UNIVERSITY OF CANTERBURY

ROBOCUP 2015

DETAILED DESIGN (DDR)

Progress Report 2

Authors:

Group 6

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Executive Summary

This report presents the detailed development of the chosen design for the 2015 UC RoboCup competition. It considers all the necessary overall design systems that were implemented and required to produce the finished design.

The systems for navigation and identification, layout and locomotion, package collection and software were all considered. The interdependencies existing between these systems are shown and reasoning for choices made, along with the choices themselves, are explored in the overall design description in Section 2.

For each of the main systems an evaluation was carried out to determine how well the design met the required specifications for the project. Various tests were performed and performance metrics recorded to provide numerical estimates of the robot's ability. In regard to battery life it was found that the robot could theoretically run for three 5 minute rounds on a single battery. The main strength found in this section was the ability for the robot to successfully hone in on weights, having a collection success rate of 95% and taking only 2 or less iterations in all but extreme cases. Conversely, the design fails in respect to collecting weights which are either on their sides or placed in a corner between two walls.

Proposed and planned future developments are laid out in the final section of the report.

Table of Contents:

1. Introduction

This report addresses the methods taken and issues faced when designing an autonomous robot able to navigate an arena and collect weights in the 2015 University of Canterbury RoboCup Challenge. Included in the navigation is the detection and avoidance of walls and a variety of obstacles. Furthermore, the robot should have the capability of storing the weights and returning them to a colour-coded home base. The contents of this report document both the design and evaluation of the robot built to complete these tasks by means of focusing on the sub-systems that make up the robot. Itemized, these include the navigation and identification, the layout and locomotion, the package collection and the software.

The detailed design description section covers the implementation and methodology behind the four primary systems listed, as well as reasons for decisions made. In this section it is important to note that due to previously unforeseen complexities in manufacturing the original designs from the Conceptual Design Report (CDR), changes were made. A large portion of the pick-up and storage systems were redesigned to conform to the resources available, and therefore only vaguely mirror the turntable design chosen from the Conceptual Design Report.

Following that, the design evaluation considers various performance metrics associated with the overall systems and analyses how well the current design meets the requirement specification set out in Progress Report 1. This section predominately consists of relevant execution times, success rates and calculations that reflect the subsections stated above. This section proved that only a small number of unnecessary requirements were not met. These requirements, as well as any desired future changes to the design are discussed.

2. Design Description

2.1 – OVERVIEW

The segmented design of our robot's operation is shown below in the Functional Flow Block Diagram Figure 1. This outlines the logical progression of the robot as it functions, with increasingly specific and complex ideas broken down into descending modules. Each discrete event is linked logically inside its own block in the diagram. This behaviour was implemented through the use of a state machine and priority based scheduler, which will be analysed in further detail in Section 2.5.2. A full Bill of Materials for the design can be found in Appendix A.

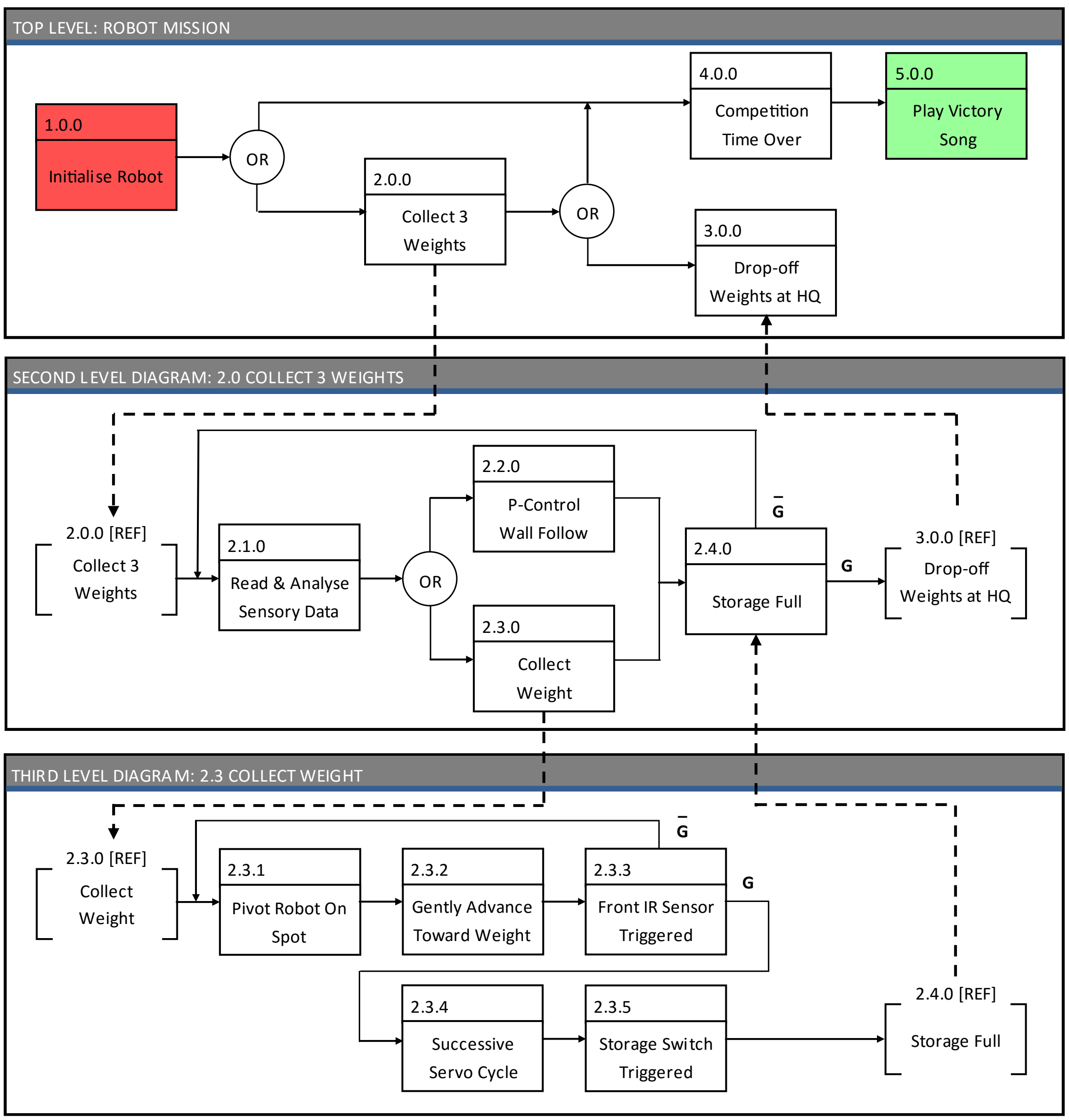


Figure 1: Functional Flow Block Diagram of Robot

In relation to navigation, analogue infrared distance sensors were used to provide the robot with basic arena awareness. Digital infrared detect sensors were used to cover blind-spots, and together enabled basic navigation and obstacle avoidance. Paired with the infrared distance sensors were two ultrasonic sensors that were used to detect weights in the arena. These were the primary sensory inputs for the overall design, and were processed in the software to produce the required output at any given time. The key dependencies and relationships between each system in the overall design are summarised in the N^2 diagram shown in Figure 2.

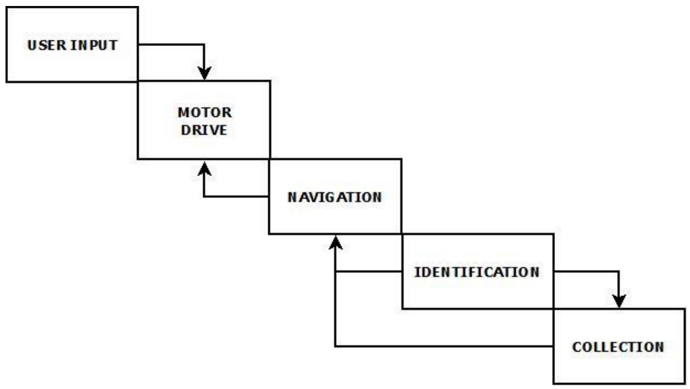


Figure 2: N^2 Diagram of System Dependencies

2.2 – NAVIGATION & IDENTIFICATION

The primary inputs to the robot originate from the arrangement of on-board sensors. These inputs are used to control the movement, detection, and avoidance algorithms of the robot thus the sensor array module will be considered in isolation. This module can be broken down into various sub-systems split up over the length of the robot, as illustrated in Figure 3.

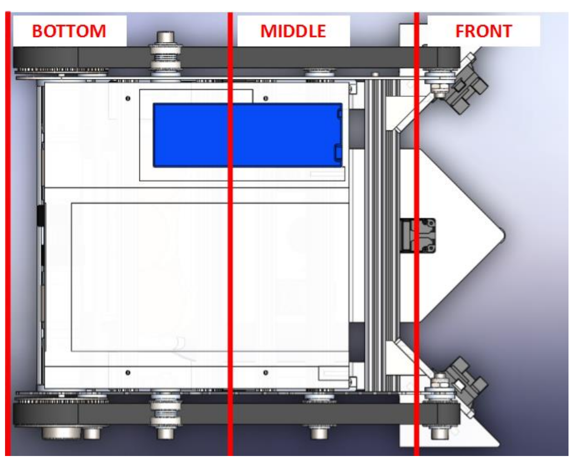


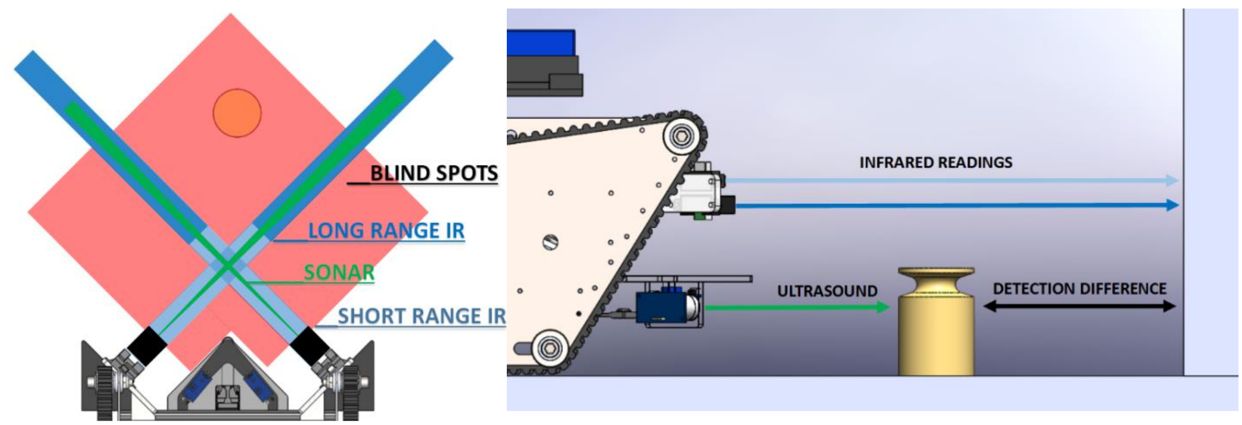
Figure 3: Sensor Breakdown

The front sub-system contains infrared and ultrasound sensors used for both wall-following and weight detection while the middle tier uses infrared sensor switches for blind-spot avoidance. Lastly the third (bottom) tier uses a colour sensor for base detection.

2.2.1 FRONT SENSOR ARRAY:

This subsystem is situated at the front facing end of the robot and consists of four infrared sensors (two short and two long) and two ultrasonic sensors. Difficulties faced when arranging this subsection included both the dependence on avoiding arena obstacles and identifying weights as well as avoiding contact with the pickup mechanism (discussed later in Section 2.4.1).

Firstly, all sensors were mounted at an angle of $45°$ from the horizontal in a cross-over fashion. It was found that a $45°$ 'cone-type' vision produced the best results for both manoeuvring and weight detection. This is due to the property of a $45°$ where both horizontal and vertical distances from the origin are equal, so sensing distances favour equally both the side and front of the robot. The symmetrical layout also ensures that the system's behaviour is identical be it in a clockwise or counter-clockwise state. Additionally, crossing over the sensors reduced the large blind spot in front of the robot which was appointed high priority as the robot will be traveling forward for the greater part of the competition. The resulting layout can be seen in Figure 4a.



(a) (b)

Figure 4: Front Sensor Identification Layout

The short (4 - 30 cm) and long range (20 - 150 cm) infrared sensors were paired up and mounted vertically. For ease of programming and sensor accuracy, both sensor values were processed to give a continuous infrared range (4 - 150 cm) for use in the control systems. A weighted average was used for the 10 cm overlap between the long-range minimum distance and the short-range maximum distance. This was done to provide consistency in sensor readings. Additionally, these sensors were restricted to 80% of their maximum sensing distance as they provided a narrow, accurate field of vision.

Conversely the ultrasonic sensors were restricted to 60 cm for detection. This was done due to the prominent spread these sensors were found to have, especially at greater distances. The raw values read up to 200 cm, but at this range the spread well exceeded the width of any weight, and was therefore restricted to a distance at which detection was consistently reliable. 60 cm was found to be the optimum distance for maintaining an acceptable level of accuracy while reducing false echo readings.

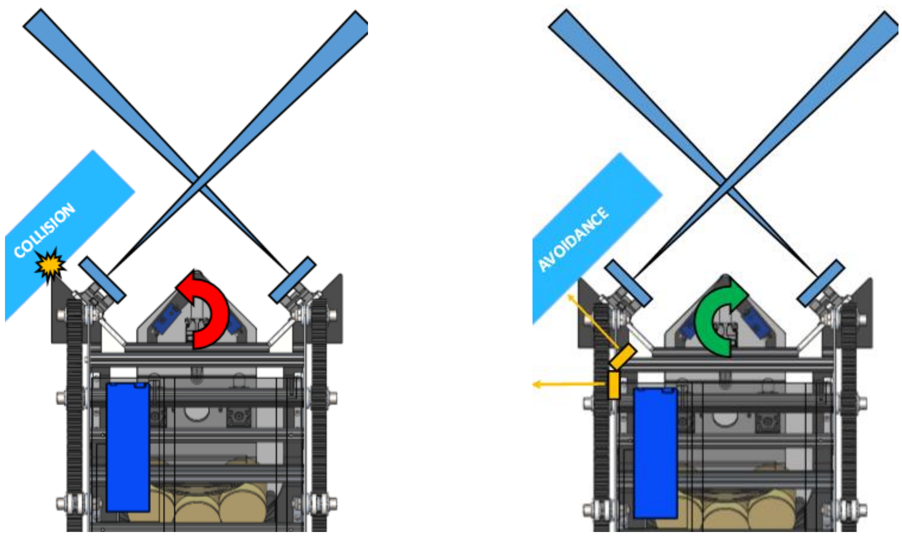
Having a vertical arrangement between infrared and ultrasound increased the accuracy in the comparison between sensor values. The infrared sensors were mounted at a distance of 10 cm off the ground, while the ultrasounds were mounted 3 cm off the ground. As weights can only be identified by the low-lying ultrasound sensors, the ultrasound readings were compared with that of the infrared's so that a weight would be detected if the difference exceeded a certain tolerance. The tolerance was selected at 4 cm as this gave a suitable trade-off between identifying weights located close to the wall and falsely identifying a weight. This detection behaviour is shown in Figure 4b.

Additionally, a 'de-bouncing' algorithm was implemented so a weight is correctly identified when 15 correct samples were taken sequentially. This sample number was chosen to be sufficiently low to produce a reasonable detection response time, whilst also maintaining a sufficiently high value to counteract false triggers. Figure 5 shows a graph of the samples taken against the corresponding response time, and the relevant regions of inaccuracy and sluggishness in response.

Figure 5: Weight Detection Response Time

2.2.2 MIDDLE SENSOR ARRAY:

This subsystem uses four infrared distance detection sensors mounted to the given Perspex board. The blind-spots in the top sensor subsystem (seen above in Figure 4a) caused collisions when the robot attempted to manoeuvre narrow obstacles removed from the wall using the wall-follow algorithm. Figure 6a below shows this behaviour. To neutralise this, two infrared sensors were mounted on each side at angles of 45° and 90° from the robot. These were set to trigger at a distance of 10 cm away from either wall or obstacle, and initiated an outwards 45° pivot, as shown in Figure 6b.



(a) (b)

Figure 6: Middle Sensor Blind Spot Correction

2.2.3 BOTTOM SENSOR SUBSYSTEM:

The bottom subsystem has a rear-mounted colour sensor 5 cm off the ground that is used exclusively for base detection. As this is positioned at the rear of the robot, base recognition is delayed as the robot must drive over the base first to trigger the sensor. Furthermore, it was found that the colour sensor had a significant execution time, so the frequency at which it was called in the scheduler was reduced significantly (seen in Section 2.5.1). This helped optimise the system as it decreased the overall load on the software without any noticeable loss in performance as the colour sensor does not require a high frequency.

2.3 – LAYOUT & LOCOMOTION

The locomotion system used consisted primarily of the robot chassis, tracks, and two given 28PA51G DC motors that were used to drive it. Initial considerations for this subsystem included the robot orientation, and it was decided that a right-way up chassis would be used. This gave the robot a smaller overall footprint, and proved to be more effective at navigating and overcoming obstacles.

In addition to the stock-chassis arrangement, an extra hub was placed at the middle of the bottom tracks to overcome cases where the robot became stuck on the speed-bumps and bases. As the robot manoeuvred over the HQ border (25 mm speed bump), it was noted that a slipping condition occurred at the tracks. Considerable track sag lead to the weight of the robot being transferred to the speed bump through the chassis itself rather than the track. Therefore, an additional hub was placed between the existing two, giving more forced contact between the track and speed bump. This led to more efficient operation as less time was spent in stalled operation. Furthermore, the robot manoeuvred bumps 100% of the time with the simple hub addition. Illustrations of this can be seen in Figure 7.

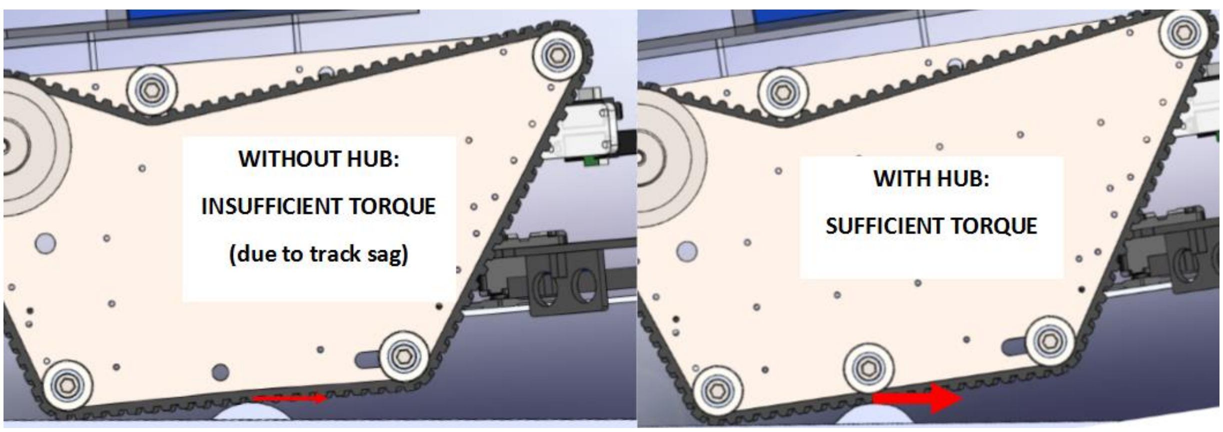


Figure 7: Chassis Orientation & Track Slip Condition

Figure 8 below shows a rendered image of the main structure of the chassis used.

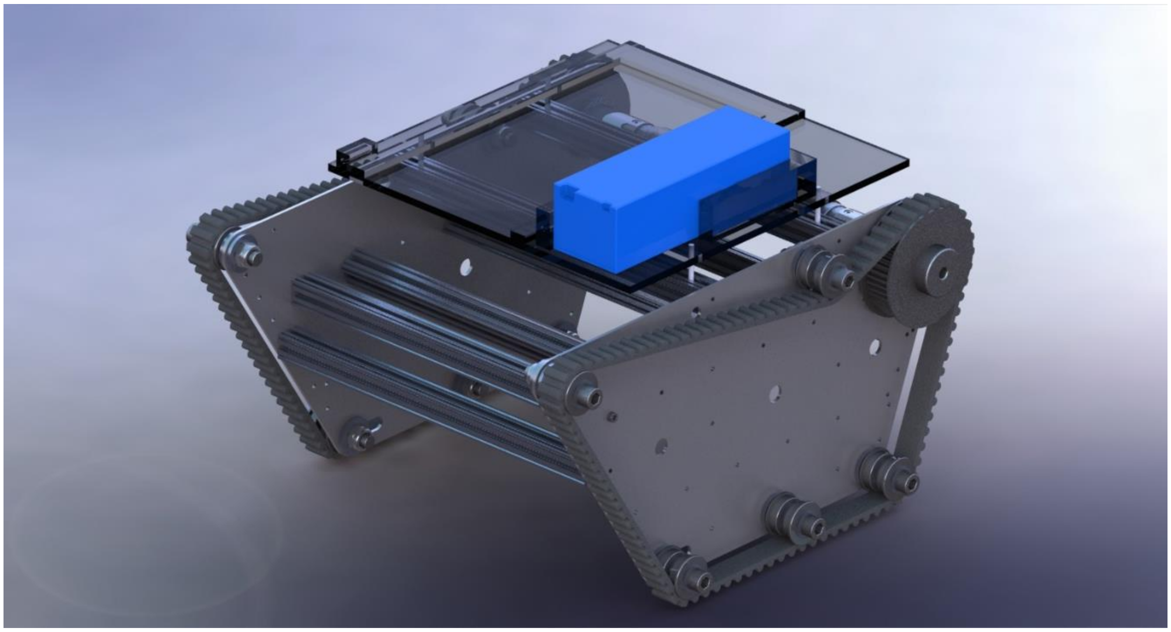


Figure 8: Rendered Image of Main Structure

2.4 – PACKAGE COLLECTION

The package collection system consists of all components used in the collection of packages, transmission to the storage bay and distribution to the HQ. As discussed in the introduction (Section 1), the pickup mechanism selected in the Conceptual Design Report (CDR) was completely redesigned due to the complexity of the build. A similar funnel, rail-type and sweeper arm pick-up mechanism was retained whilst a more robust storage mechanism was defined (in Section 2.4.2). The two primary subsystems described in this section are the pick-up mechanism, and the storage.

2.4.1 PICK-UP MECHANISM:

The pick-up subsystem comprises of a funnel mechanism to line the groove of the weight to the two identical Perspex ramps for delivery into the storage bay, and a series of Herkulex DRS-0101 Smart Servos for actuation. The weight is confirmed as aligned when triggered by infrared detection sensors which begins the series of sweeper arm movements. A rendered image illustrating the overall mechanism is shown in Figure 11 at the end of this section.

A double-funnel was used to maximise the amount of frontal area with the capability to pick up the weight. This reduced the accuracy required in the alignment process as all weights are naturally pushed into the ramp when driving forward. It was observed that a single funnel level aligned with the groove of the weight (60 mm off the arena floor) caused the weight to occasionally topple over at high speeds. It was decided that a secondary funnel would be added directly below the upright weight groove. This funnel aided in the alignment of the weight by pushing at the centre of mass, causing the weight to slide forward when traveling too fast. Figure 9 shows an array of weights and their paths that could successfully be picked up with the chosen design.

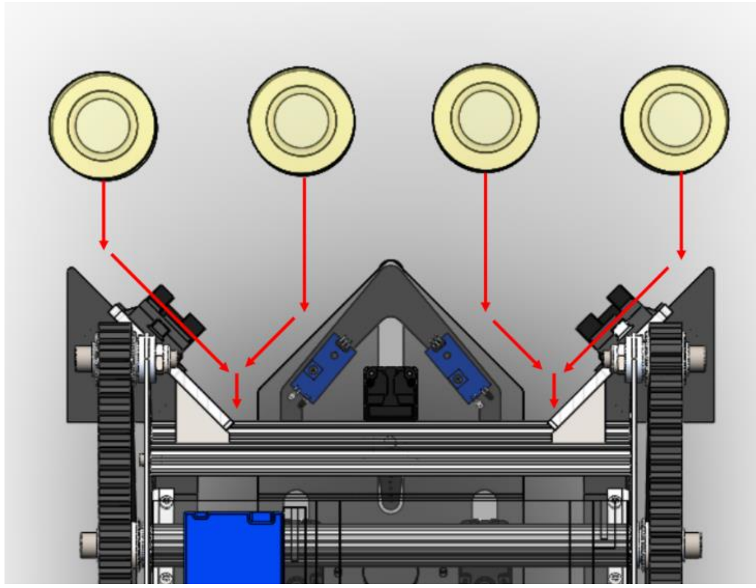


Figure 9: Path of Collected Weights against Funnel

A digital sensor switch is used to determine if the weight is in the correct position, which prompts the series of sweeper arms. Two infrared sensor switches were positioned (left and right) as seen in Figure 10 and adjusted to trip when a weight is ready to be collected. A single centre-aligned front sweeper was triggered by either the left or right infrared sensor switches, and swept the weight up the ramp in the corresponding direction. Following this initial sweep, the secondary sweeper chain initiates and pushes the weight back into the storage bay. Two independent sweeper arms were chosen over another single sweeper arm to give more freedom for electrical circuitry central to the robot. Figure 10 identifies the point of detection for the weights along with the approximate sweeping paths of the respective sweepers.

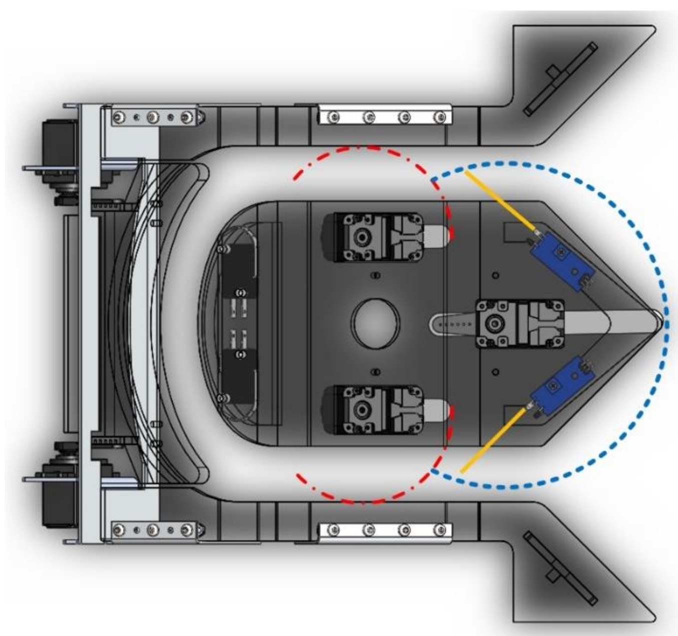


Figure 10: Sensor Switch Detection Zone & Sweeper

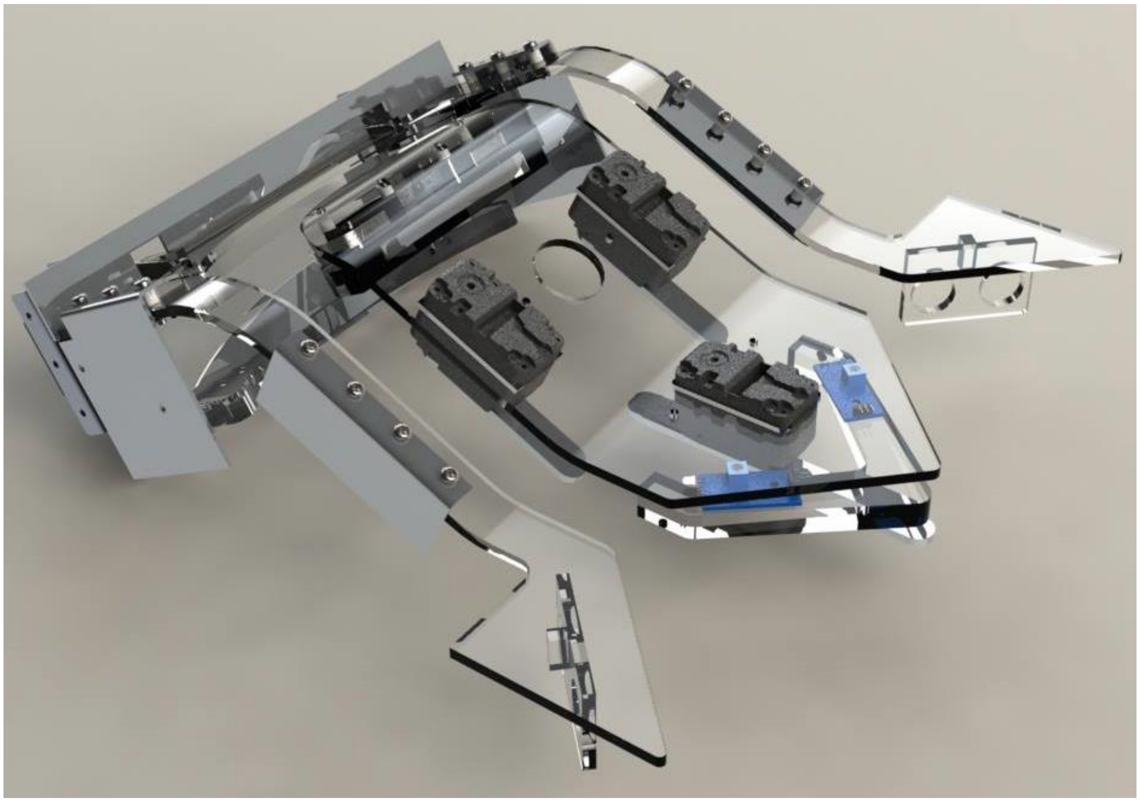


Figure 11: Rendered Image of Pick-up Mechanism

2.4.2 STORAGE & DISTRIBUTION MECHANISM:

The storage system consists of a back-angled sheet and an actuated flap on which one side of the weight's groove rests on. Directly following the sweeper arms, the ramps drop into a $-30°$ angle where the weights slide into an elliptical holder from both sides. The inside ramp piece disconnects with the angular grove, leaving the holder acting as a cradle supporting the weight at three locations. The cradle extends over the majority of the width of the robot, allowing for three weights to be held simultaneously.

When arriving at the HQ, the back flap drops out leaving no vertical forces to support the weight. The entire flap is supported by two HXT12K servos on parallel axis behind the supporting slope which pivot downward to release the packages. The weights slide down the $-30°$ slope onto the HQ floor. Simultaneously, the robot drives the main DC motors backwards, leaving the weights lying horizontally at the HQ and an empty storage system. The servos then return the flap to its original position, parallel with the supporting ramps allowing for more packages to be collected. An exploded view of the subsystem is shown in Figure 12.

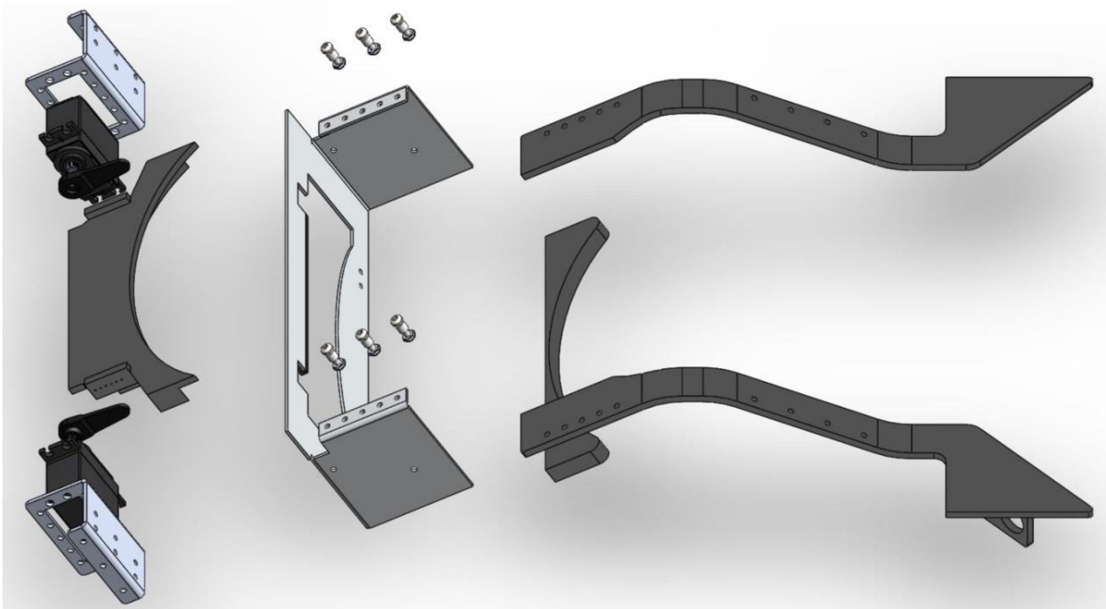


Figure 12: Exploded View of Storage Subsystem

2.5 – SOFTWARE

Although not included in the previous design report, it was decided that a large priority in the software design process was to uphold a neat coding style and efficient scheduling algorithm. This was in order to maintain a readable structure for other users of the code (team members) and was fulfilled through a consistent styling structure (Dr Michael Hayes, coding-style (MPH, Mar2008).pdf). This section will describe the methods take to develop the software through the use of scheduler and Finite State Machine (FSM) subsections.

2.5.1 SCHEDULER:

As this robot is required to operate in real time, tasks were assigned for the CPU to complete and were managed using Arduino's in-built micros function. The code is split into five modules, each reflecting the subsections of this report; sensors.ino, drive.ino, servos.ino, states.ino and main.ino. Each of these modules contains a necessary task(s) called by the scheduler as shown in Figure 13.

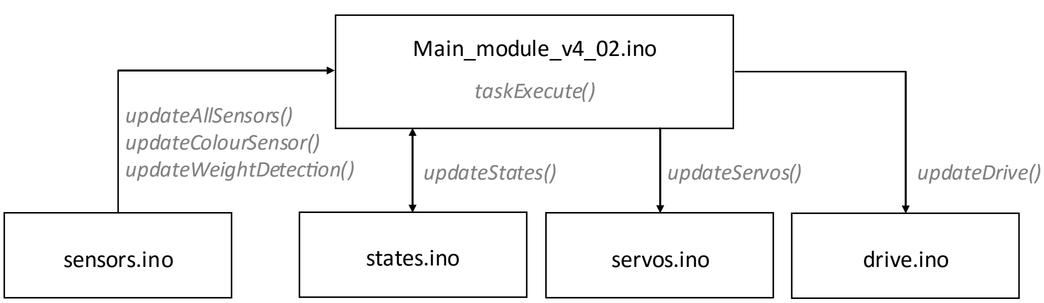


Figure 13: Code Modulation & Task Functions

Each task was prioritised (0 being the highest) and given a required frequency as seen in Table 1. It was noticed that the ultrasound sensors gave large fluctuations in execution times of the *updateAllSensors* function. This is due to the ultrasound echo pin delaying all operations until a signal is received. If no signal is received (i.e. no object is in range), the function 'hogs' the CPU for a dedicated amount of time resulting in an extended reading. Additionally, the interrupts included in the servo library affected the duration of all functions. Table 1 shows the averaged values of all task execution times.

Table 1: Task Execution Frequencies & Durations

Tasks		Required Frequency, F [Hz]	Execution Time, T [μs]	Priority *(0 = highest)*
Description	**Function**			
IR & Ultrasound Sensors	*updateAllSensors()*	20.0	18271	0
Weight Detection	*updateWeightDetection()*	20.0	64	1
State Machine	*updateStates()*	12.5	32	2
Drive Main Motors	*updateDrive()*	12.5	300	2
Drive Servos	*updateServos()*	6.7	21	3
Colour Sensor	*updateColourSensor()*	2.5	52290	4

The required task frequencies are managed using a priority based scheduler. This scheduling algorithm was chosen as it provides faster response times for the higher priority tasks and it accurately controls the rate of tasks. An illustration can be seen in Figure 14 describing the mechanics of the scheduler.

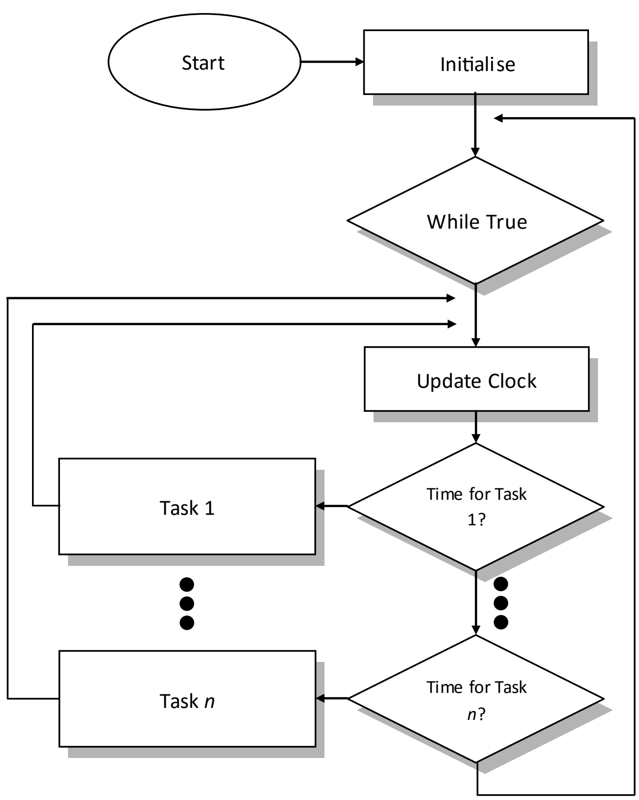


Figure 14: Scheduler Implementation

2.5.2 STATE MACHINE:

The primary drive system implemented was a proportional wall-follower algorithm. A specified distance from the wall was chosen and converted through trigonometry to an equivalent distance apparent to the front infrared sensors. This system sought to maintain a constant forward distance at a specified distance from the wall, and did so by in real-time varying the left and right track drive speeds depending on the controller error. This method made movement more efficient by minimizing any pure rotation in the majority of its operation. Furthermore the robot dealt with extreme situations by going into a full rotation mode in cases of extreme closeness, and arcing in cases of extreme distance. The overall controller behaviour is shown in the state diagram in Figure 15.

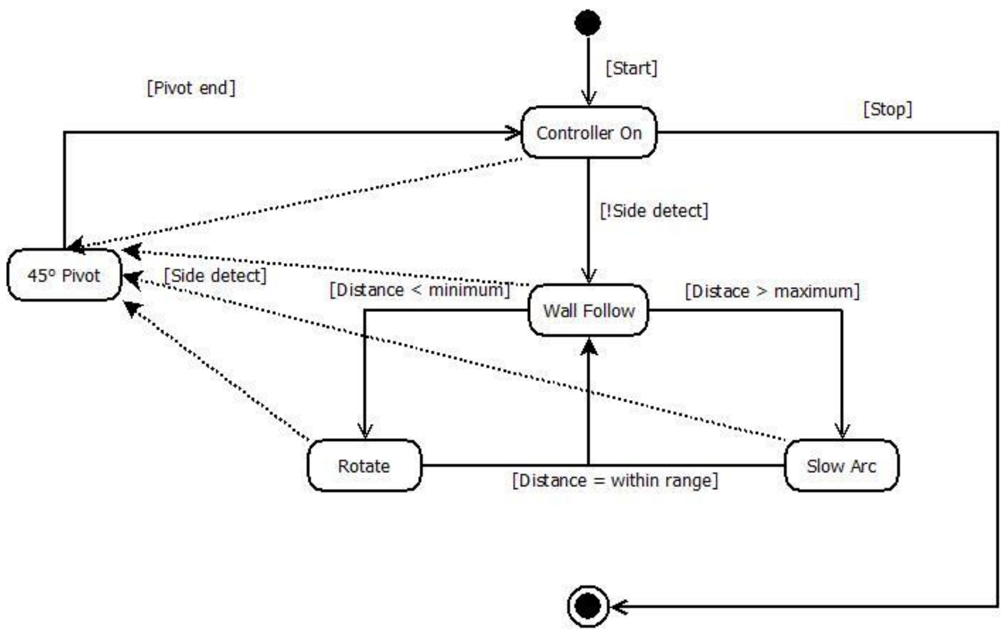


Figure 15: Driving State Machine

In cases of obstacle avoidance, the front-sensors enter a blind-spot as the robot attempts so wall-follow around obstacles. To fix this, the side infrared detection sensors made the robot enter a 45° turn state when triggered. This behaviour is also shown in the state diagram above.

2.5.3 CIRCULAR BUFFERS:

When working with the ultrasound and infrared sensors, it was found that they were prone to noise and exhibited a noticeably level of variation in readings. As the output, primarily the motors, relies directly on the accuracy of these readings, a moving averaged was implemented to eliminate some of the noise. This was done by using a circular buffer averaging over the most recent 3 samples of the sensors. For ease of programming, a circular buffer library was used that, based on the period of execution for sensor reads of 50 ms, averaged the values over the previous 150 ms at the point of a new reading.

3. Evaluation

3.1 – OVERVIEW

As a whole, this current design model has performed all of the tasks required in the First Functionality Assessment, as well as many of the demands that were set in the Conceptual Design Reports' Requirements Specification. The full details of that Specification and the current success state of the design outlined in this report can be found below in Table 2.

Table 2: Success of Requirement Specifications

1 - NAVIGATION:	
REQ 1.1 The robot shall navigate about the obstacles including:	PASS
REQ 1.1.1 Gaps in walls no smaller than 0.5m.	PASS
REQ 1.1.2 Vertical pipes and walls.	PASS
REQ 1.1.3 Speed bumps and ramps no larger than 25mm high.	PASS
REQ 1.1.4 The opposing robot in arena.	N/A
REQ 1.2 The robot shall navigate toward an identified package.	PASS
2 - IDENTIFICATION:	
REQ 2.1 The robot shall identify:	
REQ 2.1.1 Both upright and fallen packages.	PASS
REQ 2.1.2 Both home and opposition HQ by colour detection.	PASS
REQ 2.2 The robot should identify the opposing robot in the arena.	N/A
3 - EQUIPMENT:	
REQ 3.1 The robot shall be fully autonomous without human intervention neither physical nor via software.	PASS
REQ 3.2 The robot shall be controlled by an Arduino Mega ADK.	PASS
REQ 3.3 The robot shall operate on one battery for a minimum of 5 minutes.	PASS
REQ 3.4 The robot shall have a defined front end.	PASS
REQ 3.5 The robot shall incorporate a watchdog timer to identify malfunctions.	FAIL
4 - SAFETY:	
REQ 4.1 The robot shall include a power cut-off module between the battery and any electronics.	PASS
REQ 4.2 The robot shall not include:	
REQ 4.2.1 Lasers above 5mW.	PASS
REQ 4.2.2 Voltages exceeding 100V DC.	PASS
REQ 4.2.3 Spinning devices above 200rpm without guarding.	PASS
REQ 4.2.4 Chemically explosive devices.	PASS
REQ 4.3 The robot shall not cause deliberate damage to the opposing robot.	PASS
5 - PACKAGE COLLECTION, STORAGE & DISTRIBUTION:	
REQ 5.1 The robot shall have no more than 3 weights on-board while main drive motors move.	PASS
REQ 5.2 The robot shall be able to collect a maximum package mass of 1kg.	PASS
REQ 5.3 The robot shall navigate with a maximum load of 3kg.	PASS
REQ 5.4 The robot shall be capable of releasing packages.	PASS
6 – COST:	
REQ 6.1 Further components to the given parts shall not exceed $50 NZD. Additional resources are given including:	
REQ 6.1.1 200 g of 3D printing material. Additional material will be charged at 5c/g.	PASS
REQ 6.1.2 $5 per person to accommodate for printed circuit board components.	PASS

3.2 – BATTERY LIFE

Due to the minimal amount of components on the design, battery life has not limited the robots' performance. Through energy analysis, the minimum battery life was calculated and shown in Table 3. As stated in REQ 3.3;

> ***REQ 3.3:***
> *The robot shall operate on one battery for a minimum of 5 minutes.*

Table 3 below summarises battery life estimation for the chosen design, and the computed value of 15 minutes, 48 seconds far exceeds the Specification Requirement 3.3 value of 5 minutes.

Table 3: Battery Life Estimation

Components			Total Power (W)
Description	**QTY**	**Part No**	
DC Motors	2	28PA51G	86.4
Smart Servo	3	DRS-0101	18.0
Standard Servo	2	HXT12K	5.4
Controller	1	Mega ADK	25.0
Sensors	N/A	N/A	Negligible
Power Consumption			**134.8 W**
Minimum Battery Life			**15.8 minutes**

3.3 – NAVIGATION AND IDENTIFICATION

Considering the navigation and identification system, the main metrics of interest include the accuracy and timeliness of the sensors and the weight-homing algorithm. When beginning to calibrate both infrared and ultrasound sensors, it was found that largely varying data resulted. Hence all sensor values used were filtered using a simple moving average filter in order to eliminate noise and smooth out spikes in sensor readings. Because of this, a brief lag is involved whenever the sensor readings change. Given the sensor-reading period of 50 milliseconds, a worst-case averaging lag for three samples was found to be:

$$T_{sensor\ lag} = 50\ [ms] * 3\ [samples] = 150\ [ms] \tag{1}$$

This lag was found to have no visible impact on the overall performance, and so the three-sample filter was chosen.

In order to test the implemented P-control wall follow algorithm, the sensory data and corresponding error can be plotted. The robot was placed in an empty arena while printing data through the serial link. The resulting diagram is shown in Figure 16. The robot manoeuvres about a clock-wise $90°$ turn at approximately 1.2 m along the path. The robot responds to the negative error by reducing the right drive speed while increasing the left drive speed. As seen by the peak and trough of the error in Figure 16, the robot displays a significantly slow response to changing error and over compensates for the turn. However the final K_P value of 1 was chosen as it maintained a relatively constant distance from the wall. The noise fluctuation about the zero error line is due to imperfections in the sensors.

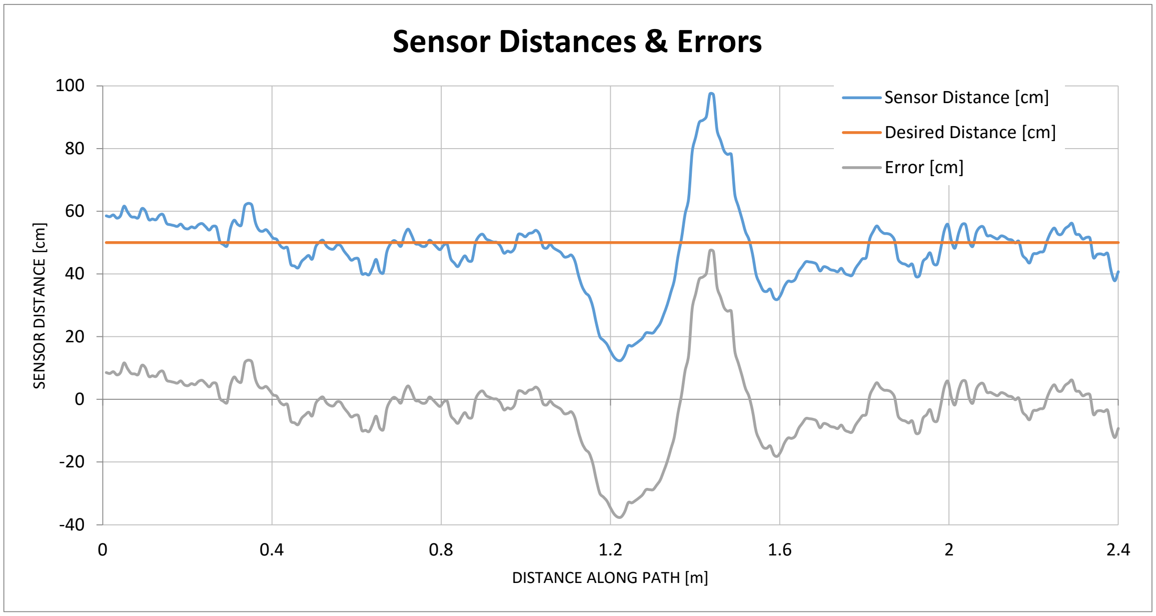


Figure 16: Sensory Data of P-control Wall Follow

One limitation in this method is translating between the sensory data and the corresponding perpendicular distance from the wall. The final value of 50 cm was chosen through a trial-and-error basis as it provided for a clean wall follow while manoeuvring obstacles well.

Furthermore, tests were performed to illustrate how the robot met Requirement Specification 1.1 shown below.

REQ 1.1:
The robot shall navigate about the obstacles including:
- *REQ 1.1.1 Gaps in walls no smaller than 0.5m.*
- *REQ 1.1.2 Vertical pipes and walls.*
- *REQ 1.1.3 Speed bumps and ramps no larger than 25mm high.*

Additionally, a similar test was carried out to demonstrate meeting both REQ 1.2 and REQ 2.1.1 shown below.

> ***REQ 1.2:***
> *The robot shall navigate toward an identified package.*

> ***REQ 2.1:***
> *The robot shall identify:*
> *REQ 2.1.1 Both upright and fallen packages.*

This test consisted of placing a weight directly in front of the robot at various distances. The time taken to correctly collect the weight into the storage bay as well as the number of iterations pivoting was recorded. The robot wall followed until identifying the weight, then continued to iterate toward the weight until correctly picked up. An appropriate pivot was easily recognised by eye once it entered the specific pivot state as described in Section 2.5.2. The results are illustrated in Figure 17 while tabulated data is shown in Appendix B.1.

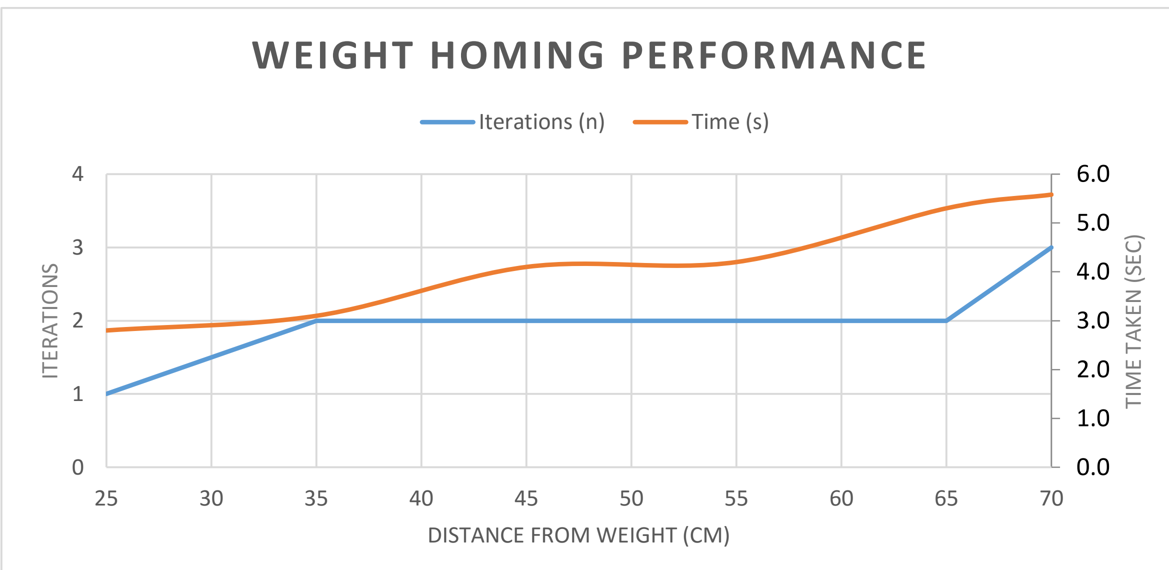


Figure 177: Converging on Weights Results

3.4 – LAYOUT AND LOCOMOTION

Considering locomotion, the addition of the middle track hub ensured that the robot could overcome the HQ borders 20 times out of 20 during a simple wall-following test. This compares favourably to other groups, who often had difficulty overcoming the HQ bumps.

A simple obstacle course was prepared and times were measured with a varying payload. This course consisted of 2 m of wall follow, a 90° turn while manoeuvring the HQ border and another 2 m wall follow. Payloads of 0.0 kg to 3.0 kg were recorded, giving the resulting Figure 18 while the full results can be found in Appendix B.2.

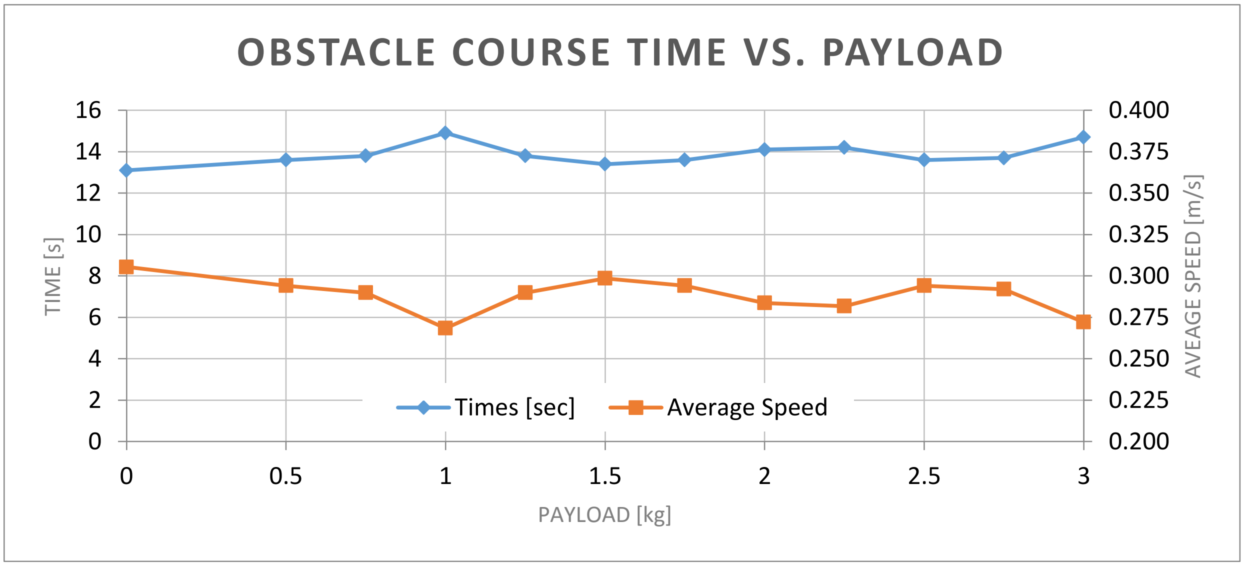


Figure 188: Speed of Robot with Varying Payload

It can be seen that the payload does not greatly affect the speed of the robot. However it was observed on various occasions that tracks began to slip on the HQ border which can be presumed to be due to the constrained front track hub radius. This shortcoming, although not preventing meeting REQ 1.1.3, could be avoided by adding larger radius track hubs to the front. This however will obscure the current height of the pick-up mount.

3.5 – PACKAGE COLLECTION

The main considerations with regard to the package collection system are the capability of the servo's actuating the packages up the slope as well as the ability of the two storage servos holding a 3.0 kg payload. These two matters are isolated and discussed in the following sections. The relevant requirement for this section, REQ 5.3 states that:

> ***REQ 5.3:***
> *The robot shall navigate with a maximum load of 3 kg.*

3.5.1 PICK-UP MECHANISM:

To justify that the HerkuleX DRS – 0101 frontal smart servos provide sufficient torque to push the maximum load ($1.0\ kg$) up the $25°$ slope, a FBD and calculations were analysed. Figure 19 illustrates the simplified free body force diagram where rational assumptions and SolidWorks dimensions were used. These assumptions include a linear acceleration over the path of contact of the weight and a constant sweeper torque radius. Full calculations can be found in Appendix C.

Constant assumptions:

- Static coefficient of friction, $\mu_s = 0.5$.
- Contact angle between arm and weight, $\theta_c = 80°$.
- Constant radius of contact, $r_{av} = 80$ mm.
- Maximum weight is considered, $m_w = 1.0$ kg.
- The smart servos are driven for $130°$ in 2 seconds (software).

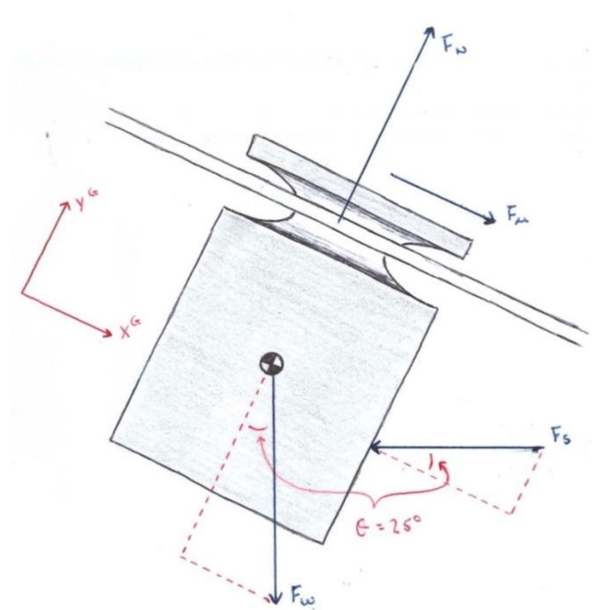


Figure 19: FBD of Weight on Slope

Equation 2 shows that the single sweeper DRS-0101 with a stall torque of 12.0 kgf.cm is more than capable of providing sufficient torque for a 1.0 kg package.

$$F.o.S = \frac{\tau_{allow}}{\tau_{req}} = \frac{12.0\ kgf.cm}{7.76\ kgf.cm} = 1.55 \tag{2}$$

Further tests were completed where a weight was placed within range of the robot and the number of times it successfully acquired it was recorded. Out of 20 trials, the weight was collected a total of 19 times, giving a collection success rate of 95%.

3.5.2 STORAGE & DISTRIBUTION MECHANISM:

In order to determine if the storage system design is feasible, a force diagram was defined in Figure 20 and analysed. The required torque was compared to the two HXT12K servos present in the design. Once again, key dimensions were taken off the SolidWorks design and assumptions were made.

Key assumptions made are:

- The storage is required to hold a full payload of 3.0 kg.
- Two weights are at a larger distance from the servo, $r_2 = 61$ mm in comparison to the middle weight, $r_1 = 47$ mm.
- Supports do not carry frictional forces.

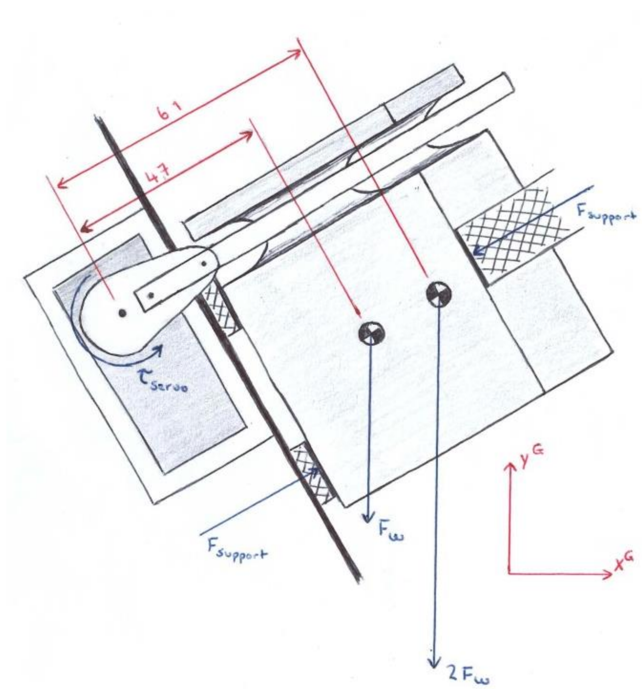


Figure 20: FBD of Weights on Storage Flap

As described in Appendix D, the resulting torque from *one* HXT12K servo is 7.32 $kgfcm$. Each servo provides 14 $kgfcm$ stall torque, which demonstrations that a design of two servos will hold the full payload (3.0 kg) with a safety factor of:

$$F.o.S = \frac{14\ kgf.cm}{7.318\ kgf.cm} = 1.91 \tag{3}$$

3.6 – SOFTWARE

Although no specific requirements for the software were defined in the Conceptual Design Report (CDR), the scheduling algorithm's timeliness described in Section 2.5.1 was analysed. This was accomplished through CPU load analysis and task latency. The software implementation of this scheduler can be seen in the extracted code seen in Figure 21.

```
void loop (void)
{
  schedClock = millis();

  int i;
  /* Iterates through all the tasks. */
  for (i = 0; i < NUM_TASKS; i++)
  {
    /* Checks if that task is ready to be carried out . */
    if (schedClock >= schedTime[i])
    {
      schedTime[i] += schedInterval[i];
      taskExecute(i);
      break;
    }
  }
}
```

Figure 21: Scheduler Code Implementation

The calculation of CPU load seen in Equations 4-6 shows that the system is considered realisable as total load is *less than* 0.7.

$$L_{CPU} = \sum_{k=1}^{N} F_k . T_k \tag{4}$$

$$L_{CPU} = \begin{Bmatrix} (20 * 18271) + (20 * 64) + (12.5 * 32) + \\ (12.5 * 300) + (6.7 * 21) + (2.5 * 52290) \end{Bmatrix} * 10^{-6} \tag{5}$$

$$L_{CPU} = 0.502 < 0.7 \tag{6}$$

As the scheduler implemented (priority based) has a tendency to block certain low priority tasks, the latency of each task was recorded and can be seen in Table 4. It can be observed that the maximum latency for any task is 26 ms. This is considered in the boundaries of effective response as it is small in comparison to the period of occurrence. Additionally, the robot responded well to all tasks as discussed in Section 3.3.

Table 4: Latency of Priority Based Scheduler Tasks

Clock	Task to Execute	New time [ms]	Lateness, [ms]
`schedClock`	`taskExecute(i)`	`schedTime[i]`	
1	Task 1	time[1] = 51	0
20	Task 2	time[2] = 70	19
21	Task 3	time[3] = 101	18
22	Task 4	time[4] = 102	18
23	Task 5	time[5] = 173	18
24	Task 6	time[6] = 421	18
76	Task 1	time[1] = 126	25
95	Task 2	time[2] = 145	26
101	Task 3	time[3] = 181	0
102	Task 4	time[4] = 182	0
126	Task 1	time[1] = 176	0

Where:

- Task 1: `updateAlllSensors()`
- Task 2: `updateWeightDetection()`
- Task 4: `updateDrive()`
- Task 5: `updateServos()`
- Task 6: `updateColourSensor()`

3.7 – COST

When considering the cost, the relevant requirement REQ 6.1 states that:

> ***REQ 6.1:***
> *Further components to the given parts shall not exceed $50 NZD.*

The Bill of Materials shown in Appendix A shows that the total cost of further components came to:

$$Cost_{purchased} = \$6.6 \tag{7}$$

The cost budget well exceeds the cost of purchased components, so this requirement was easily passed. There is flexibility in any potential future developments due to this large amount of unspent money, and it is not expected that any changes will increase the cost to a level at which it fails this requirement.

4. Further Development

4.1 – NAVIGATION & IDENTIFICATION

The main focus for future development in regard to navigation and identification is the searching algorithm. The identification algorithm, at this stage, behaves well enough for it to be maintained at its current level. The current wall-following form of navigation only effectively scans a small area of the arena, focused around the perimeter. The first potential navigation algorithm is a wall bouncer that tracks forward in a wave-like motion until it hits a wall, at which point it rotates by a random number within a given range, and repeats the process. The wave-like motion increases the area scanned when moving without too much loss to speed, therefore increasing the chance of a weight being encountered.

The second possible navigation algorithm is a modification of the wall follower where the robot halts its progress periodically to pivot on the spot and scan the nearby area. To create this algorithm effect, the wall following distance as well as the detection distance would be increased so that a maximum area in the arena would be covered. The benefit of this over the wall bouncer is that it steadily progresses through the arena in a known manner while the bouncer can cover areas multiple times.

Lastly, a change in placement of the colour sensor to the front side of the robot would eliminate issues of identification lag in base detection.

4.2 – LAYOUT AND LOCOMOTION

For locomotion, the current speed of the robot is inferior when compared to other robot's that take advantage of modified tracks and wheels. To try compensating this disadvantage, a larger hub wheel could be used at the output of the DC motors to increase the overall linear speed of the robot.

Furthermore another potential change is for the DC motor encoders to be used. With these, reasonably accurate measurements of rotation, position and speed could be found to enhance the navigation and identification systems.

4.3 – PACKAGE COLLECTION

To increase overall efficiency it is proposed that the package collection servo cycle could take place while the robot continues searching. Currently, the robot halts its progress to complete this cycle, however there is no need for this. This change would ensure that there would be no wasted time in waiting for a weight to be transferred on board.

4.4 – SOFTWARE

Sensor monitoring through pin-change interrupts, if possible, would increase the output performance due to an increased accuracy in sensor measurements.

5. Contribution Statement

Tui Ninness-Clarke:

- Report Writing
- Proof-reading and editing

Frank Sullivan:

- Report Writing
- Proof-reading and editing
- Solidworks models and drawings
- Force calculations
- Robot testing
- Introduction
- Design Description
- Evaluation
- State machines and Diagrams

Ambrose Warburton:

- Report Writing
- Proof-reading and editing
- Solidworks exploded views
- Robot testing
- Executive Summary
- Design Description
- Evaluation
- Further Development
- Figures and Renders

6. Appendices

APPENDIX A: BILL OF MATERIALS

Item	Unit Price	Quantity	Supplier	Model	Total Price ($)
					PROVIDED
Parts					
Motor DC	53	2	DFRobot	FIT0277	106
Servo Standard	12	2	Hobbyking	HXT12K	24
Servo Smart	50	3	DFRobot	DRS-0101	150
IR Distance Sensor	17	2	Sparkfun	2D120X	34
IR Distance Sensor	18	2	Sparkfun	2Y0A02	36
Digital IR Distance sensor	9	2	DFRobot	SEN0019	18
Colour Sensor	10	1	AdaFruit	TCS34725	10
Micro Switch	1.5	2	SonarPlus	SM1039	3
Switch	1.8	1	SonarPlus	ST0335	1.8
Materials					
Perspex 300*300*5	6	1	Ullrich		6
AL Flat Bar 25mm	1.1	1	Ullrich		1.1
AL Square	1	1	Ullrich		1
				Subtotal:	**$390.9**
					PURCHASED
Parts					
Ultrasound Sensor	1.3	2	Aliexpress	HC-SR04	2.6
Digital IR Detect sensor	1	4	Aliexpress		4
				Subtotal:	**$6.6**
				Total:	**$397.5**

APPENDIX B: EVALUATION DATA TABLES

B.1: WEIGHT HOMING PERFORMANCE

A weight was placed directly in front of the robot at various distances. The time taken to correctly collect the weight into the storage bay as well as the number of iterations pivoting was recorded.

Table 3: Raw Weight Homing Data

Distance to weight [cm]	Iterations [n]	Time [s]
25	1	2.8
35	2	3.1
45	2	4.1
55	2	4.2
65	2	5.3
70	3	5.58
Average	**2**	**4.18**

B.2: COURSE TIME VERSUS PAYLOAD

The time taken to travel 2 m (wall follow), turn a 90° corner over the HQ border and another 2 m (wall follow) was recoded with the payload as the control variable.

Table 4: Raw Obstacle Course Data

Weights [kg]	Times [sec]	Average Speed
0	13.1	0.31
0.5	13.6	0.29
0.75	13.8	0.29
1	14.9	0.27
1.25	13.8	0.29
1.5	13.4	0.30
1.75	13.6	0.29
2	14.1	0.28
2.25	14.2	0.28
2.5	13.6	0.29
2.75	13.7	0.29
3	14.7	0.27
Average	**13.875**	**0.29**

APPENDIX C: SWEEPER ARM FORCE CALCULATIONS

$$\sum F_x = m\ddot{x}$$

$$\{\cos(25°)\,F_s\} - \{\sin(25°)\;F_w\} - \{\mu_s\,[\cos(25°)\,F_w]\} = m_w\,\ddot{x}$$

$$\ddot{x} = \cos(25°)\,F_s - \sin(25°)\,9.81 - 0.5[\cos(25°)\,9.81]$$

$$F_s = \frac{\ddot{x} + 8.591}{\cos(25°)}$$

$$\omega_f^2 = \omega_i^2 + 2\alpha\theta$$

$$\left(1.134\frac{rad}{s}\right)^2 = (0)^2 + 2\alpha\left(80° \times \frac{2\pi}{360°}\right)$$

$$\ddot{x} = \alpha \times r_{avg} = 0.4605\,rad/s^2 \times 0.08\,m = 0.03684\,m/s^2$$

$$\tau = F_s r_{avg} = \frac{0.03684 + 8.591}{\cos(25°)} \times 0.08$$

$$\tau = 0.7616\,Nm$$

$$\tau = 0.7616\,Nm \times \left(\frac{1\,kgf.cm}{9.81\,Nm}\right) \times \left(\frac{100\,cm}{1\,m}\right) = 7.76\,kgf.cm$$

APPENDIX D: STORAGE FLAP TORQUE CALCULATIONS

$$\sum M_{servo} = 0$$

$$2\tau_{servo} - r_1[\cos(30°)\,.\,m_w.\,g] - r_2[\cos(30°)\,.\,2m_w.\,g] = 0$$

$$2\tau_{servo} = 0.047\ (8.498) + 0.061\ (16.99)$$

$$\tau_{servo} = 0.7179\ Nm$$

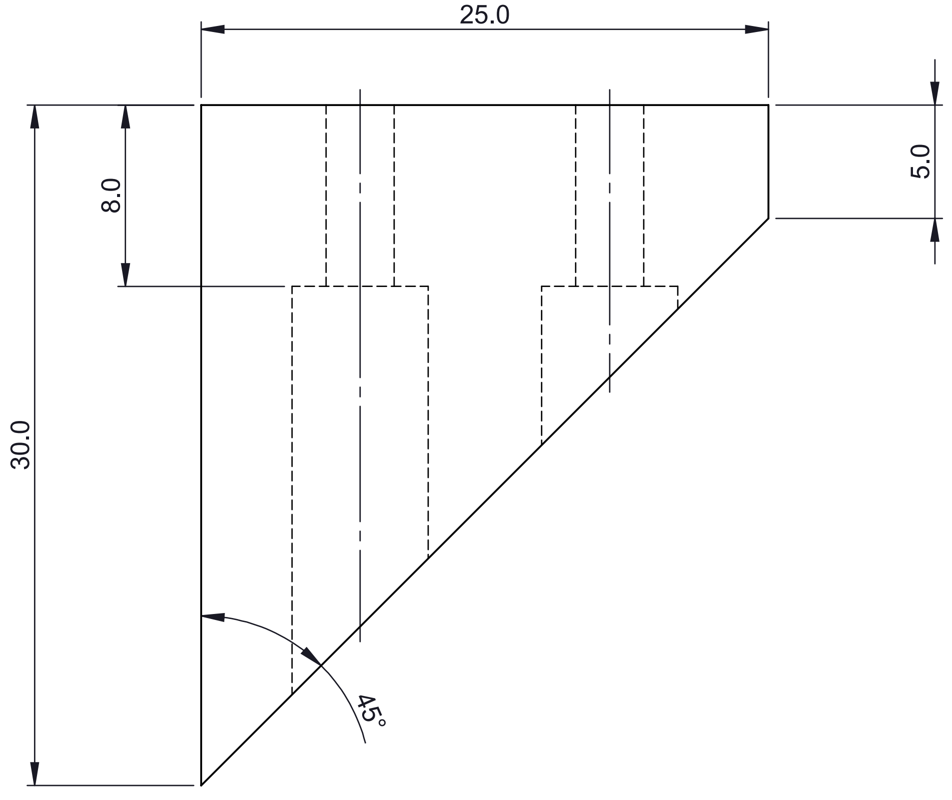
$$\tau_{servo} = \ 0.7179\ Nm \times \left(\frac{1\ kgf.cm}{9.81\ Nm}\right) \times \left(\frac{100\ cm}{1\ m}\right) = 7.318\ kgf.cm$$

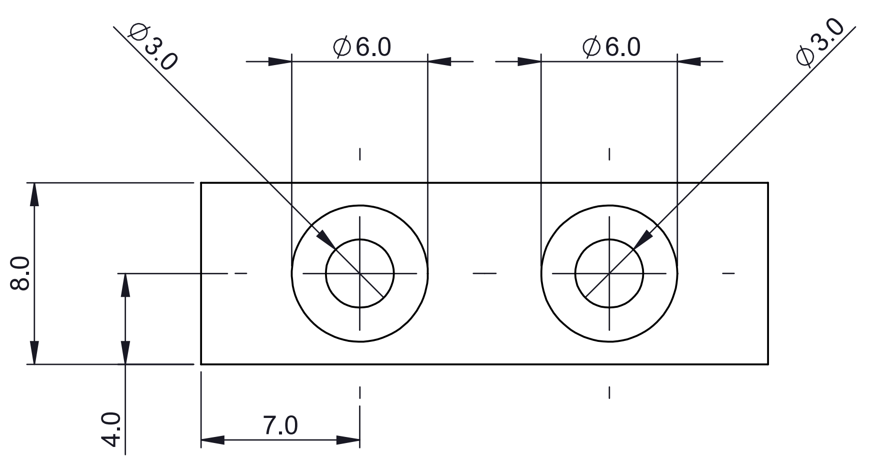
APPENDIX E: DRAWINGS & DIMENSIONS

NOTES - (UNLESS OTHERWISE SPECIFIED)

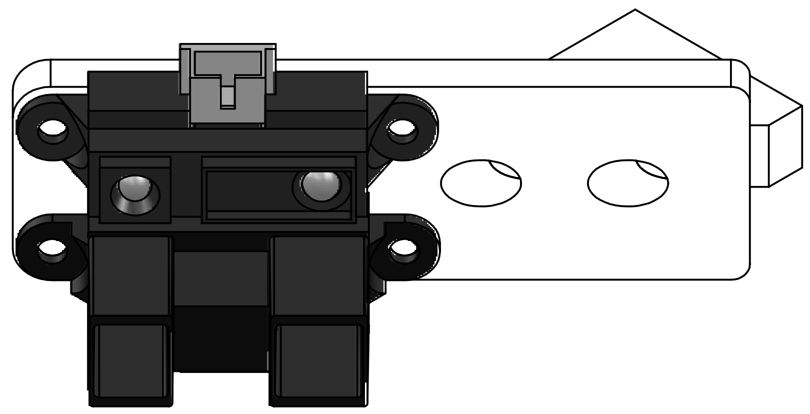
1. ALL DIMENSIONS IN MILLIMETERS.
2. GD&T AS PER ISO1101-2004.

REVISIONS					
ZONE	REV.	DESCRIPTION	ECO	APPROVED	DATE
	REV1	RELEASE		XXX	21AUG15

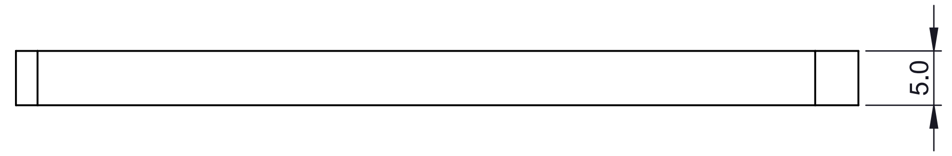


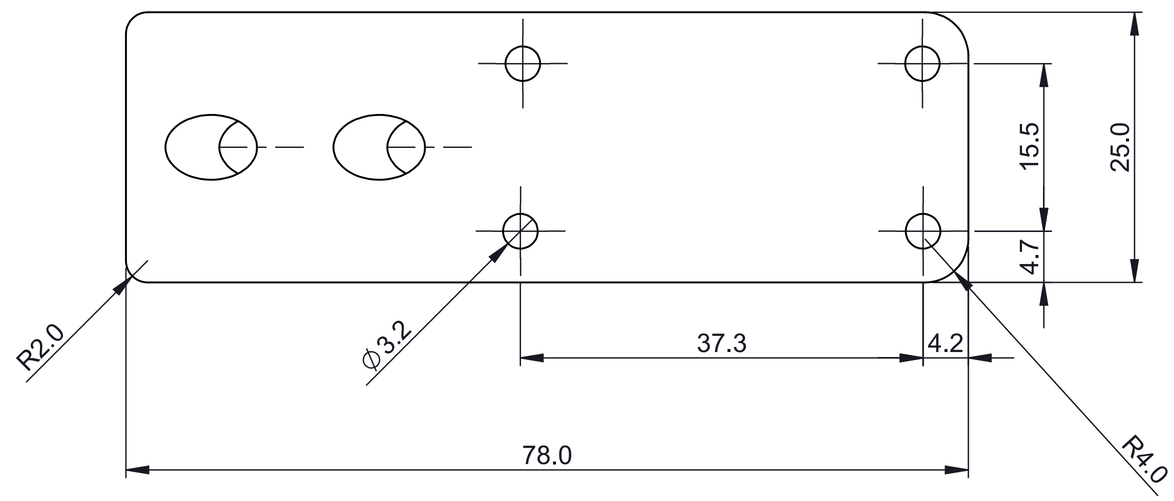


Angled Base Mount



Sensor Mount





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MATERIAL: Perspex		SENSOR MOUNT	
FINISH: As Manufactured		DESIGN: Frank Sullivan	DWG NO. baseanglemount	REV Vers. 2
TOLERANCE (UNLESS OTHERWISE SPECIFIED) DECIMAL mm		DRAWN: Frank Sullivan	PROJECT: UC RoboCup 2015
.X ± .1 .XX ± .05 .XXX ± .010 ANG. ± 1°		SUPERVISOR: Ambrose Warburton	ISSUE DATE 21AUG15	DRAWING NOT TO SCALE	SHEET 1 OF 1

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2. GD&T AS PER ISO1101-2004.

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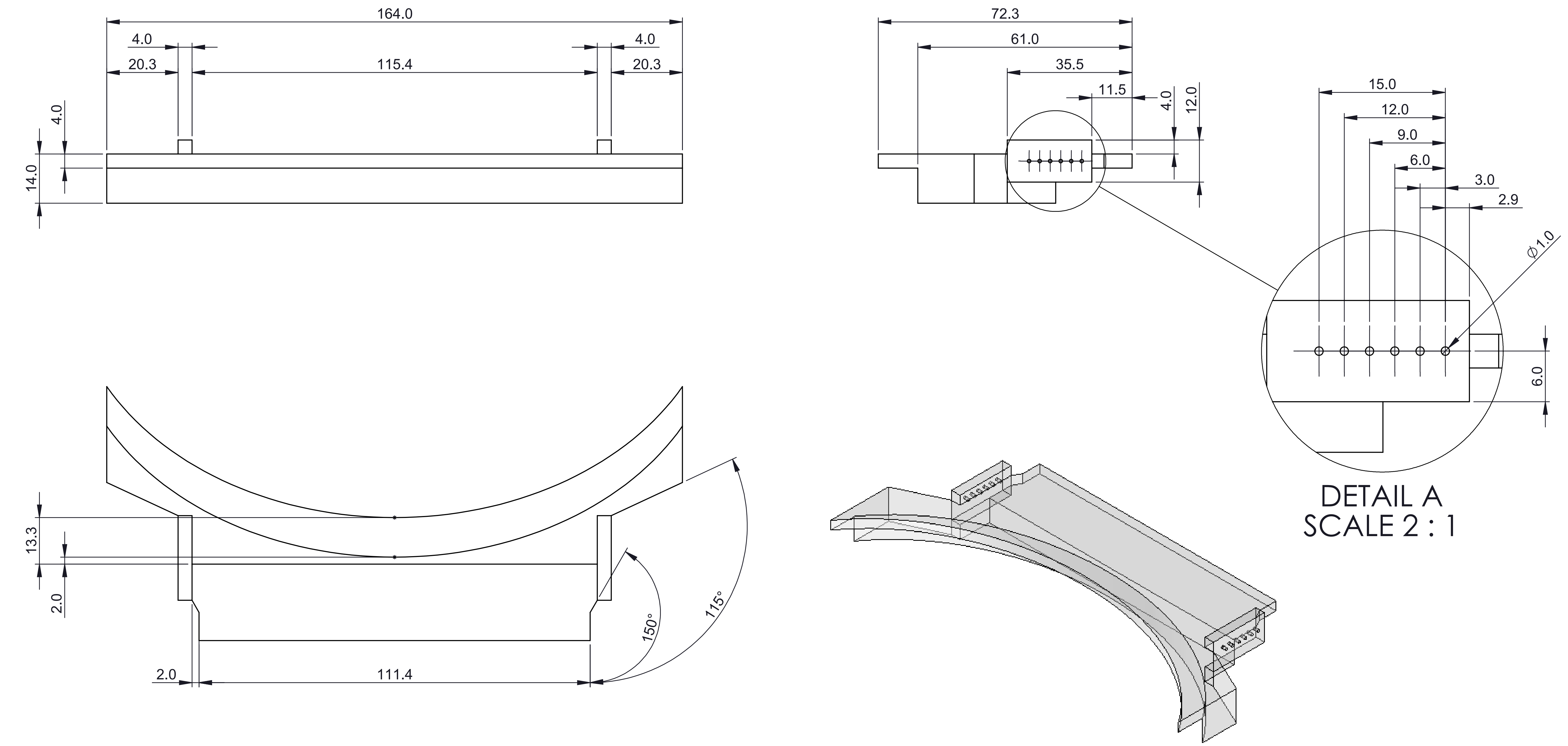

PLEASE NOTE:
Both elliptical cuts have major axis length of 92.75mm and minor axis length of 70mm.

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DEPARTMENT OF MECHANICAL ENGINEERING

MATERIAL: 4mm & 10mm Perspex

BACK FLAP OF STORAGE

FINISH: As Manufactured

DESIGN: Frank Sullivan | DWG NO.: flap of holder | REV: Vers 3.

DRAWN: Frank Sullivan | PROJECT: UC RoboCup 2015

TOLERANCE (UNLESS OTHERWISE SPECIFIED)
DECIMAL mm
.X ± .1 **.XX** ± .05 **.XXX** ± .010 **ANG.** ± 1°

SUPERVISOR: Ambrose Warburton | ISSUE DATE: 21AUG15 | DRAWING NOT TO SCALE | SHEET: 1 OF 1

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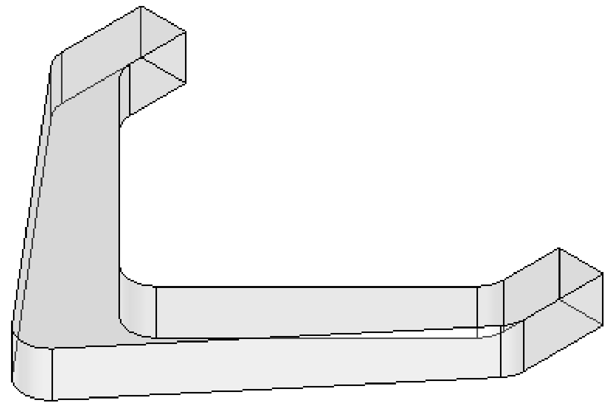
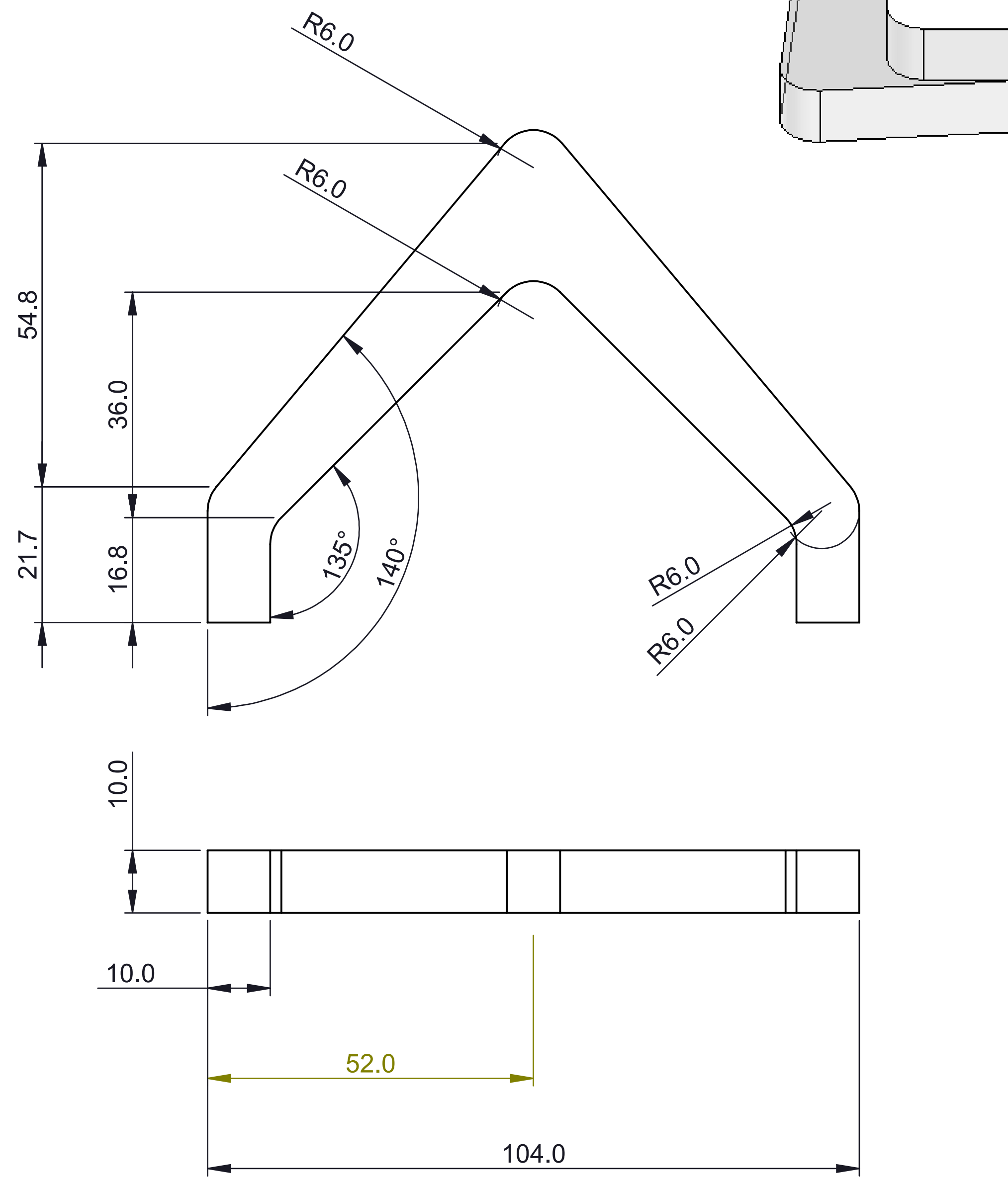
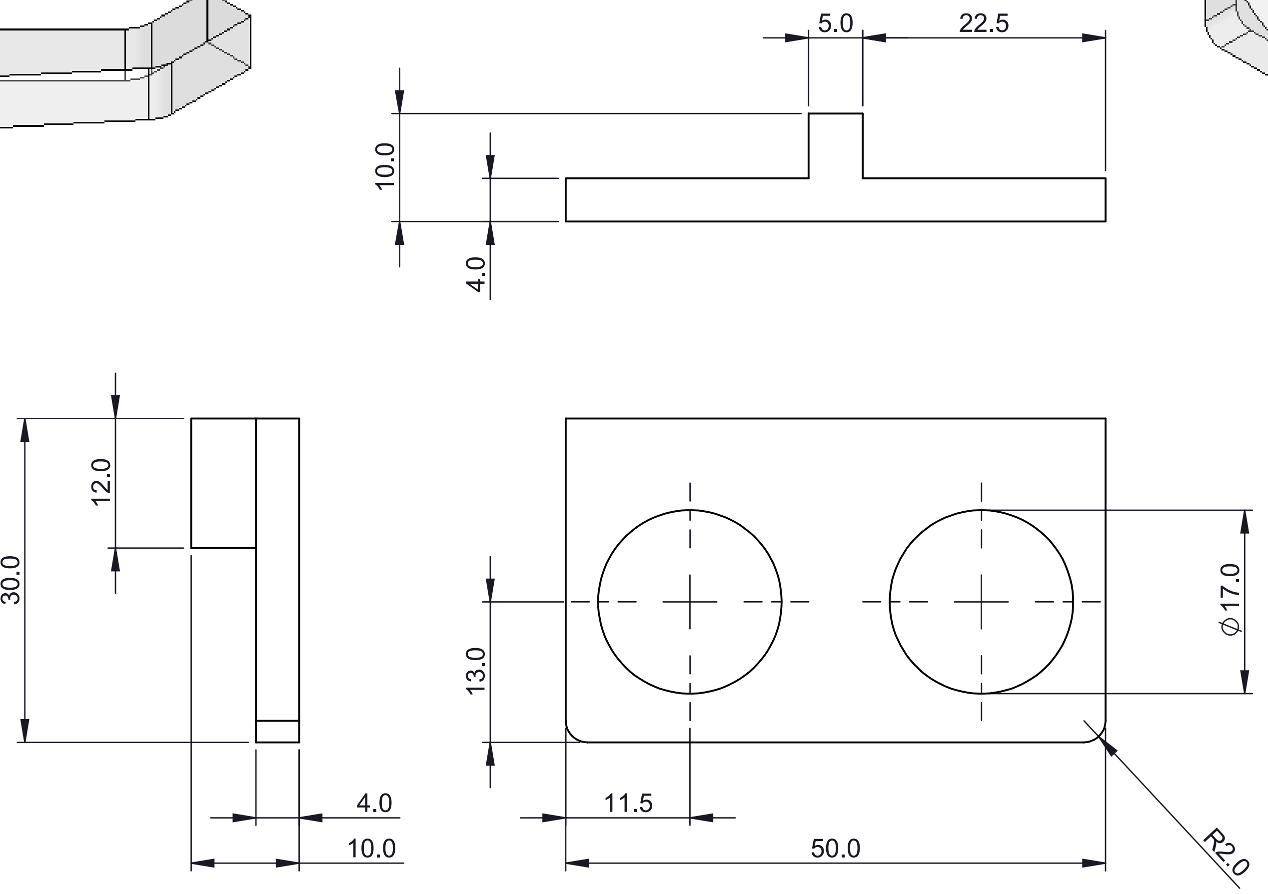
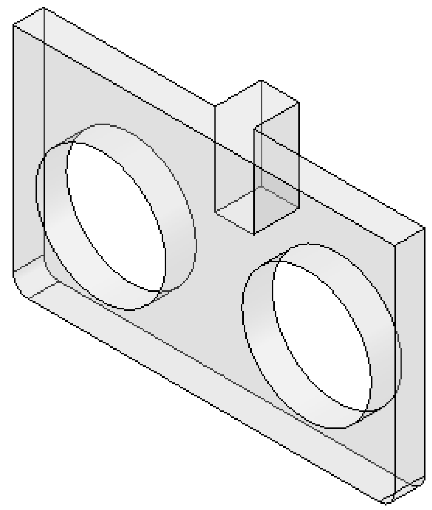
ZONE	REV.	DESCRIPTION	ECO	APPROVED	DATE
	REV1	RELEASE		XXX	21AUG15









Lower Outside Sonar Supports

Lower Centre Funnel

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MATERIAL: 4mm & 10mm Perspex		PICKUP SECONDARY FUNNEL	
FINISH: As Manufactured		DESIGN: Frank Sullivan	DWG NO.: frontPushUp	REV: Vers 3.
TOLERANCE (UNLESS OTHERWISE SPECIFIED) DECIMAL mm		DRAWN: Frank Sullivan	PROJECT: UC RoboCup 2015
.X ± .1 .XX ± .05 .XXX ± .010 ANG. ± 1°		SUPERVISOR: Ambrose Warburton	ISSUE DATE: 21AUG15	DRAWING NOT TO SCALE	SHEET 1 OF 1

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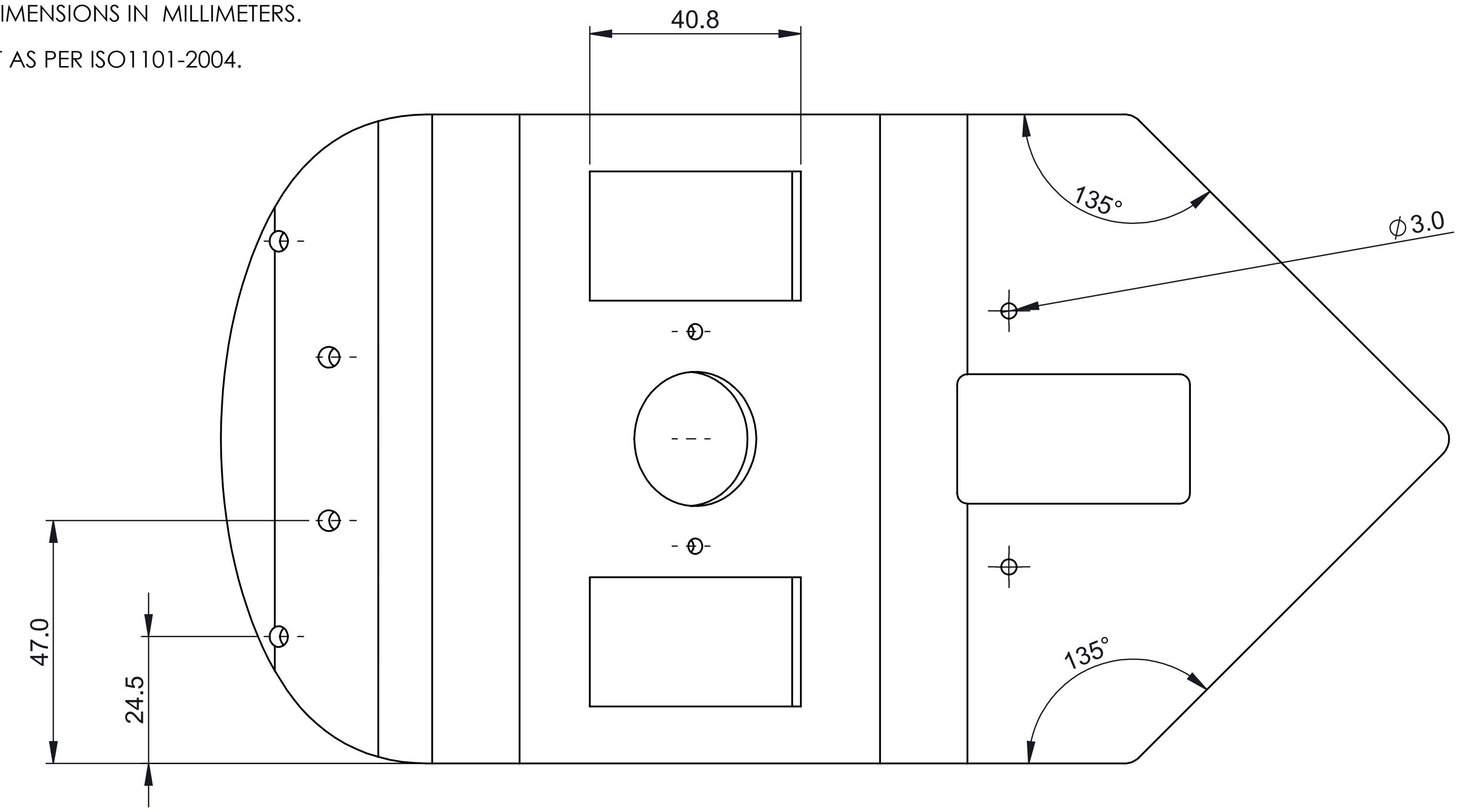
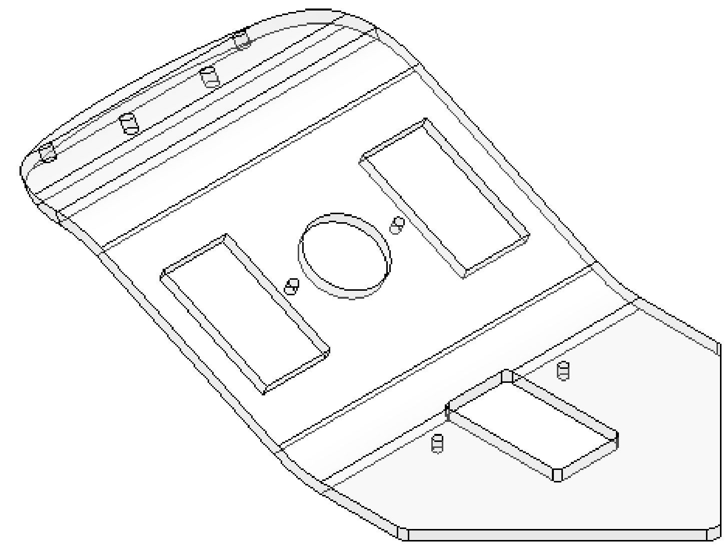
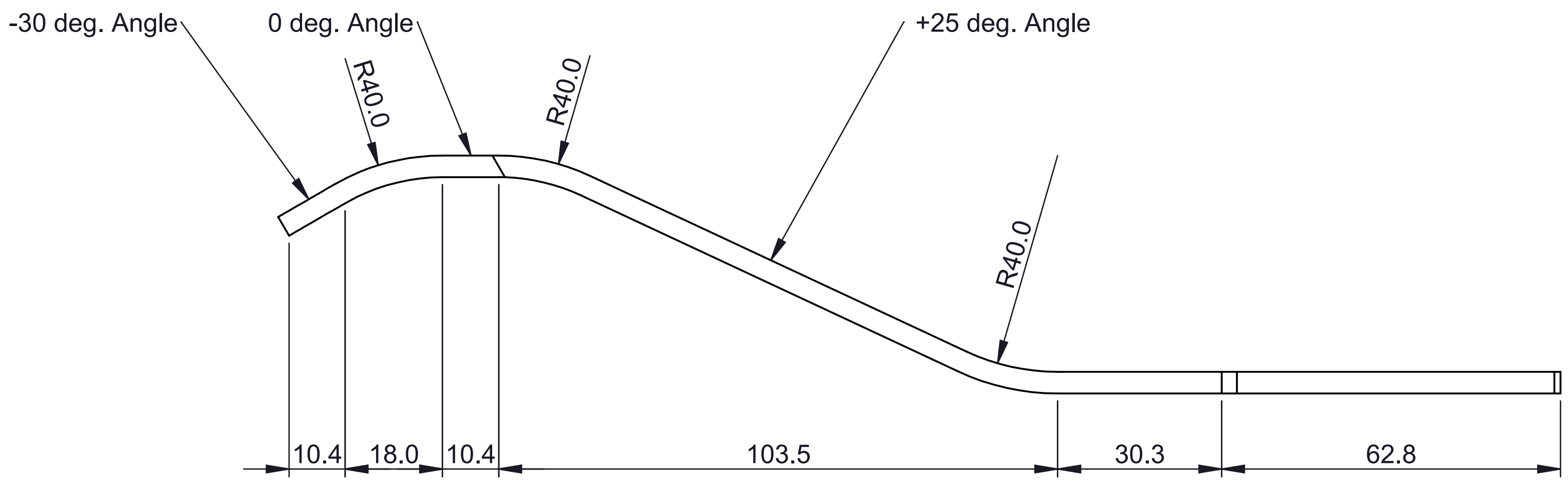
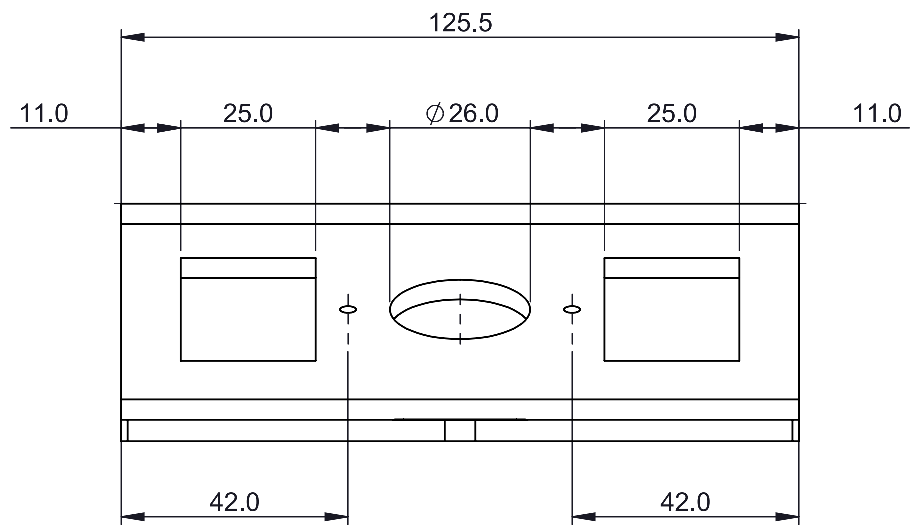
	REV1	RELEASE		XXX	21AUG15





PLEASE NOTE:
- Elliptical Cut has major axis length of 125.5mm and minor axis length of 40mm.





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MATERIAL: 4mm Perspex		PICKUP INSIDE RAMP	
FINISH: As Manufactured		DESIGN: Frank Sullivan; DWG NO.: Inside support perspex	REV: Vers 3.
TOLERANCE (UNLESS OTHERWISE SPECIFIED) DECIMAL mm		DRAWN: Frank Sullivan; PROJECT: UC RoboCup 2015	
.X ± .1 .XX ± .05 .XXX ± .010 ANG. ± 1°		SUPERVISOR: Ambrose Warburton; ISSUE DATE: 21AUG15; DRAWING NOT TO SCALE	SHEET 1 OF 1

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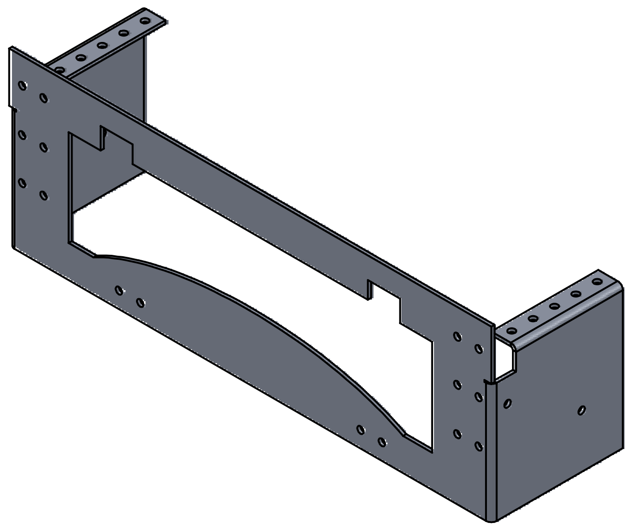
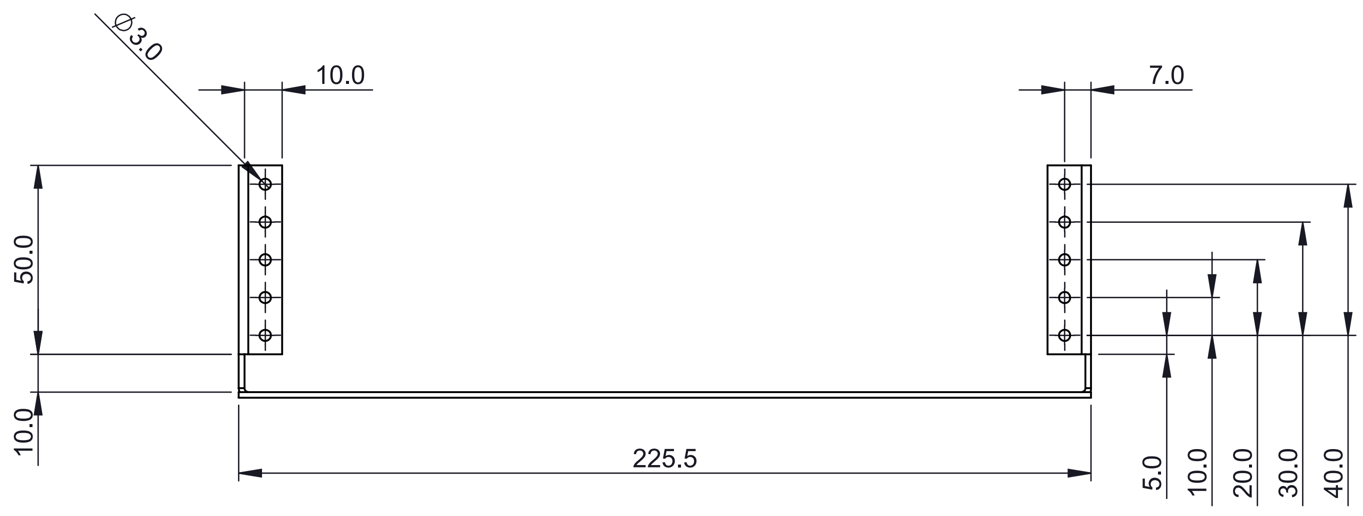
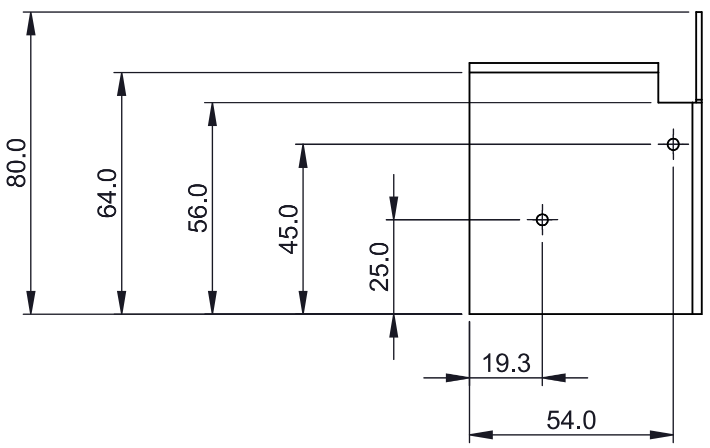
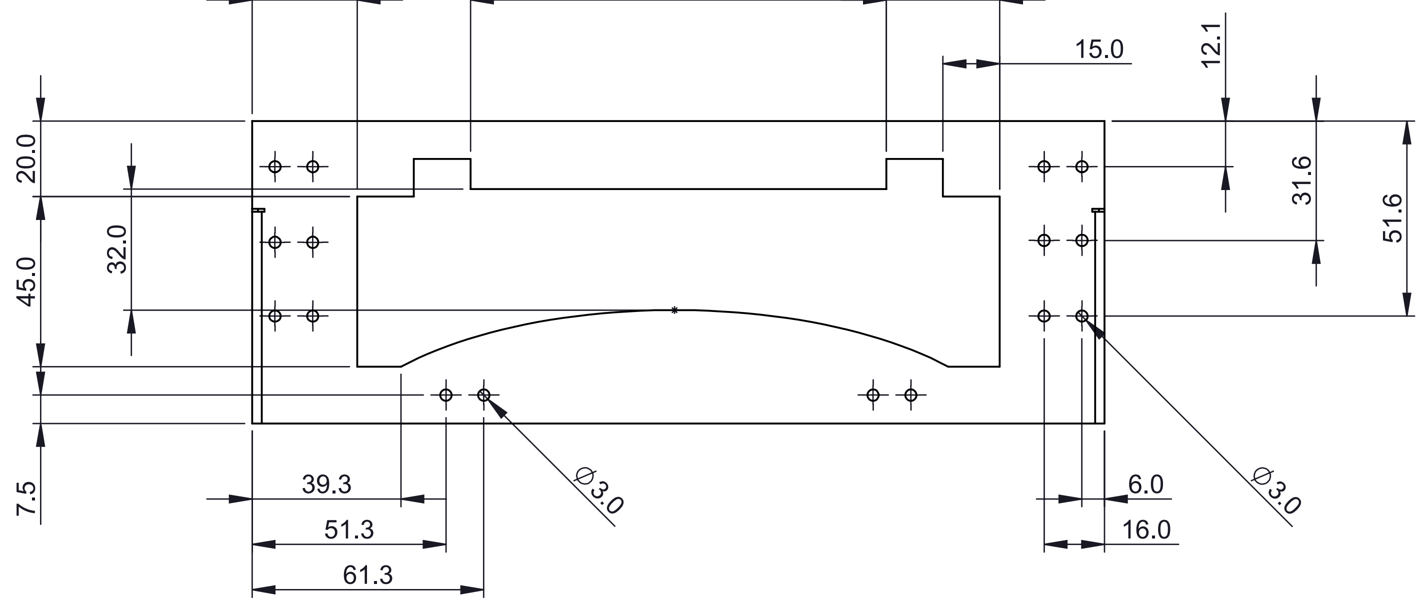
	REV1	RELEASE		XXX	21AUG15









PLEASE NOTE:

- Sheet metal has a 1.5 mm width and 1mm bend radius.
- Elliptical Cut has major axis length of 185.5mm and minor axis length of 40mm.

THIRD ANGLE PROJECTION

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DEPARTMENT OF MECHANICAL ENGINEERING

MATERIAL: Aluminium

ANGLED STORAGE SUPPORT

FINISH: As Manufactured

DESIGN	DWG NO.	REV
Frank Sullivan	metal slope	Vers 3.

DRAWN	PROJECT
Frank Sullivan	UC RoboCup 2015

TOLERANCE (UNLESS OTHERWISE SPECIFIED)
DECIMAL mm

.X ± .1 .XX ± .05 .XXX ± .010 ANG. ± 1°

SUPERVISOR	ISSUE DATE		SHEET
Ambrose Warburton	21AUG15	DRAWING NOT TO SCALE	1 OF 1

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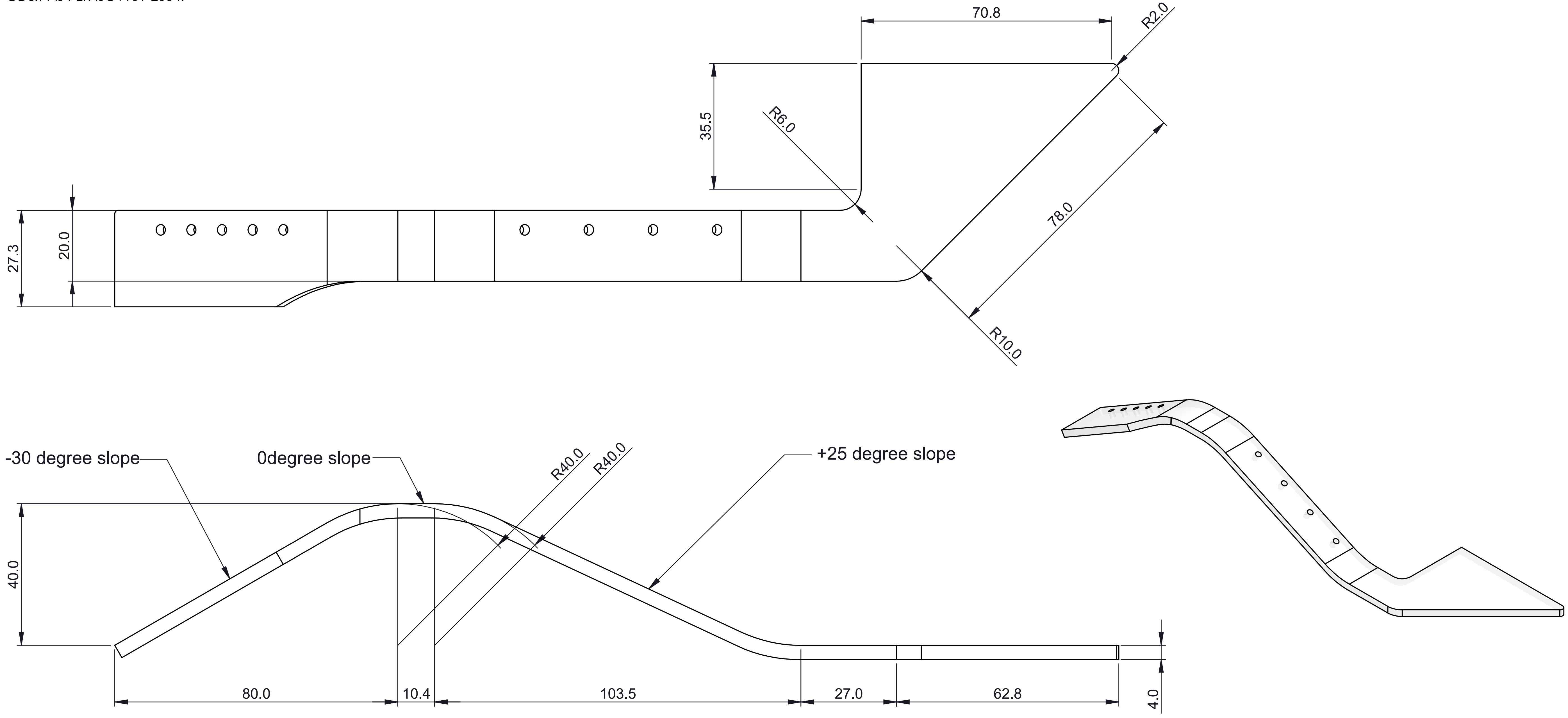

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MATERIAL: 4mm Perspex		LEFT SUPPORT RAMP	
FINISH: As Manufactured		DESIGN: Frank Sullivan	DWG NO.: outside_support_perspexLEFT; REV: Vers 3.
TOLERANCE (UNLESS OTHERWISE SPECIFIED)		DRAWN: Frank Sullivan	PROJECT: UC RoboCup 2015
DECIMAL mm .X ± .1 .XX ± .05 .XXX ± .010 ANG. ± 1°		SUPERVISOR: Ambrose Warburton	ISSUE DATE: 21AUG15; DRAWING NOT TO SCALE; SHEET 1 OF 1

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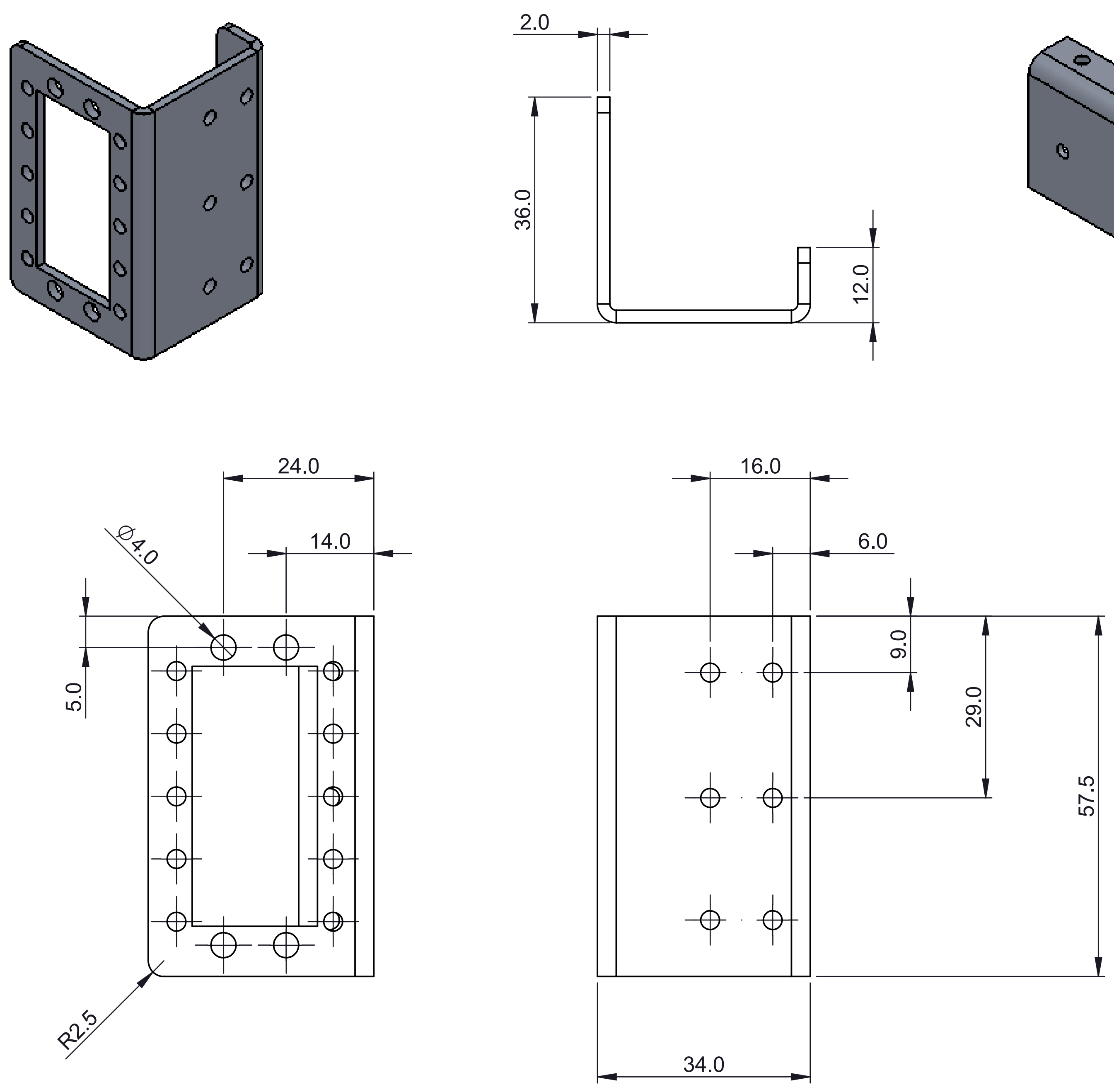

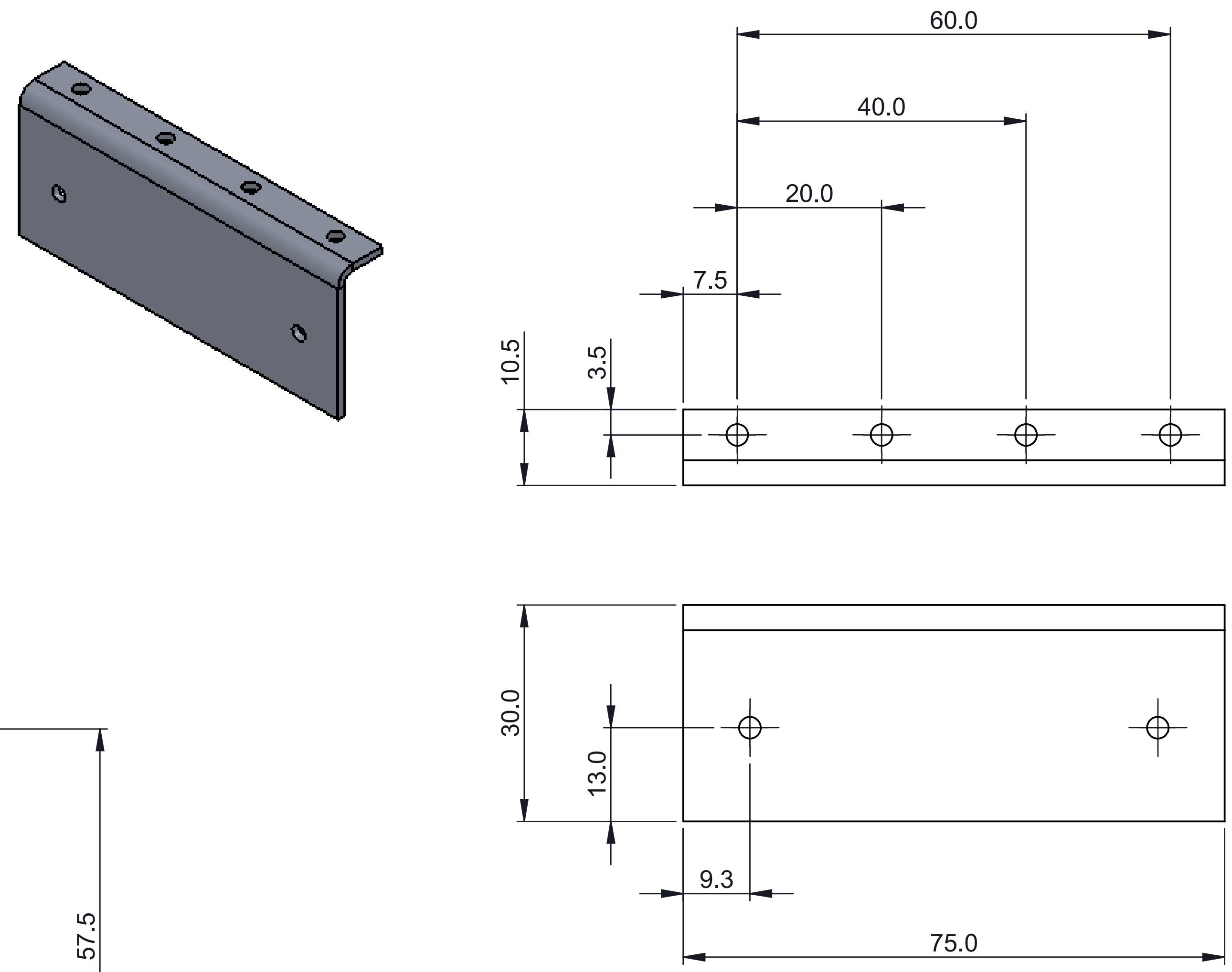

Pick-up Attachment

PLEASE NOTE:
Sheet metal thickness is 1.5mm and 1mm bend radius

Given Servo Mount

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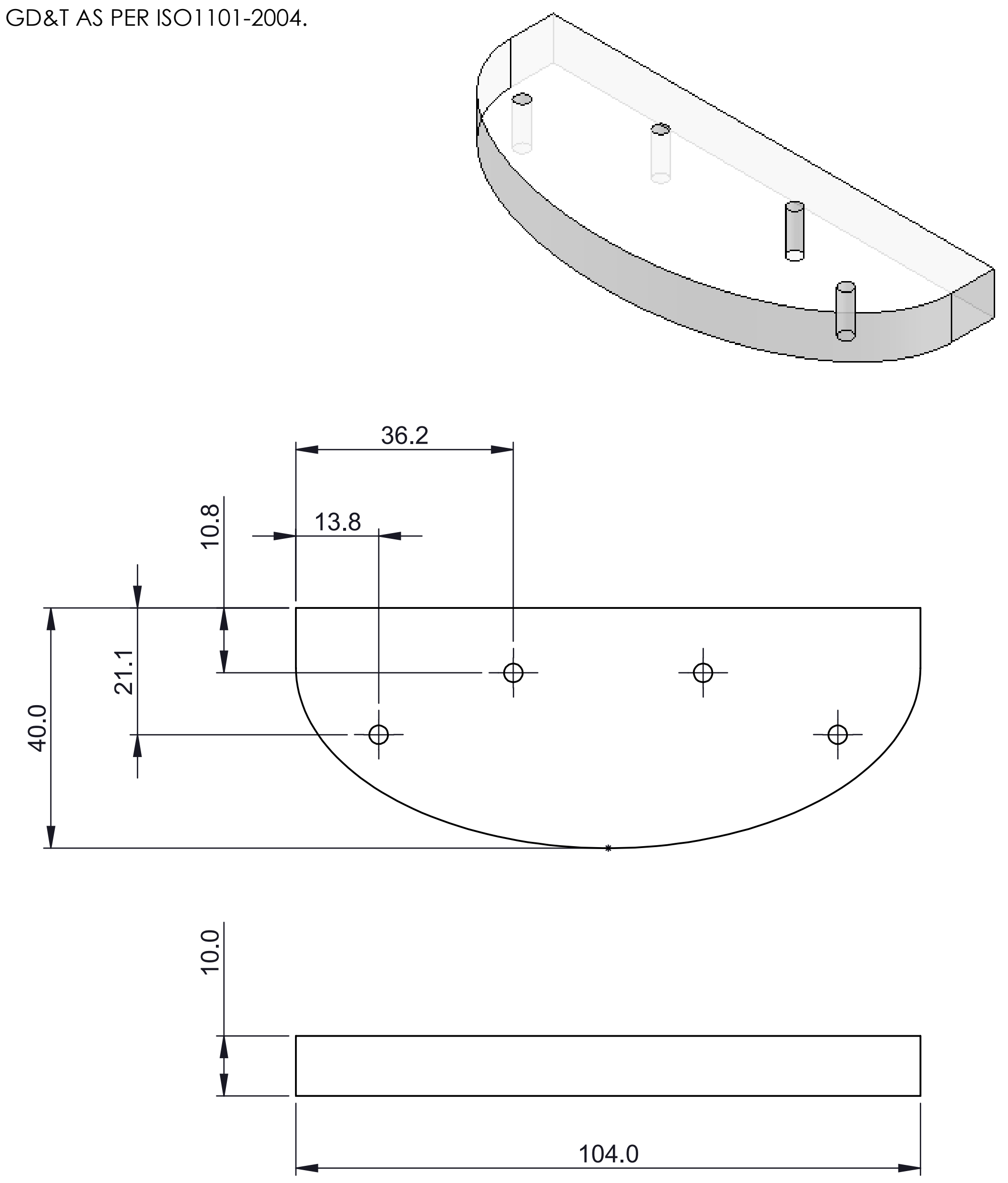
MATERIAL: Aluminium		PICK-UP SUPPORTS		
FINISH: As Manufactured		DESIGN: Frank Sullivan	DWG NO.: sideAttachments	REV: Vers 3.
TOLERANCE (UNLESS OTHERWISE SPECIFIED) DECIMAL mm		DRAWN: Frank Sullivan	PROJECT: UC RoboCup 2015	
.X ± .1	.XX ± .05	.XXX ± .010	ANG. ± 1°	
		SUPERVISOR: Ambrose Warburton	ISSUE DATE: 21AUG15	DRAWING NOT TO SCALE	SHEET 1 OF 1

NOTES - (UNLESS OTHERWISE SPECIFIED)

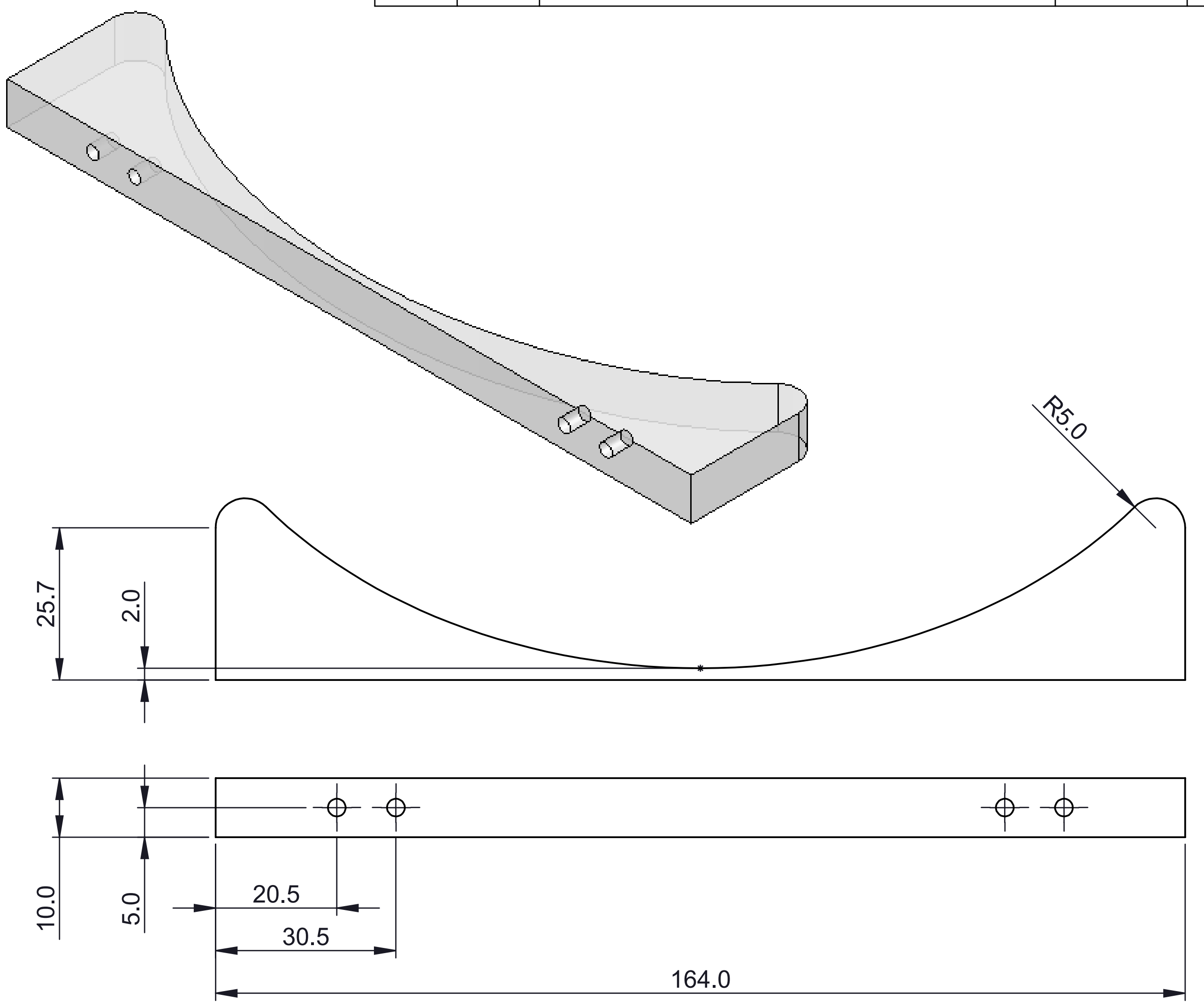
1. ALL DIMENSIONS IN MILLIMETERS.
2. GD&T AS PER ISO1101-2004.

REVISIONS					
ZONE	REV.	DESCRIPTION	ECO	APPROVED	DATE
	REV1	RELEASE		XXX	21AUG15



Front Storage Support

PLEASE NOTE:
Elliptical Shape has major axis length of 104mm and minor axis length of 30mm.



Back Storage Support

PLEASE NOTE:

- Elliptical Cut has major axis length of 92.75mm and minor axis length of 70mm.
- Depth of four tapped holes is 5mm

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MATERIAL: 10mm Perspex		STORAGE SUPPORT COMPONENTS		
FINISH: As Manufacured		DESIGN: Frank Sullivan	DWG NO.: lowerPlateSupport	REV: Vers 3.
TOLERANCE (UNLESS OTHERWISE SPECIFIED) DECIMAL mm		DRAWN: Frank Sullivan	PROJECT: UC RoboCup 2015	
.X ± .1 .XX ± .05 .XXX ± .010	ANG. ± 1°	SUPERVISOR: Ambrose Warburton	ISSUE DATE: 21AUG15	DRAWING NOT TO SCALE	SHEET: 1 OF 1

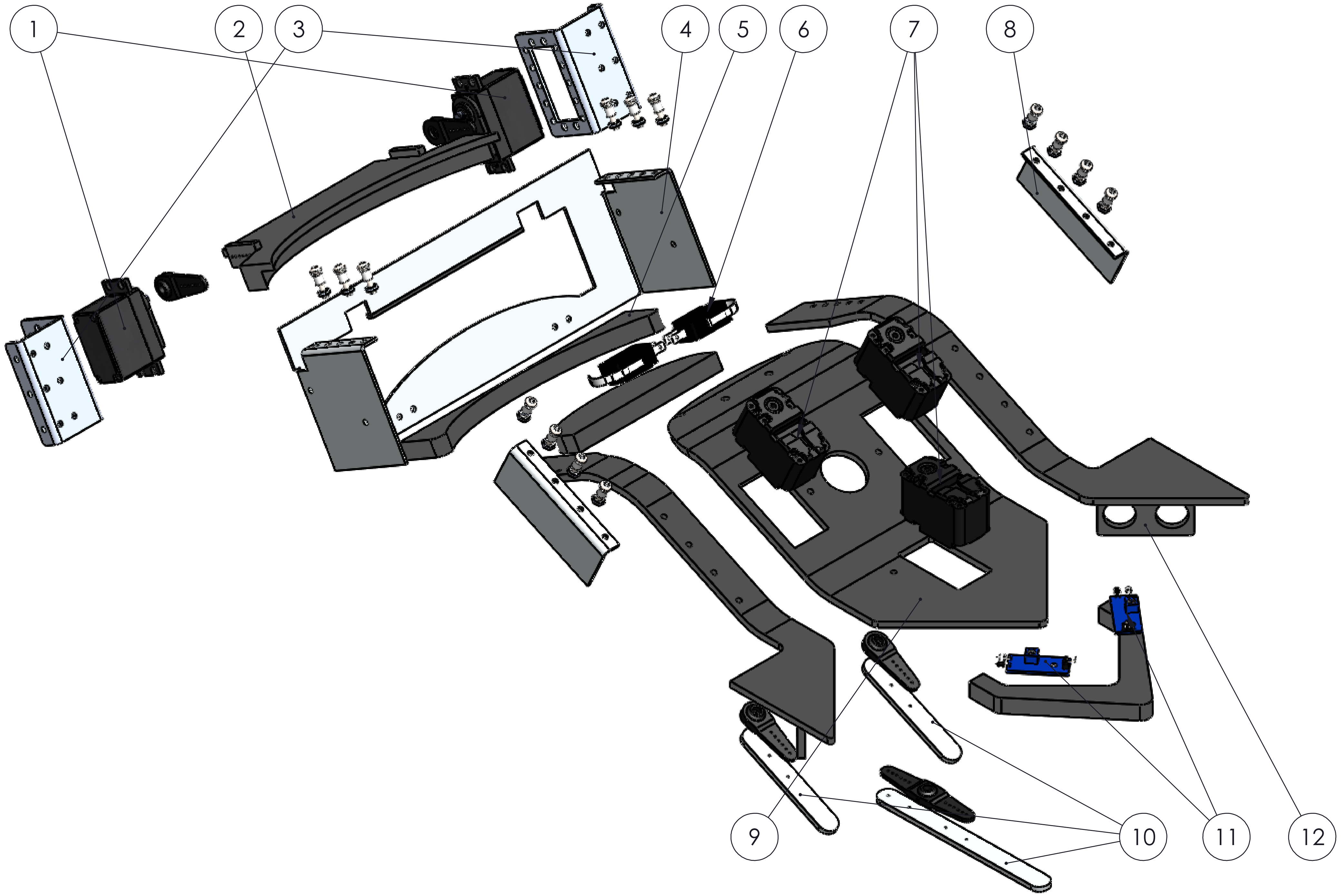
NOTES - (UNLESS OTHERWISE SPECIFIED)

1. ALL DIMENSIONS IN MILLIMETERS.

2. GD&T AS PER ISO1101-2004.

REVISIONS

ZONE	REV.	DESCRIPTION	ECO	APPROVED	DATE
	REV1	RELEASE		XXX	21AUG15



Feature	Description
1	Standard Servo
2	Storage Ledge
3	Back Mounts
4	Storage Tray
5	Lower Support
6	Limit Switches
7	Herkulex Servos
8	Side Mounts
9	Main Funnel Body
10	Sweeper Paddles
11	IR Detect Sensors
12	Sonar Mounts

THIRD ANGLE PROJECTION

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DEPARTMENT OF MECHANICAL ENGINEERING

COLLECTOR MECHANISM

MATERIAL: SEE PART DRAWINGS

FINISH: As Manufactured

TOLERANCE (UNLESS OTHERWISE SPECIFIED)

DECIMAL mm

.X ± .1 .XX ± .03 .XXX ± .010 ANG. ± 1°

DESIGN: FRANK SULLIVAN

DWG NO.: pickup_full_assem

REV: REV1

DRAWN: AMBROSE WARBURTON

PROJECT: UC RoboCup 15

SUPERVISOR: FRANK SULLIVAN

ISSUE DATE: 21AUG15

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SHEET: 1 OF 1