
Weights on home base	3	0	0	0	0	1
Winner	X		X			X

*Round ended before reaching home.

3.3 Post-mortem Summary

Our robot came 6th in the 2024 Robocup Competition [2]. The main reason for our elimination was the lack of proper return home logic which resulted in the robot either getting stuck or lost on the way to home base to drop off weights once it had collected three. This was clear in round 60 where we lost due or robot driving in the opposite direction of the home base after getting trapped by the opponent's robot. This could have been achieved in multiple ways. One way this could be achieve was to implement a system like Group 27's robot had with known path for the robot using an encoder and IMU heading to get an exact position within the arena. This would have then been implemented instead of the wall following method which was used. Another method was to implement a more robust homing logic but due to the time constraints was not able to be implemented leading to the poor homing system implemented for the competition.

4. Conclusion

In conclusion our robot was not fit for purpose when compared to our requirements. As requirement 2.2 the robot should return to its home base within 20 seconds when required was not achieved. Although when looking at the competition results our robot performed well. As it was able to collect 11 weights throughout five rounds returning five weights to the home base. Excluding our first round where the IMU failed causing the robot to get stuck leaving home base. This is the same amount of weights collected by the winning robot and three more than the winner returned home over there seven rounds competed. This led our robot to place highly in the competition which with a more developed homing system or a different opponent in our last round could have led to our victory in the competition. With this improved homing system, requirement 2.2 would have all requirements and would be fit for purpose without question. Other subsystems which could have been improved was developing a new track system with bigger drive track supports resulting in the robot being able to travel faster around the arena. This would result in faster movement meaning the robot would be able to encounter more weights and travel home faster.

References

[1]

D. Eele, J. Edwards, and E. Kleiner, “ENMT301 Group 10 Robocup Detailed Design Report,” Sep. 2024.

[2]

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[3]

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Appendices

Appendix A – Bill of Materials

Part	Part number	Quantity	Material for Manufactured parts	Cost (NZD) per Quantity
TOF Sensor	VL53L1	6	N/A	10
Colour Sensor	TCS34725	1	N/A	14
Smart servo	DRS-0101	1	N/A	58
Large Servo	RDS5160	1	N/A	60
DC Motor 143RPM	28PA51G	2	N/A	70
Low Cost Ultrasound Sensor	HC-SR04	4	N/A	1.80
Internal Passage part 1	N/A	1	3D Printed (PLA)	123.22 (grams)
Internal Passage part 2	N/A	1	3D Printed (PLA)	29.97 (grams)
Internal Passage part 3	N/A	1	3D Printed (PLA)	83.07 (grams)
Internal Passage part 4	N/A	1	3D Printed (PLA)	35.44 (grams)
Gate door	N/A	1	3D Printed (PLA)	10.23 (grams)
Pushing door	N/A	1	3D Printed (PLA)	12.84 (grams)
Smart servo mount (aluminium cutout)	N/A	1	Water Jet cut Aluminium	2.5
Ultrasound Sensor mount	N/A	4	Water Jet cut Aluminium	2.5
Smart servo mount (3d printed part)	N/A	1	3D Printed (PLA)	12.17 (grams)
Chassis left side	N/A	1	Water Jet cut Aluminium	4
Chassis right side	N/A	1	Water Jet cut Aluminium	4
Inductive Proximity Sensor	LJ18A3-8-Z/BY	1	N/A	25
Drive track support hardware	N/A	12	N/A	3
Robot tracks	880-8M	2	N/A	Supplied in kit w/o cost
Main drive wheel	N/A	2	N/A	Supplied in kit w/o cost

Teensy 4.0 CPU	N/A	1	N/A	Supplied in kit w/o cost
Internal mounting plate	N/A	1	Laser Cut Perspex (6mm depth)	9
Top mounting plate	N/A	1	Laser Cut Perspex (4.5mm depth)	6
Structural bracket 1	N/A	2	3D Printed (PLA)	4.52 (grams)
Structural bracket 2	N/A	2	3D Printed (PLA)	3.94 (grams)
Structural bracket 3	N/A	4	3D Printed (PLA)	3.44 (grams)
Battery holder	N/A	1	3D Printed (PLA)	32.97 (grams)
Bolt caps	N/A	12	3D Printed (PLA)	2.06 (grams)
Belt Sleds	N/A	2	3D Printed (PLA)	21.18 (grams)
4000mAh 3 cell LiPo battery	N/A	1	N/A	Supplied in kit w/o cost
Stop Go button	N/A	1	N/A	Supplied in kit w/o cost
Power supply board	N/A	1	N/A	Supplied in kit w/o cost
Motor drive board	N/A	1	N/A	Supplied in kit w/o cost
Smart Servo IO Board	N/A	1	N/A	Supplied in kit w/o cost
Encoder IO Board	N/A	1	N/A	Supplied in kit w/o cost
Digital level shift IO Board	N/A	1	N/A	Supplied in kit w/o cost
Inductive level shift IO Board	N/A	1	N/A	Supplied in kit w/o cost
Ultrasound IO Board	N/A	1	N/A	Supplied in kit w/o cost
Assorted fasteners (nuts, bolts, washers)	N/A	100+	N/A	Supplied w/o cost
Total Filament		500 grams supplied	3D Printed (PLA)	437.67 (grams)
Total Cost				457.58*

*This is the total cost of the robot including any cost give to the parts supplied by the kit with the cost for items not included in the kit being 3 extra VL53L1 costing $30 NZD total.