Ascender

A cost-effective, mass-producible, stair-climbing solution for urban search and rescue robotics

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Abstract

This report details the investigation and development of a low-cost, mass-producible stair-climbing mechanism that can be introduced into robots for use in urban search and rescue (USAR) environments.

Research included topics such as existing USAR, stair-climbing and low cost robotic solutions. Particular focus was kept on the works of Haskel and Wilson who had made previous efforts to create stair-climbing robot solutions at the University of Cape Town (UCT).

Development of the robot, Ascender, was carried out through an iterative design process whereby prototypes would be designed, assembled and tested - iteratively. Locally available materials were sourced to minimised costs. Furthermore, the robot was designed to be man-packable and could function on relatively low-torque motors which considerably decreased the weight and cost of the robot. This process saw the completion of three prototype stages.

It was concluded that the Mark 3 prototype was suited to climbing a stair of a maximum height of 120 mm but that more changes would need to be made to the body design to prevent it from unintentionally beaching on the edge of a step. Ascender was considered a suitable size to house the electronics design by Haskel but that Mark 3 would first need improvements most notably in controllability and strength.

It is recommended that Mark 3 be improved and then integrated with the electronics developed by Haskel that would give the Ascender tele-operation and live video feed functionality which is crucial to USAR robots. Future work included the optimisation of the gearing, mass and rigidity of the robot along with more exciting prospects like a dynamic tail.

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Chapter 1

Introduction

The following report details the research and development of a wheeled Urban Search and Rescue (USAR) robot frame designed to be the primary means of observation reconnaissance in a disaster zone. From a functional point of view, the robot must be able to ascend or descend stairs while remaining small enough to move through small spaces. It is imperative that each unit be inexpensive so as to enable most search and rescue teams to afford at least one; having a USAR robot(s) available gives protection to teams who would otherwise endanger themselves during urban rescue operations.

1.1 Background to the study

Disasters and tragic events occur frequently and, in urban settlements where people are densely packed, a single disaster can cause harm to many. Instead of sending more people into dangerous environments for search and rescue operations, robots can be used as they are considered to be expendable owing to their lack of life. These robots are used to survey dangerous environments and search for survivors until the risk of sending in human search and rescue teams is acceptable. However, in the past, highly advanced and generalised robots have been designed to handle many situations and as such have been extremely costly - one such university-developed robot cost roughly $3,900 to produce and was referred to by Mahmud et. al[6] as "relatively inexpensive". As is typical of expensive solutions, they become affordable only to a few rescue teams. Furthermore, the potential loss of a costly robot in a hazardous environment may inhibit the owner's willingness to deploy it.

Development was needed of a USAR robot that is inexpensive enough that it is affordable for most - if not all - search and rescue teams, and thus can be considered expendable in all situations where human life may be at risk. Thus began the development of 'Ascender'.

1.2 Objectives of this study

The main objectives of this research investigation were to design a robot that:

1. Is capable of ascending and descending stairs.
2. Is able to manoeuvre through small spaces.
3. Is small and light enough to be carried in a backpack by an average-strength human.
4. Is inexpensive enough to be considered expendable in all situations where human life is at risk.
5. Is mass-produceable.
6. Can be manufactured with readily-available materials and components.
7. Can, in future, accommodate tele-operation functionality.

Furthermore, the investigation aimed to uncover areas of research that may further improve the proposed solution. As such, the designed robot's limits should be tested.

1.2.1 Problems to be investigated

Problems to be investigated included the following:

1. Creating a robot sturdy enough to withstand the harsh environments caused by disasters while remaining as inexpensive as possible.
2. Being able to ascend a staircase while minimising the unit's size.
3. Using a design that doesn't require a high torque motor as this a substantial difference to the overall cost of the build.

1.2.2 Purpose of the study

Currently, highly-capable USAR robots are not affordable by the majority of rescue teams. This is typically due to robots being designed to cope with many different obstacles and challenges, i.e. being generalised in design. The purpose of this investigation was to determine whether a specialised USAR robot could be built such that it is affordable enough to be considered expendable; this would have ensured it would be deployed especially in the most dangerous environments. The intention was that if a specialised USAR robot could be successfully manufactured, search and rescue operations may be more frequently successful and the loss of human life may be substantially decreased in these situations. The specialisation is specifically the robot's ability to ascend a staircase and manoeuvre through small spaces typical of urban environments.

1.3 Scope and Limitations

The scope of this project included the following:

1. Investigating the dynamics behind potential robot designs to understand the ability of the mechanism to climb staircases.
2. Designing and developing prototypes for the decided solution.
3. Building prototypes and testing their ability to ascend a staircase.

The following was not in the scope of this project:

1. Investigation and optimisation of the electronic system.
2. Investigation into the implementation of a remote video feed.
3. Implementation of the tele-operation feature.
4. Designing of other possible solutions.
5. Minimising costs, weight and size of the design.
6. Using computer software to make accurate simulations of the dynamic gear system and Load-Intuitive Module (LIM).

7. Optimisation of the final build.
8. Testing the build's ability to ascend a flight of stairs.

The following limitations are associated with the project:

1. All research, design, simulation and testing was to be done inside a 12-week period.
2. A limit of R1500 was permitted for the project.
3. A limited testing environment was available.
4. There were time allocation constraints placed on usage of specialised tools such as laser cutters and 3D printers.
5. A limited supply of 3mm acrylic material was available.
6. The available motors were limited to a maximum torque of 0.196 Nm.

1.4 Plan of development

This project was split into multiple phases that are outlined in the following chapters:

1. **Literature:** details initial research into available literature associated with similar projects or parts of this project. Investigates some of the inner operation details of the LIM's complex gearbox.
2. **Methodology:** details the phases of Ascender's design process and details surrounding how its physical prototypes were designed and implemented.
3. **Results:** reports the extent to which Ascender met the design requirements in the simulation and testing phases respectively.
4. **Discussion:** critiques the abilities of the final build design, the iterative design process and the results of the testing of the final build.
5. **Recommendations:** explores alternative paths of investigation that may solve the outlined problems of Ascender.

Chapter 2

Literature Review

In a world where human lives are said to be priceless, it is a wonder that there are still circumstances where the value of human life is still compared to that of a machine.

Disaster events are unstoppable inevitabilities - and have been since before the existence of humans. As humans built higher and chose to live in more densely-packed areas, the prevalence and toll of disasters increased severely through the years. Currently, disasters are not only occurring naturally but are also the result of wars, failed human infrastructure and other technological malfunctions. Disasters have become increasingly frequent.

As civilisation advanced and humankind discovered more efficient and effective technologies, humans became capable of creating machines to do their so-called 'dirty work' - work which was considered to be too dangerous, dull or dirty to be carried out by human beings. Search and rescue is one of those dangerous tasks - particularly in urban environments where damaged infrastructure can pose a threat. Soon after development of complex machines and electronics came the dawn of Urban Search and Rescue (USAR) robots. They were designed specifically to operate in dangerous environments with the purpose of saving human lives. It was well put by Blitch[7]: Urban Search and Rescue is "...a very dangerous job for human rescuers, poses an almost infinitely difficult spectrum of challenges, and yet provides an opportunity for robots to play a pivotal support role in helping to save lives."

With the realisation of this opportunity came the development of many kinds of robots. The robots' operating environments were harsh, often tough to traverse, and involved challenging obstacles. As such, many of the most capable robots had highly-funded research and development plans and were extremely expensive to manufacture. This extreme investment of resources associated with each robot made them highly valuable in the eyes of their creators; generalised USAR robots were known to cost as much as $4500 [6]. But what if this value was high enough that it be compared to the value of a human life? Or what if this value was too high for the robot to even be affordable by search and rescue teams - particularly in developing countries like South Africa.

In their paper investigating the features needed in general purpose, first response rescue robots, Booysen et al. [8] stated that high-cost robots are simply not affordable by many rescue teams and, for the few teams that can afford one or two, the financial risk of losing the unit heavily impacts the decision of whether to use it at all. They conclude that the robot needs to be of low cost such that "the operator's decisions [do] not [get] constrained by the risking of losing [the robot]" - among other necessities. The same article also mentioned that in past situations, unpredictable terrain like rubble and other debris was often too difficult for the robots to traverse. This required that the units be moved closer to the target location by a person(s). Naturally, the larger robots were much more difficult to carry leading them to conclude that USAR units need to be small enough to be easily transportable by people.

2.1 USAR robots

This section explores literature based on urban search and rescue robots and the approaches taken to design solutions to the tasks demanded by disaster zones.

As stated by Moosavian et al. [9], "The mission for the robots and their operators would be to find victims, determine their situation, and then report back their findings..." These mission parameters closely represented the intended use for the USAR robot designed in this project. The authors later go on to state that the manoeuvrability of rescue robots is the characteristic that dictates their capability and that this is dependent largely on the robot's dimensions and system of locomotion.

Moosavian et al. [9] also discussed the three categories of USAR robot locomotion: wheeled, tracked and legged. Wheeled robots were reported as being the simplest and least expensive although they lacked the ability of tracked robots to navigate uneven terrain and maintain good traction. The most manoeuvrable of the three was the legged robot however it was noted that these typically require a high number of actuators which complicates the dynamic analysis and modelling. With a limited a budget and time, this would not be thought to be a good locomotion method. Furthermore, the development of wheeled robots was considered easier than that of tracked systems as the dynamics were simpler.

The search and rescue robot solution in Muthukrishnan et al. [10], used tracks for its ability to climb stairs and other obstacles generally quicker than wheeled robots. The authors to state that their robot's speed needed to be prioritised "especially during rescue operations where there is a need of evacuation and urgency."

Drawing more on locomotion techniques, a bio-inspired approach to creating an inexpensive, fast, legged robot resulted in the VelociRoACH which was a millirobot capable of running 2.7 m/s. The robot, shown in Figure 2.1, features six semicircular legs each pinned at one end. This is an example of a robot making use of the generally more expensive and complicated locomotion category - legged - while remaining extremely low cost. It was noted that some of the USAR technology rules may have exceptions.

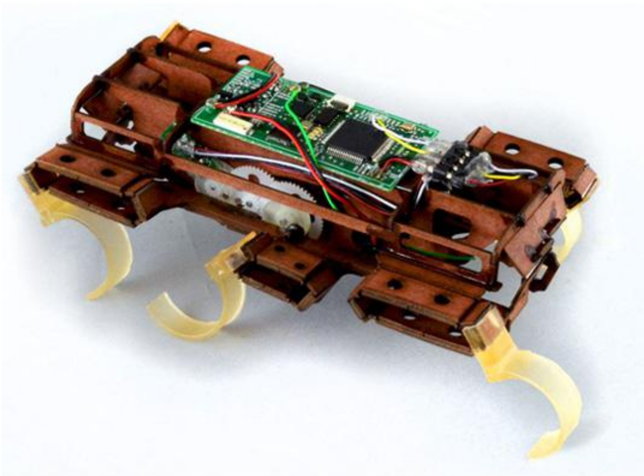

Figure 2.1: VelociRoACH [1]

According to Haldane et al. [1], the robot used two motors - one for each side - which allows differential steering. The inner electronics and motors were placed as low as possible to the ground to lower the centre of gravity which provided greater stability. Furthermore, it was noted that the motor housing provided noticeable structural support which decreased the amount of structural material needed in the body. This robot can also collaborate with an identical unit to climb obstacles as shown in Figure 2.2.

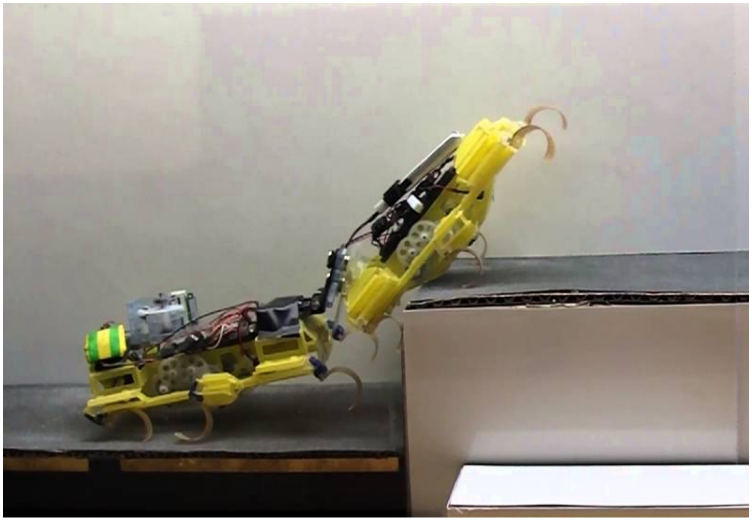

Figure 2.2: Multiple VelociRoACH units climbing an obstacle [2]

According to Mahmud et al. [6], most search and rescue teams only require tele-operable robots while autonomous solutions are only typically used by the military. Special mention was firefighters' general concern for the reliability and adaptability of autonomous robot solutions. As a result, firefighters would generally prefer tele-operation. The paper found that the inclusion of a robot to the firefighting team improved the quality of missions, particularly with regard to speed of the mission and decreased danger posed to the firefighters.

According to Murphy et al. [11], rescue robots can be categorised mainly be modality (how the robot manoeuvres) and size. Size was further defined by being either *man-packable*, *man-portable* and *maxi*. Man-packable robots - along with all tools, batteries and control units - must be able to fit inside one or two backpacks while man-portable robots can be carried over a short distance by two people or a small vehicle. Special transportation efforts are needed to move maxi-sized units. Given the easy portability of man-packable units, they are reportedly more often used in immediate response to disasters since they can be transported by humans "over debris and up and down ladders into the core of the disaster..." As such, objective 3, previously listed in the introduction chapter, was determined to be synonymous with being man-packable.

2.2 Low-cost robot development strategies

Mahmud et al. [6] realised that while many USAR technologies existed in the world, most were affordable only to developed countries. Developing and under-developed countries did not have the budget to afford the implementation of these technologies nor did they have research work to develop innovative methods for mass-producible rescue robots (owing to the lack of funds). The paper investigated the development of rescue robots with limited budgets typical of developing countries; further research was conducted into the effectiveness of reusable materials in robot part production. The authors found that sourcing locally-available materials and components, or re-purposing materials from junkyards, made a significant difference to the cost of the robot. Motors were collected from surplus stores, and wheels were custom made by re-purposing rejected aluminium alloy components from junkyards. Using standardised parts - like metric sized nuts and bolts - also made a significant difference in local availability.

2.3 Rugged terrain and sturdy builds

A military robot named the *RHex* was a larger, more robust robot that had a similar limb-mechanism to the VelociRoACH as seen in Figure 2.3, below. This limb configuration, however, has each semi-circular leg rotating 360 degrees for each cycle. This means that the minimum space the robot can enter is significantly reduced - almost by half. With the objective to keep the robot build small enough to manoeuvre in small spaces, this concept was not thought to be appropriate to the specifications outlining this project. Furthermore, the sturdiness of the robot was largely owing to the entire body being built of hard steel which is a very dense material.

Figure 2.3: RHex - a military solution [3]

2.4 Stair-climbing solutions

This section draws on literature surrounding the solutions to stair climbing in robots.

By using the model of balance or support arms attached to a regular four-wheeled robot, Robillard [4] was able to design an extremely low-profile wheeled robot that was capable of climbing stairs as demonstrated in Figure 2.4.

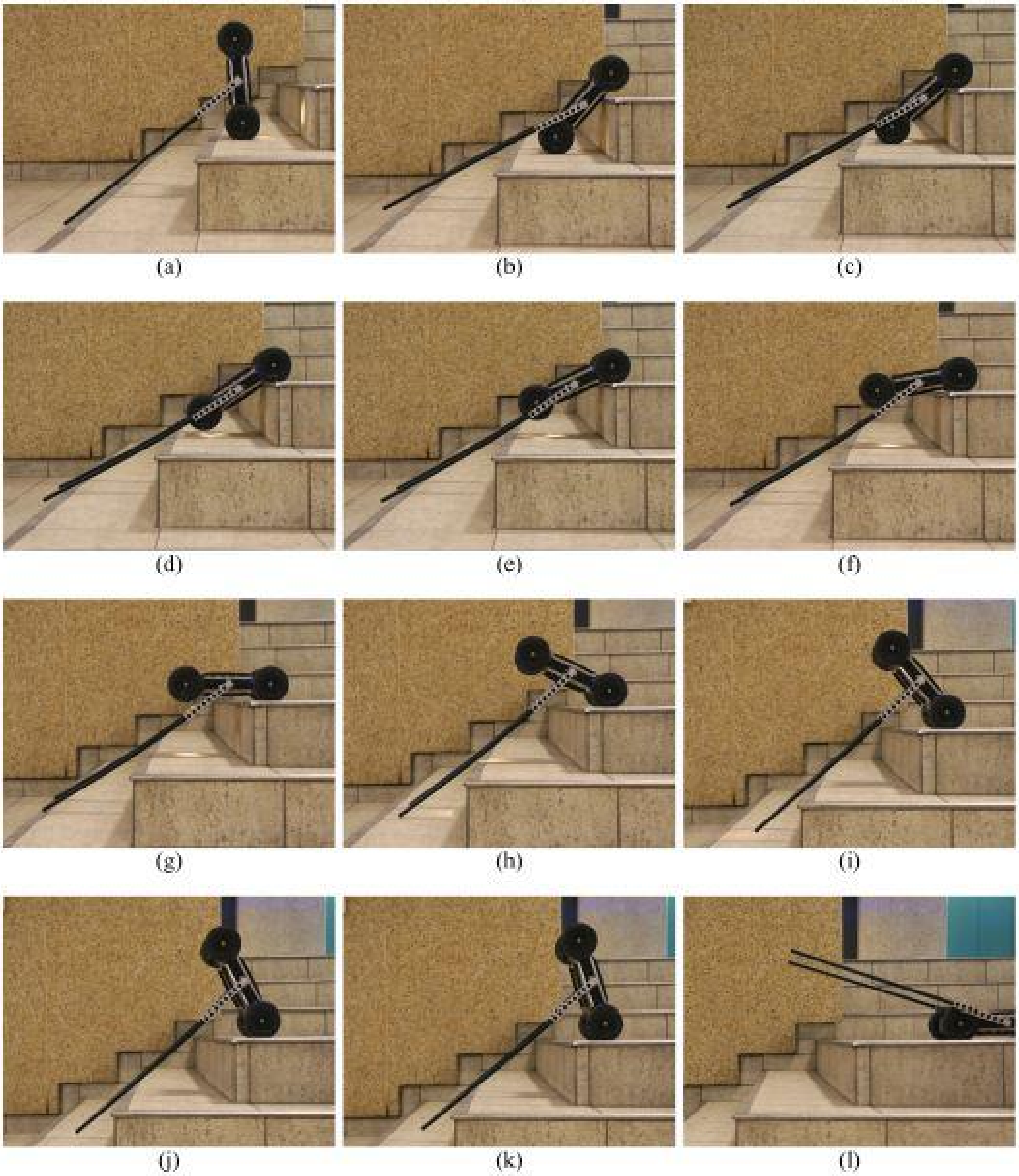

Figure 2.4: Using an arm to provide support while climbing stairs [4]

Upon inspecting images of the inside of the robot build featured Robillard's [4] report, it was surmised that each wheel pair was run by a separate motor, of which there were three in total. Furthermore, a video showing the operation of the robot's stair-climbing ability indicated that the arms/rods that were connected to the middle of each side of the robot body were controlled independently of the wheels. This meant that two parts of the robot needed to be operated for the climbing motion to be initiated. Furthermore, large amounts of computer programming would be needed to gain fine control of this robot. Lastly, with little to no gearing present the three motors needed to have very high torque capabilities to produce the results listed; this had extremely large weight implications on this 5kg robot and was assumed to have equally large cost implications but the overall cost was not included.

The method of overcoming slippage is demonstrated in Figure 2.5. Note that at the points when neither wheel is contacting a surface (a situation referred to as "beaching"), the robot would usually slip (as shown in the top row). Adding grousers to the robot's body prevented slippage (shown in the bottom row). This robot was capable of climbing at a 45 degree angle, was reversible and very robust. Battery life was not tested. Robillard [4] added that future improvements to consider would be autonomous stair climbing.

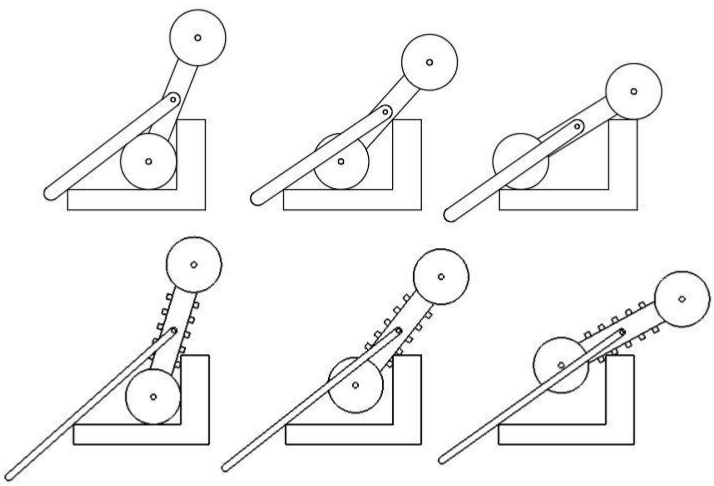

Figure 2.5: The robot without (top row) and with (bottom row) grousers added to its body [4]

It should also be mentioned that one of the main objectives of this robot was to be self-balancing when the robot was in a vertical orientation i.e. it's back wheels were on the ground and front wheels were balanced above its centre of mass in the air. This would have made significant impact to the design choices made in selecting the requirements for the robot.

A University of Cape Town (UCT) masters project by Wilson [5] developed a low-profile robot that could also climb stairs autonomously, i.e. the robot climbed stairs when it reached them without the need of a separate command signal to initiate the climb. While autonomous systems are often much more complicated to design given the complex control feedback programming needed, this specific configuration was automated by its *mechanical design*. This was done through the use of a bi-star drive train connecting two wheels on an arm. These components were named *LIMs* (load-intuitive modules) so-called because of their different behaviours under different loads; refer to the sketches shown in Figures 2.6 and 2.7, following.

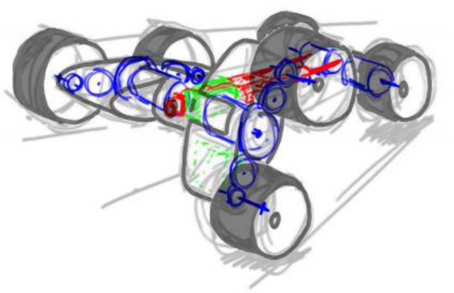

Figure 2.6: A sketch showing the full layout of the robot[5]

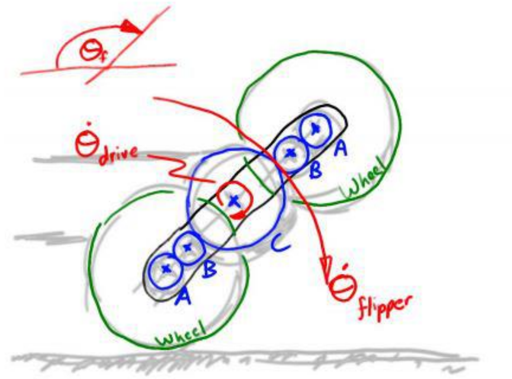

Figure 2.7: A sketch showing the bi-star module kinematics [5]

According to Wilson [5], "when the robot ran up against an obstacle and the wheels jammed, motor torque would be transferred to flipping pairs of wheels over each other to climb the obstacle. This offered a high degree of driving freedom while keeping the number of motors minimised ..." (pp 4). The complexity of autonomous stair-climbing generally relies on complex programming but this elegant design simplified the concept significantly. This design was thought appropriate for a low-cost stair climbing solution. Wilson also carried out limited computer simulations to determine the impact of LIM lengths, distances between front and back LIM pairs and size of wheels to determine the best configuration for climbing the stairs he modelled. A screenshot of this is shown in Figure 2.8, below.

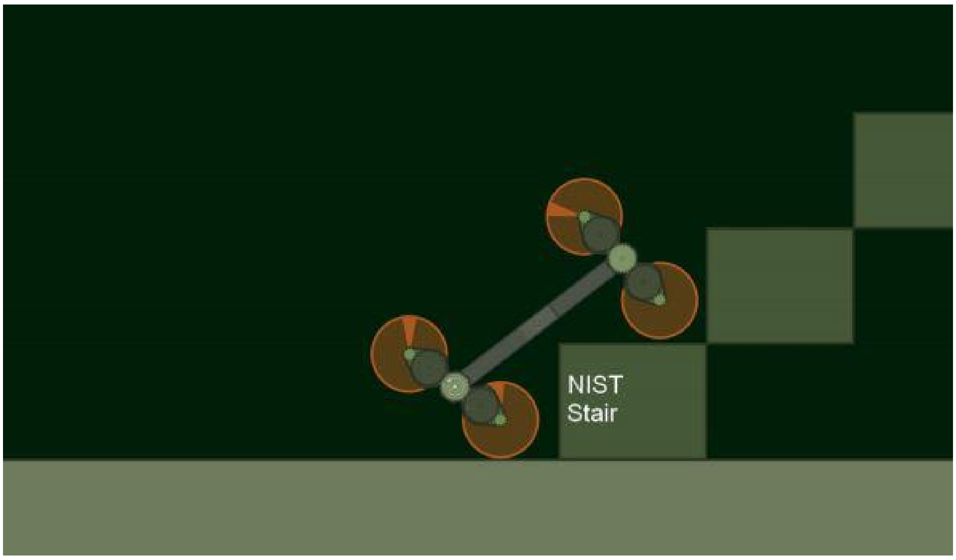

Figure 2.8: Demonstrating the method of climbing stairs [5]

In conclusion, it appeared that Wilson's [5] LIM mechanism would be ideal to provide the stair-climbing functionality required. Generally, the more rugged USAR builds made use of metal components however this would cost more and required slower machining. Maintaining a man-packable size would allow the robot to be deployed deeper into disaster environments more easily than larger ones. Costs could be minimised by using locally sourced materials and components; this was important such that the robot can be affordable to developing countries along with the rest of the world.

Chapter 3

Methodology

It was expected that a small USAR robot - even though inexpensive - would still be complex in nature and would require a design method proven to work over numerous occurrences. The design method used was based on that of Mark Rober [12]. Rober had four stages to every engineering design he had produced: *Research*, *Prototype*, *Sensitivity Analysis*, and *Final Build*. The second and third stages were used repeatedly as iterative changes to the build were made; as issues were solved, others would make themselves known. As such, Rober's four stages were slightly adapted for the development of this project as explained below. Chapter 4, Iterative Design, details and discusses the prototype and sensitivity analysis stages of Rober's method for each design and draws conclusions on each build that would be implemented in future prototypes.

3.1 Research

The initial investigation into solutions to the problem is mostly included in the Literature Review chapter. As the project development progressed, more research was completed as necessary. The initial USAR robot build was based largely on work completed by a student, Jordan Haskel [13] in 2017, who named his build 'Theseus'. The general body structure, LIM shape and much of the dynamics of the complex gearing of Ascender was based on Haskel's project with the intention of later drawing on other literature to overcome its shortcomings. This saw the production of the first prototype.

3.2 Prototype

The prototype stage consisted of two main sections: *design* and *implementation.* This section outlines and discusses the design choices made for each prototype - which are referred to as Mark 1, 2, or 3 from here on. The design stage consisted mainly of introducing new ideas to solve problems that occurred with each build that prevented successful robot function.

Prototypes were each designed using a CAD software, Solidworks, and were later laser cut from acrylic or hardboard as these were able to be locally sourced and would contribute to cost minimisation according to Mahmud et. al. [6]. Generally, parts that needed to maintain high structural integrity were made out of acrylic as hardboard was known to weaken with use. Parts were generally bolted together using small (M3-M4) bolts - particularly the parts that needed to rotate such as gears. Where parts needed to be permanently secured together in a rigid manner, locally-sourced super glue was used as this dried quickly, was inexpensive, was easy to use, and reduced the complexity of assemblies like the motor gearbox. All Solidworks models - including other videos and photos - are available through my GitHub profile, *murrayb52*, or through the following URL: bit.ly/BuchananUSARThesis.

The implementation section in each prototype briefly discusses the assembly process; it also discussed the design choices made for the current iteration that could be improved in the following iteration in regards to the practicality and speed of assembly, or in the interest of repairability and mass-producibility.

3.3 Sensitivity Analysis

The sensitivity analysis stage assessed the limitations of each prototype; for each iteration, the sensitivity analysis is discussed in the testing section and conclusions drawn relating to the design. Generally, the testing would be done in a lab environment to protect the parts of the robot as some parts were reused in other prototype iterations. The inefficiencies or faults found through the testing stage were improved in the prototype phase of the subsequent build iteration. Testing also uncovered limitations in each iterative prototype's ability. These were factors that did not prevent the prototype from functioning outright (like faults did) but that could be improved to prevent future potential faults or to accommodate foreseen potential benefits.

3.4 Final Build

The final build stage incorporated all the investigation from the previous prototypes into one final robot design. It discusses the design choices made and outlines the expectations of the design's ability.

Chapter 4

Iterative Design

This chapter details the life cycle of the Ascender's development. Each iteration of the cycle comprised a design, implementation and testing phase as previously explained in the Methodology chapter - to produce a new prototype and determine which improvements were needed. The aim of the initial stages of the iterative design process was to design a build with LIMs that would flip when the wheel rotation was halted upon making contact with a stair. The first build was based largely on that of Haskel's Theseus robot [13] followed by the carrying out of an iterative improvement process drawing from other literature as necessary, until the final build requirements were determined.

4.1 Elements used in all design iterations

Some elements of the project were used in all design iterations - or at least were relevant to all design. These elements are included following, before the sections discussing each iteration.

4.1.1 Motors

The motors used were the same as those used by Haskel - the Mantech EGB 12 V motor - as this was a relatively low cost motor and was readily available. Secondly, it was thought important to determine whether recreating the Theseus build with the same motor would produce similar results. The 0.196 Nm brushed motor is shown in Figure 4.1.

Figure 4.1: The Mantech EGB 12 V (0.196 Nm) DC motor.

The technical drawing of the motor can be seen in Figure 4.2. These dimensions were used to design the gearbox which is introduced later. Notice how the motor output shaft is offset from the centre of the motor - this helped create a simple mount to house the motor securely as is detailed later on.

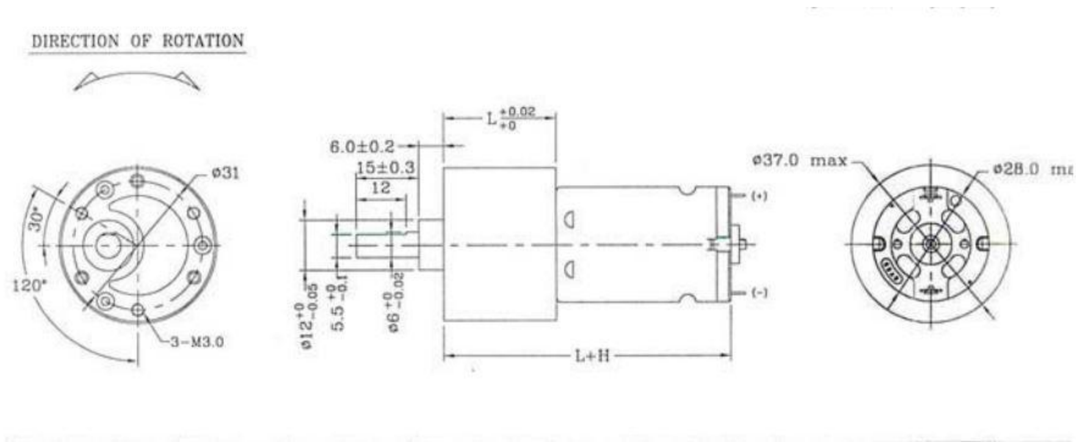

Figure 4.2: The physical dimensions of the Mantech EGB 12 V (0.196Nm) DC motor.

The inexpensive materials available at the time were hardboard (3 mm) and acrylic (2 mm and 3 mm). Haskel constructed Theseus using multiple 3 mm acrylic and hardboard parts that he had designed and laser cut using the UCT Engineering and the Built Environment (UCT EBE) department's laser cutter. It was decided that Haskel's approach to forming the robot's parts had obvious merits, as listed below:

- Rapid design: designing flat parts meant that only two dimensions of the part had to be designed.
- Rapid production: the laser cutter was expected to be able to produce a whole robot build within an hour.

- Accurate: Haskel reported that using the laser cutter produced parts that fitted well.*
- Laser cutting is much cheaper and quicker than methods like 3D printing which can take hours to print a single part.

*Haskel did also mention that - owing to the 0.2 mm tolerance - some circular cuts did not turn out as accurate as intended. However it was thought that this could be compensated for.

Due to these advantages, it was decided to follow the same process as Haskel - laser cutting multiple flat parts and fastening them together to create the assembly. This method was later found to be forgiving when attempting to space the gears sufficiently but meant that builds had a restriction on the order in which parts could be assembled.

4.1.2 LIM kinetics

The most important element of the stair-climbing design was that of the LIM (Load-Intuitive Module) mechanism which Haskel had previously developed from Wilson [5]. The LIM's 'flipping' motion is shown in Figure 4.3. The orange, green and turqouise circles represent spur gears which interact with each other to form a complex gear train. The drive gear A (orange) drives the wheels that are connected to gear C (turqouise) through the idler gear B (green). All the gears' shafts are housed by the arm.

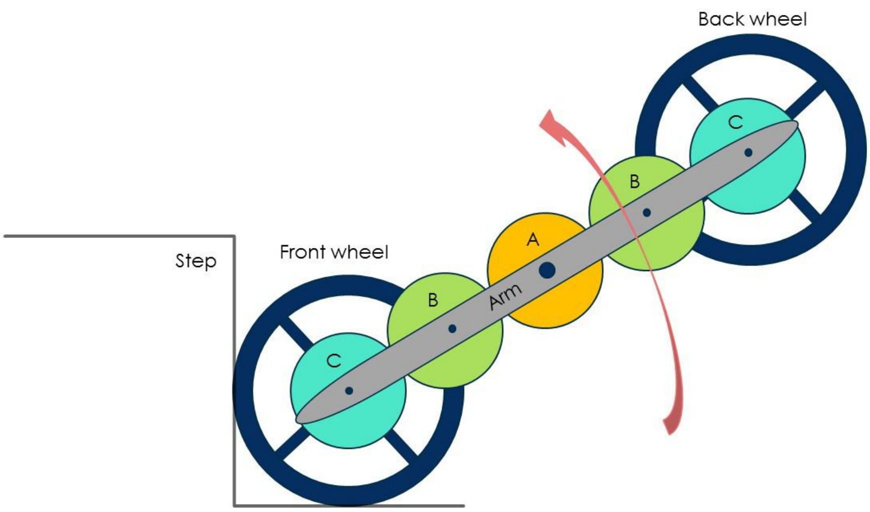

Figure 4.3: A model of the Load-Intuitive Module (LIM) as described by Wilson [5].

Due to the complex gear train setup, when wheel rotation is halted, the arm of the LIM rotates - in the direction of rotation of gear A - *instead* of the wheel as indicated by the red arrow. During normal operation, the wheels simply rotate in the direction of the drive gear A and propel the body along the ground but the LIM's ability to 'flip' was harnessed in the development of a prototype build that could climb stairs. It was intended that a robot, featuring two LIMs, would drive along until it came into contact with an obstacle such as a step; the friction between the front wheels and the ground and step surfaces was intended to halt wheel rotation such that the LIMs flipping motion would climb the stair.

Table 4.1 below shows the dynamic gearbox method used to better understand the working of the complex gear train in each LIM and how each gear affects LIM functionality. These calculations were based on the model in Figure 4.3. In order to work out the functioning of the LIM gear train, Gear C was rotated by an angle θ with the arm locked to it and then rotated back by the same angle without it being locked to the arm. The angles were translated into rotational speeds in Table 4.1 such that they would be useful in subsequent calculations. The interactions with the other gears are shown in terms of the number of teeth and other significant speeds.

	Gear A	Gear B	Gear C (fixed)	Arm
Motion relative to frame	$\dot{\theta}_{wheel} = \dot{\theta}_{arm}$	$\dot{\theta}_{arm}$	$\dot{\theta}_{arm}$	$\dot{\theta}_{arm}$
Motion relative to arm	$-\frac{N_C}{N_A}\dot{\theta}_{arm}$	$\frac{N_B}{N_A}\dot{\theta}_{arm}$	$-\dot{\theta}_{arm}$	0
Total	$\dot{\theta}_{arm}(1 - \frac{N_C}{N_A})$	$\dot{\theta}_{arm}(1 + \frac{N_C}{N_A})$	0	$\dot{\theta}_{arm}$

Table 4.1: Determining the factors of the gear train that affected its operation.

The total movement of Gear A - which was rotated with the drive shaft - was equal to the rotation of the drive shaft, resulting in the following expression:

$$\dot{\theta}_{drive} = \dot{\theta}_{arm}\left(1 - \frac{N_C}{N_A}\right) \tag{4.1}$$

It was noticed that the direction of the arm rotation was dependent on the drive shaft rotation. Since it was intended that these rotate in the same direction, the following expression was reached:

$$1 - \frac{N_C}{N_A} \geqslant 0$$

$$\therefore \frac{N_C}{N_A} \leqslant 1$$
$$\therefore N_A \geqslant N_C \tag{4.2}$$

According to Equation 4.2, in order for the LIM to flip in the same direction in which the drive shaft and wheels rotated, the number of teeth on Gear A needed to be greater than that on Gear C.

Equation 4.1 could also be rewritten as $\omega_{drive} = \omega_{arm}\left(1 - \frac{N_C}{N_A}\right)$ to better represent the expression in terms of torque and angular velocity. And since the power of an ideal gearbox was known to be $P = T\omega$, the following expression was reached:

$$T_{arm} = T_{drive}\left(1 - \frac{N_C}{N_A}\right) \tag{4.3}$$

Including a gearbox with a torque reducer/multiplier was expressed by Equation 4.4:

$$T_{drive} = T_{motor}\frac{N_{drive}}{N_{motor}} \tag{4.4}$$

This resulted in a final equation - Equation 4.5 - that expressed the torque exerted on the arm of the LIM due to the complex gear train. Note: this equation was only applicable to the LIM's flipping motion and, hence, required wheel rotation to be halted in order for it to hold true.

$$T_{arm} = T_{motor}\frac{N_{drive}}{N_{motor}} \times \left(1 - \frac{N_C}{N_A}\right) \tag{4.5}$$

Note that T_{motor} is a constant value of 0.196 Nm as specified by its datasheet [14]. Analysing this equation shows that the torque applied to the LIM arm for the flipping motion is affected by both the LIM gear ratio and gearbox gear ratio.

4.2 Mark 1: first prototype

The first prototype was designed similar to Haskel's build in an attempt to further develop his design. Haskel named his robot *"Theseus"* which is what his build shall be referred to henceforth. The LIM specifications such as the gear ratios and diameters, horizontal length of the LIM and the general construction were kept almost entirely the same as those of Theseus. It was intended to determine if recreating the same LIM build would produce similar results to those found by Haskel. Some minor changes were made to increase the practicality of the build - for example, a third support frame was used to support the wheel shaft and prevent wobbling in the wheels which was one of the problems that Haskel found with Theseus.

Given that Mark 1 was based on Theseus, some context is provided of Theseus' characteristics and features, before detailing the iterative design process that saw the development of this project's stair-climbing USAR robot solution. Theseus' hardboard body was box-shaped and measured roughly 180 mm by 130 mm by 60 mm with multiple small holes cut out of the sides of the box. Haskel had chosen to initially secure the two motors to the body using cable ties, however this was never changed and the hardboard body significantly weakened with time due to these holes. This resulted in the motors having lots of play, i.e. their shafts were not kept collinear with each other as their positions could be adjusted by hand with a relatively low amount of force. This was especially problematic when the robot was placed on a surface as the LIM wheels forced the motors' centre axes to point upwards slightly. Haskel reported that he faced problems with wheels being skew and wobbling under the weight of the body - this was assumed to be due to ineffectiveness of securing the motor to the body with cable ties. Furthermore, because the cable ties simply wrapped around each motor body, which was cylindrical, the motors were able to rotate slightly too which introduced delayed LIM reactions to motor shaft rotation directions. therefore, Haskel's body was redesigned from scratch to accommodate the motors better. Thus Mark 1 featured a rigid motor housing whose purpose was to properly secure each motor shafts rotational axis parallel to the ground and collinear with each other to prevent either motor from shifting.

4.2.1 Design

LIM mechanism

As previously mentioned, the first LIM design was based closely on the ones featured in Theseus - with some minor changes. It was thought to only use acrylic in the construction of the LIM since acrylic wouldn't flake, weaken or warp the way hardboard might - and did, in the case of Theseus - particularly if super glue were to be involved. Haskel took largely the same approach, but used hardboard for smaller parts. The Solidworks modelling of the Mark 1 LIM is shown in Figure 4.4 below.

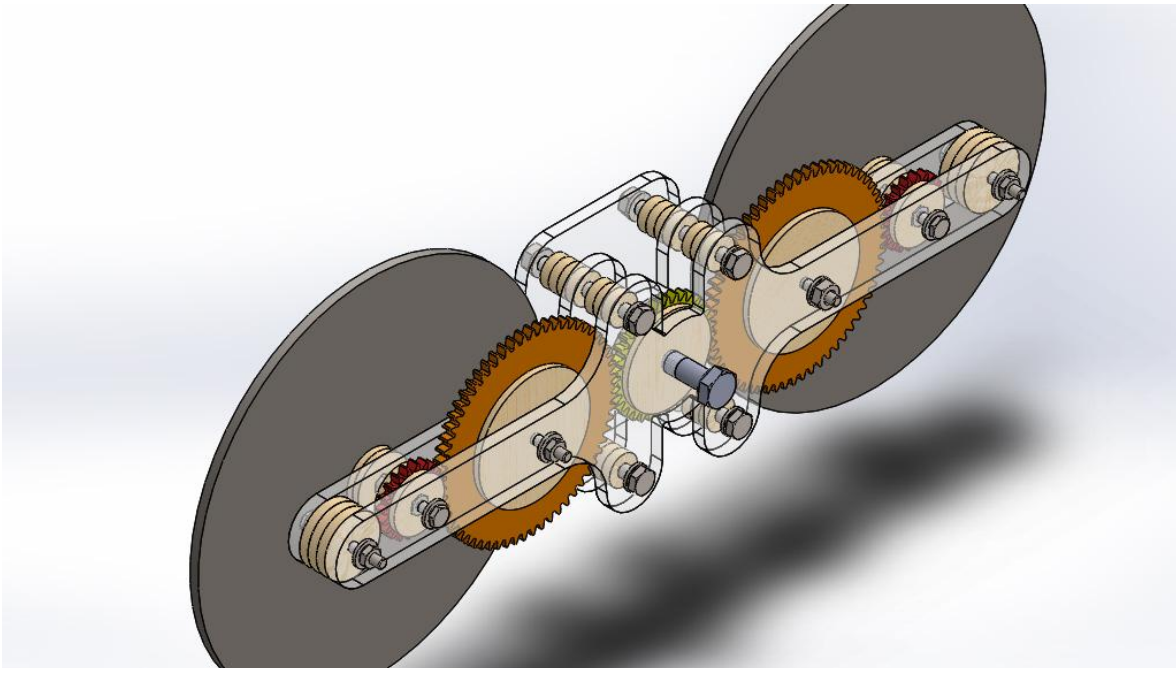

Figure 4.4: Recreation of Haskel's Load-Intuitive Module (LIM).

Since Theseus suffered from wobbling, it was decided to redesign the LIM with more attention to gear spacing and shaft support. It was first noticed that Theseus' wheel shafts were only supported on one side of the wheel as seen in Figure 4.5 below.

Figure 4.5: Haskel's Theseus robot showing wheel shaft only supported on one side of the wheel (top view).

It was thought that the main contributor of Theseus' skew wheels was the lack of wheel shaft support and that by fastening another support frame to the LIM on the far side of the wheel, the wheel shaft would be better supported and thus provide more stability for the wheel. Thus the outer support frame was included in Mark 1; Figure 4.6 shows this outer support frame (green).

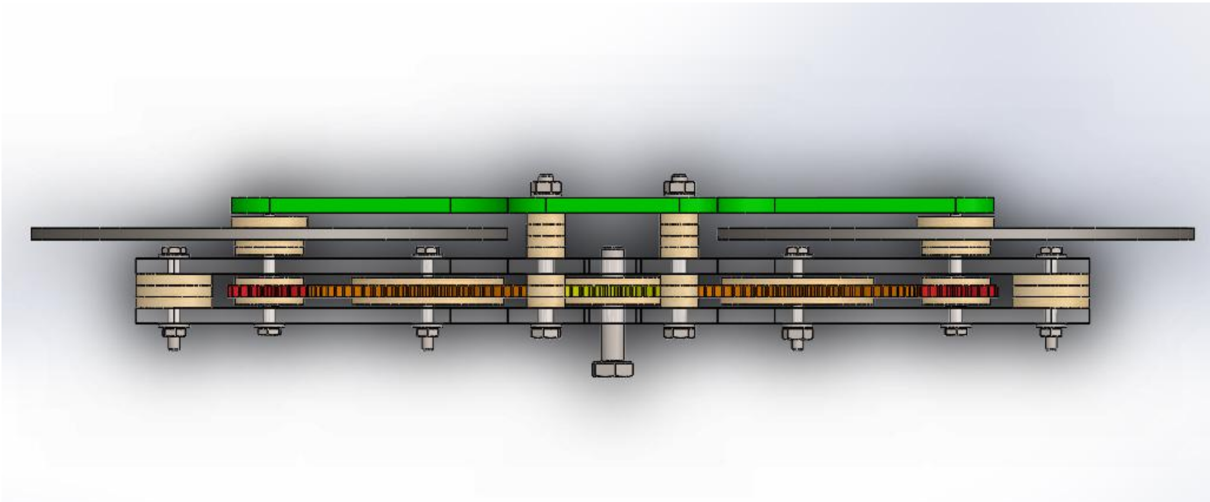

Figure 4.6: Top view of the LIM showing the outer support frame (green) added to LIM Mark 1.

The next step was to focus on successful gear spacing such that there was enough of a clearance for the gears to spin easily while not giving them too much room that they may wobble on the shaft. Assessing Theseus' build indicated that the LIM gears experienced significant friction from the spacers as there was not a large enough clearance and the adjacent support frame. Furthermore, the spacers - which had been cut from hardboard - had appeared to have swelled slightly at their ends which was assumed to be due to moisture getting into the hardboard through the un-sealed circumference of the spacers. therefore, the spacers were chosen to be made of acrylic. Further, it was designed to create an accept spacer-frame clearance by taking advantage of the different thicknesses of acrylic material locally available.

Figure 4.7, a zoomed top view of the LIM shows the technique used to create adequate spacing for the gears. Note that the purple parts are the inner support frames, the yellow parts are 3 mm spacers and the green parts are 2 mm gear spacers. The two inner support frames were placed at a distance of 9 mm apart from each other using three 3 mm spacers at their ends. Each gear was designed with a thickness of 3 mm while each gear spacer was kept at 2mm. This resulted in a clearance of 1 mm between each gear spacer and inner support frame

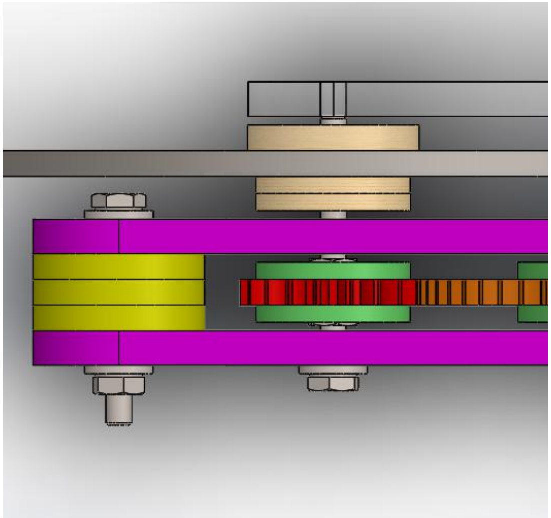

Figure 4.7: An enlarged top view of the LIM showing the gear spacing technique.

It was thought that completely removing the gear spacers to further reduce the distance between the inner support frames might result in the inner support frames directly interfering with the gear teeth. This would have increased transmission power losses or halted gear rotation entirely which reinforced the design choice of using spacers on either side of gears.

M3 bolts were chosen to serve as all fastening bolts except for those that fastened the inner and outer support frames together - these were M4 as they needed to be longer than the longest available M3 bolt. The spacer diameters were not thought to be crucial dimensions. Generally, they were just made big enough such that they could be put in place easily during the assembling of the build; to do this meant being able to hold the gear spacers in place while threading the M3 bolt through the parts. The spacers were made smaller than all their corresponding gears so that they didn't interfere with the teeth of adjacent gears. The spacers were on average 25 mm in diameter but some sizes varied according to use.

Motor Gearbox

As previously shown in Figure 4.2, the motor shaft was offset from the centre of the motor. Taking advantage of this meant that a simple mount could be designed to keep the motors secured to the body of the robot while also preventing unwanted motor body rotation (not to be confused with motor shaft rotation which is what would drive the LIM mechanism).

Theseus' LIMs were driven directly by the motor - which had a very short shaft of 15 mm - which sometimes caused interference with the body as is evident by the marks on the body shown in Figure 4.8, right. In order to prevent this, it was decided that the LIM drive shaft needed to be longer. Therefore the motor mount was also made to accommodate two gears, one of which would accommodate the drive shaft. Furthermore, this allowed for the gear ratios to be easily explored later.

As the motor mount also featured two gears, it is henceforth referred to as the *gearbox*. The first gearbox design can be seen in Figures 4.9 and 4.10 below.

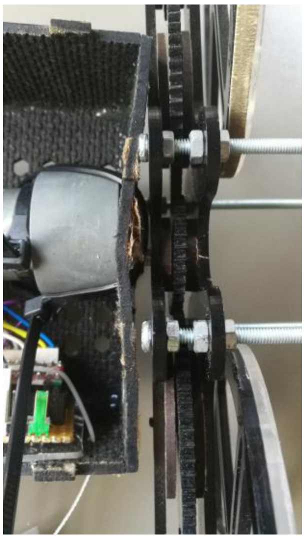

Figure 4.8: Top-down view showing small clearance between Theseus' body (left) and LIM (right).

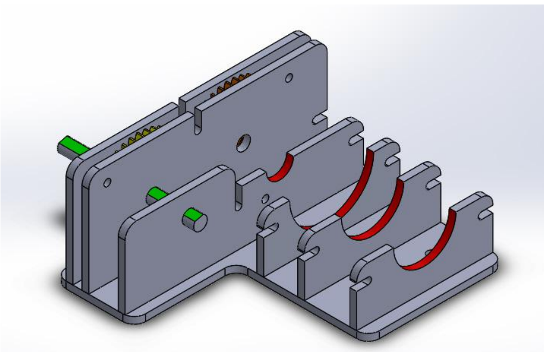

Figure 4.9: Motor gearbox isometric view: motor side

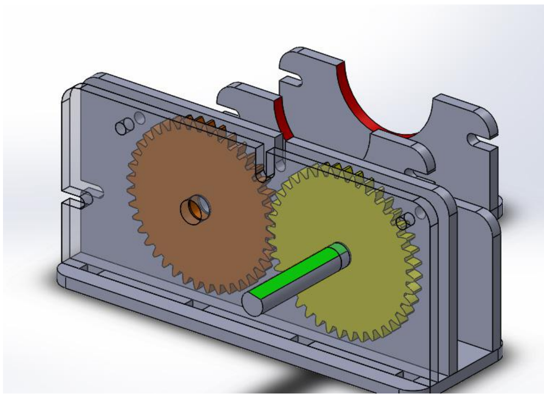

Figure 4.10: Motor and drive gears displayed in orange and yellow respectively.

The uprights of the gearbox were designed to fit into the gearbox base in a tooth and slot puzzle-like manner as shown in Figure 4.11 below.

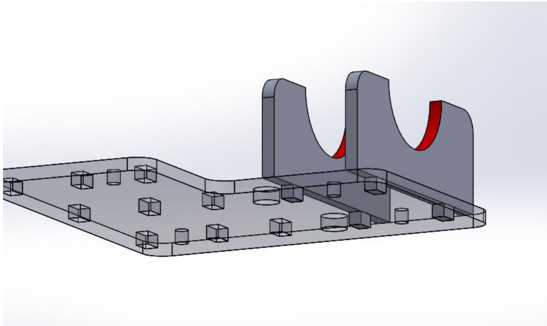

Figure 4.11: A view of the underside of an incomplete gearbox showing the tooth and slot method for uprights.

The motor gearbox was designed to accommodates one motor (not shown), motor gear (shown in orange) and drive gear (shown in yellow). Note that the drive gear refers to what drives the LIM - the drive gear itself is actually *driven* by the motor gear. The faces shown in red indicate where the motor was to be positioned. The red surfaces are concentric to the motor's faces which allowed the weight to be spread along a larger surface. The motor shafts had a D-shape profile on them so by cutting a hole with the same profile on the centre of the motor gear, torque could be transmitted from the motor to the motor gear along the motor shaft. This system was mimicked for the drive gear: the flat section of the D-profile shaft is show in green in Figure 4.9. This was intended to further transmit the motor torque to the LIM via the drive shaft.

Notice in the same figure that the drive shaft protrudes through three uprights in the gearbox. This was designed to increase the distance over which the drive shaft was supported on the gearbox side; if the third, closer upright - from the perspective of Figure 4.9 - had not been included, the drive shaft would have only been supported over a 10 mm distance which would likely have resulted in an unacceptable amount of play. It was thought that play would prevent the drive shaft from rotating smoothly in the uprights which may have caused further assorted problems such as excessive wear of the holes, or gear rotation being halted by the gearbox uprights because their rotational plane was not vertical.

The gear ratio was initially chosen to be 1:1, i.e. the number of teeth on the motor gear was the same as the number of teeth on the drive gear. This was decided so that the LIM mechanism would receive roughly the same amount of torque in Mark 1 compared to that of Theseus. An advantage of this design was that the gear ratio could be changed in future with relative ease - an adjustment that was thought likely to be needed in future iterations.

The build's body was to feature two gearboxes - one for each of the two LIMs - which would be secured to a 3 mm hardboard base as show in Figures 4.12 and 4.13 following. Both the gearboxes and the body base - which was shown as wooden in the same figure - had collinear holes cut out of them such that the parts could be easily secured together using M3 bolts; this also meant that gearboxes could be easily replaceable if they were to ever break or need improvements. In order to secure the motor to the gearbox mount/housing, an M6 U-bolt was chosen to be placed over the motor and through 6 mm holes that were cut through both the gearbox and hardboard; this was designed to be fastened with nuts on the underside of the base. An M6 U-bolt was used because the radius of its curve happened to be almost exactly the radius of one of the sections of the motor body.

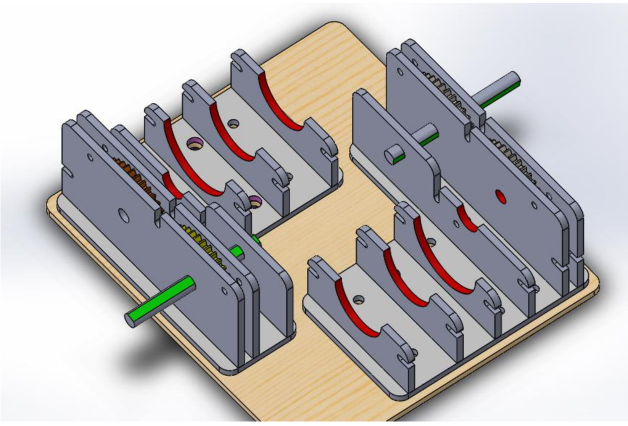

Figure 4.12: Both gearboxes positioned over the body base.

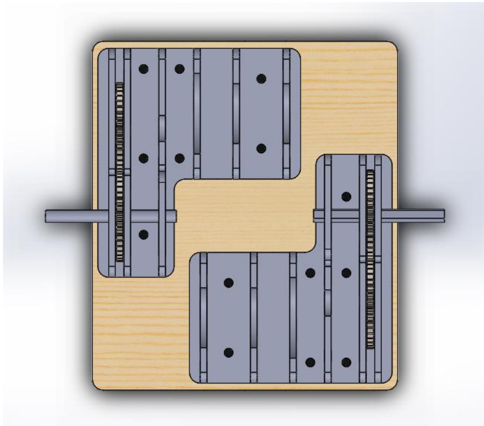

Figure 4.13: Each gearbox secured to base using bolts.

The full Mark 1 robot assembly is shown from different views in Figures 4.14 to 4.17 to provide a better understanding of the shape of the full robot build. In some of the views, certain parts -generally gearbox uprights - have been made transparent to show more detail - generally gears. This is indicated in each figure's caption.

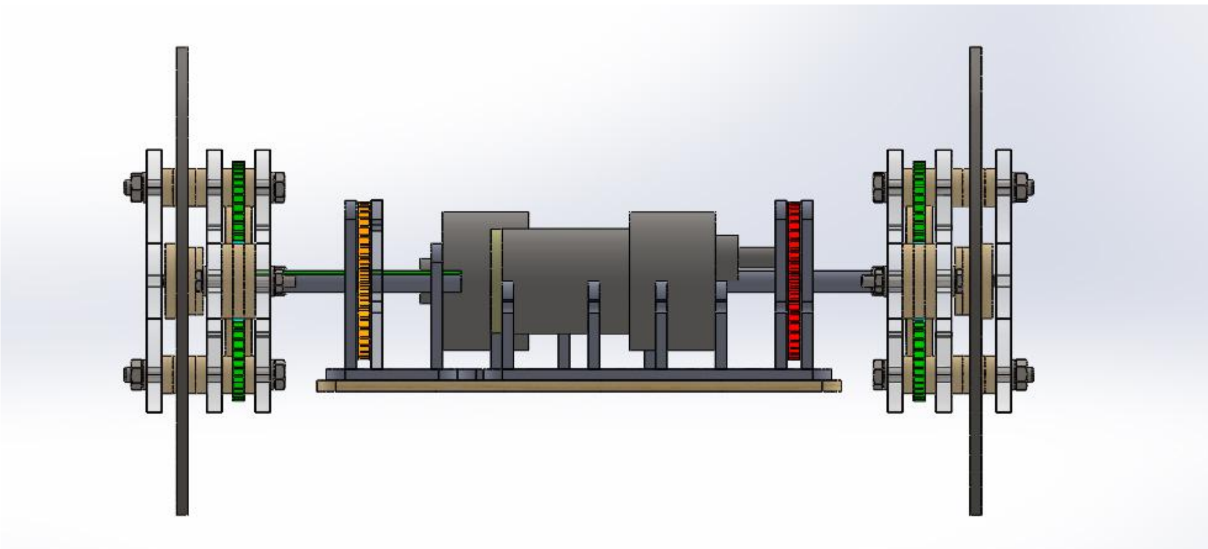

Figure 4.14: Front view of Mark 1 assembly.

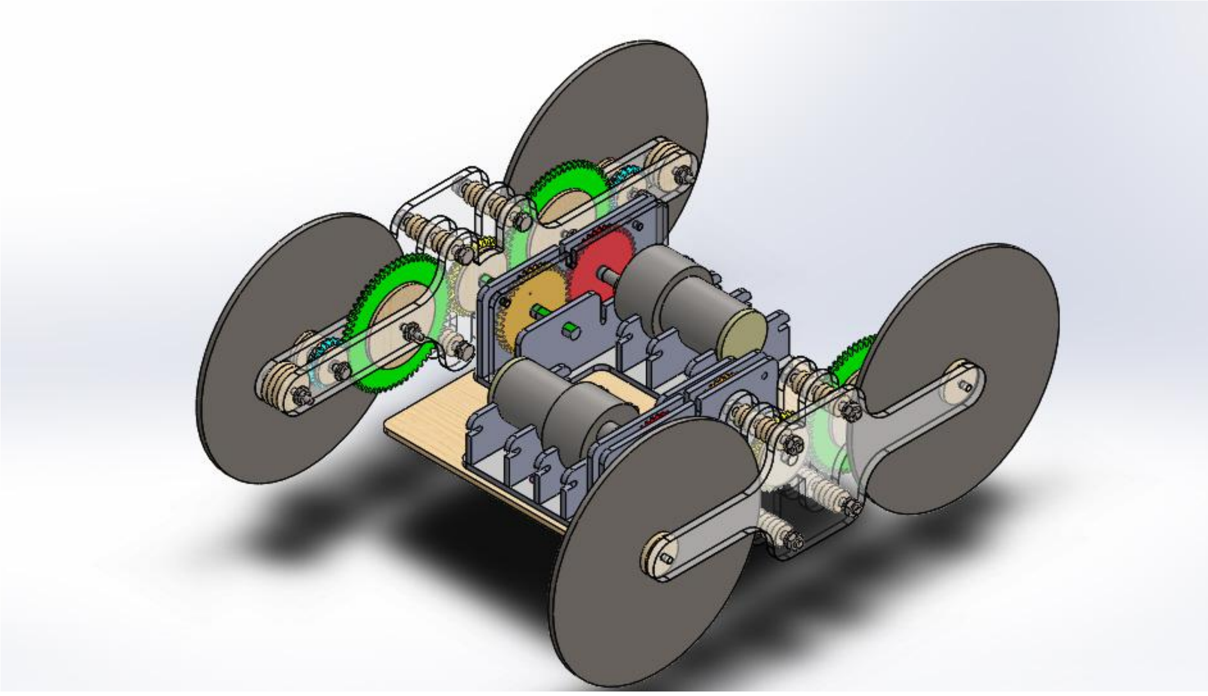

Figure 4.15: Isometric view of Mark 1 assembly (transparent gearbox upright to show gearbox gears).

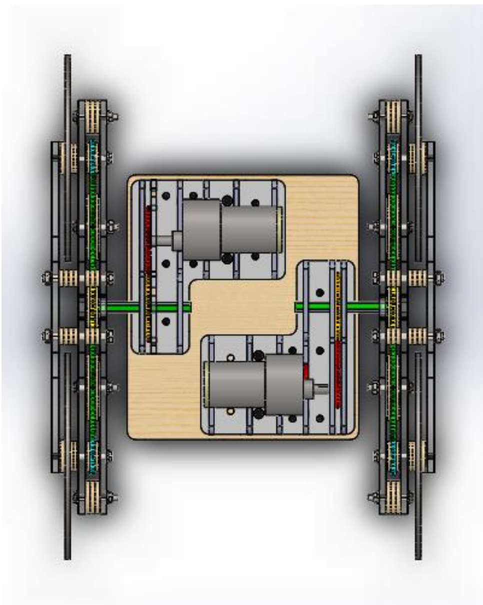

Figure 4.16: Top view of Mark 1 assembly.

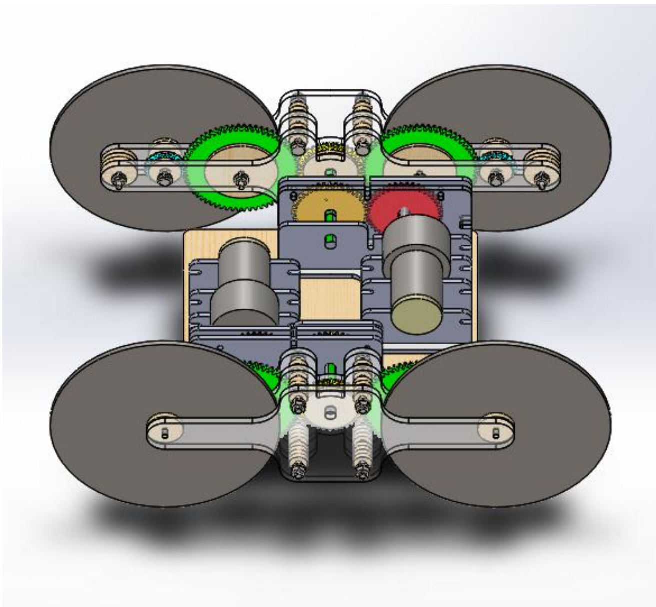

Figure 4.17: Raised side view of Mark 1 assembly (transparent gearbox upright to show gearbox gears).

4.2.2 Implementation

The implementation briefly describes some of assembly that may be useful to the reader. Impracticalities with assembling the build are discussed.

Gearbox

The drive shafts with D-profiles that were designed to transmit torque from each drive gear to each LIM could not be sourced cheaply at the time. It was thought that the UCT mechanical workshop would be able to accurately machine them, however it was decided that this would require too much wait time - especially if multiple attempts needed to be made to perfect its cross-sectional shape. Instead, a metre-long M6 threaded bar was purchased cheaply, cut down to size and filed down to the correct shape. This was done by securing the threaded bar in a vice with a small portion protruding out the top (when looking at it horizontally) and filing it down to the vice 'teeth'. Using a metal vice ensured that filing the threaded bar would produce a flat surface as designed; this was because the metal vice was made of a much harder material than the threaded bar. This process was less accurate than machining a shaft with D-profile but was considered a good compromise with the view of continued rapid prototyping.

It was noticed that motor mounts of Mark 1 were positioned on the body in such a way that meant the drive shafts were not actually collinear. This was only realised upon closer inspection after the build had been completed. It was noted as an obvious flaw that needed to be changed but testing continued despite the flaw. Since the drive shafts were not collinear, this meant that one of the LIMs was situated further towards the front of the robot in relation to the other. Therefore it was realised that, during the climbing process, the further forward LIM would collide with the step first and likely cause the robot to turn until the further backward LIM collided with the step. This would have resulted in the robot climbing up staircases skew which may have further resulted in it eventually falling off the staircase or being stopped by a wall running parallel to the staircase. It was concluded that this needed to be changed in Mark 2.

During construction of the first gearbox, it was realised that the motor shaft only protruded 15 mm from the motor which was less than the distance to the intended position of the motor gear. This is shown in Figure 4.18, right.

Unlike the drive shaft (which could be made for the required length) the motor shaft was a fixed length as it was part of the motor. therefore, an impromptu remedy was made by removing the left upright - from the perspective of Figure 4.18 - that accommodated the motor shaft and positioning the motor gear between the motor and the middle (and only remaining) upright that supported the motor shaft.

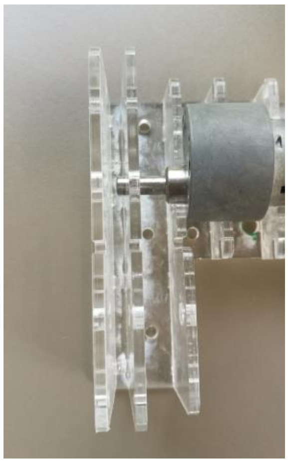

Figure 4.18: Motor shaft not long enough reach left gearbox upright.

This decreased the distance over which the drive shaft was supported by 7mm, leaving a relatively small support distance of 13 mm between uprights. This resulted in an unacceptable amount of play, most noticeable with the LIMs attached to the body and the robot resting on the ground. After connecting the LIMs to the drive shaft, it was noticed that an unacceptable leverage force was being placed on the gearbox uprights by the body and LIM configuration.

The laser cutter, which was able to cut very complex shapes, was found - as Haskel had warned - to have a slight error value due to its beam width. The firmware operated in such a way that the beam cut in the middle of any cut lines which resulted in features like holes and slots for shafts being slightly bigger than intended. therefore, this resulted in a noticeable amount of play when fitting parts together or inserting shafts into their housings. It was concluded that crucial fits should compensate for the beam width.

However, it was noticed that the slots which had been designed to tightly accommodate the teeth of the uprights were wider than intended which resulted in the uprights being able to lean at about a 10 degree angle to the vertical. These were then secured to the gearbox base using super glue and held in place until dry. However, after super gluing the gearboxes, it was noticed that some of the uprights on the second gearbox were not vertical. This difference was not noticeable enough in photographs for an image to be provided, however it was significant enough to prohibit the motor shaft from lying horizontally - an effect that carried through to the motor gear and caused it to lie askew to the vertical - and the drive gear. The spur gears were designed to interact within the same plane and since these two did not - since the motor gear was skew - it was surmised that this reduced the efficiency of their interaction considerable. This assumption was based on the fact that the second gearbox was noticeably noisier than the first during motor operation; the interlocking teeth on the two gears appeared to snag each other at times too, although the extent to which this occurred could not be measured.

LIMs

The LIMs slotted over the drive shaft securely and with little force required. However, it took roughly 2 minutes to insert each drive shaft through a LIM's drive gear and coaxial spacers - all of which had a D-profile opening - because the gear and spacers were difficult to grasp over the LIM frame. It would have required less effort if the diameter of the spacers was larger such that they protruded slightly, however assembly continued. The spacer diameters were changed in a later iteration. It was fortuitous that the spacers and drive gear could not fall out from in between the inner frames as the M4 support bolts were positioned close enough together to prevent this.

The LIM inner frames had been designed to be 9 mm apart by using sets of three spacers (of 3 mm thickness) and fastening the frames together using a bolt through these spacers. However, upon construction of the LIMs, it was noticed that a 1 mm clearance on either side of each gear was too large as this resulted in gears wobbling significantly on their shafts. Secondly, pushing one gear up to an inner support frame and pushing an adjacent gear up to the *other* frame, left only a 1 mm gear overlap; this could have resulted in gear teeth breaking off due to excessive forces at their edges. Furthermore, if the gears were to tilt on each of their shafts slightly, the overlap may have decreased until gears lost contact with each other entirely. therefore, the distance between the inner support frames was decreased to 8mm. Since the M3 nuts were roughly 2 mm deep, this remedy was completed by replacing two of the 3 mm spacers in each set with M3 nuts. This resulted in the inner frames being secured at roughly 8.3 mm apart. This made the assembling phase of the LIM slower and more cumbersome but it was an effective solution that did not produce any problems during the duration of the assembling process.

There were five different gears positioned in each gearbox-LIM pair. The gearbox featured the motor and driver gears. The LIM featured one *Gear A*, two *Gear B*'s, and two *Gear C*'s. The torque chain followed this order: motor gear, drive gear, Gear A, Gears B, Gears C - the last of which were required to drive each wheel. Each Gear C had to be secured to the wheel shaft such that the two rotated at the same speed at all times. Initially, this was attempted by positioning two nuts on the shaft - one on either side of the gear - and screwing them together as tight as possibly. However, since Gear C was subjected to an immense amount of torque over just 20 teeth, it often would come loose and spin freely on the wheel shaft. Although it was not considered to be a neat solution, squeezing super glue over the thread and repeating the previously mentioned solution again (such that the nuts were threaded over super glue) appeared to be effective. Neither Gear C came loose for the duration of testing of Mark 1. Unfortunately, this compromised the ability to make adjustments to the positioning of the shaft and any parts positioned on it.

4.2.3 Testing and Analysis

This section details the testing that Mark 1 underwent as well as analysing its strengths and weaknesses. These are then discussed and conclusions are made which influenced the following build iteration. Neither the motors, nor any parts were replaced between tests unless explicitly indicated. All tests made use of a 12 V ATX power supply to power the motors; this was done by connecting the supply directly to the motors - no control systems were used.

The first round of testing aimed to determine whether Mark 1's torque abilities met the minimum requirements for the LIM to flip starting stationary at the worst possible angle. Therefore, the system needed to be modelled to determine this worst angle. Refer to Figure 4.19 below showing the forces and torques acting on the LIM. Note: the diagram was limited to only including the forces that affected the LIM arm.

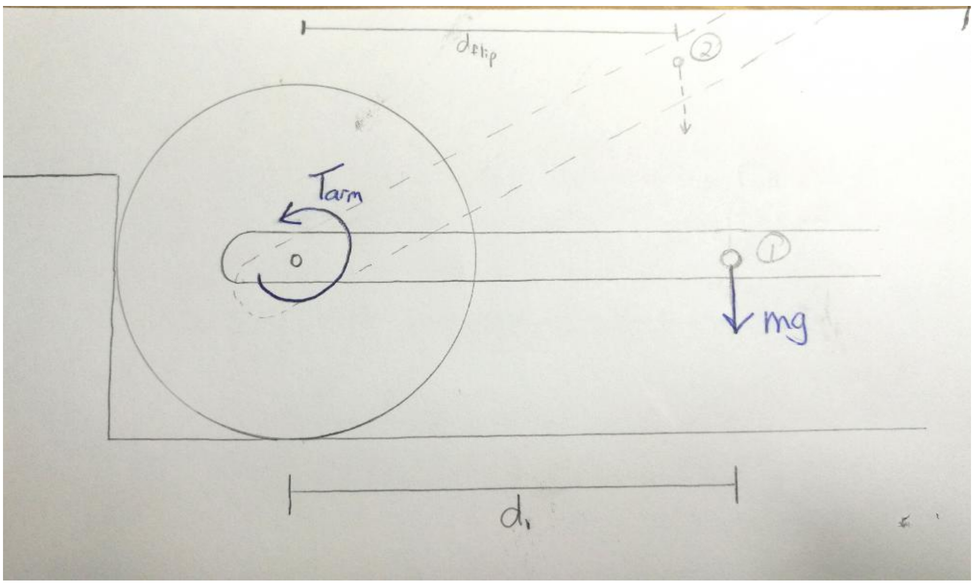

Figure 4.19: Free body diagram showing the forces and torques acting on the LIM arm (not to scale).

Based on this diagram, it can be seen that the mass of the robot was the only factor resisting the LIM flipping motion (apart from minor frictional resistances which were ignored). This produced the following expression where mg was the weight of the robot acting at a distance d from the centre of rotation at the front wheel, T_{arm} was the torque that the LIM gear train exerted on the arm and T_{net} was the the total torque acting on the arm.

$$T_{net} = T_{arm} - mgd_1 \tag{4.6}$$

By analysing Equation 4.6 above, it can be seen that the torque acting in resistance to the flipping motion was due only to the weight acting at a distance; and, since the weight of the robot remained the same and always acted vertically, the largest distance d would occur when the robot was at a horizontal position. Therefore, it was concluded that if the LIM could flip from the horizontal position, it could flip from any angle to the horizontal as well. Therefore, a successful flip from the horizontal would indicate that the robot design satisfied the minimum torque requirements for climbing.

Therefore, Mark 1 underwent testing whose aim it was to determine if the build met the minimum torque requirements. In preparation for the test, the robot was placed on a horizontal surface with its front wheels in contact with a vertical surface. It was decided to not allow the robot a 'run-up' as this kinetic energy may have helped in the climbing motion and would have undermined the validity of the test. The test would be started when the motors were simultaneously connected to the power source.

The intended outcome of these tests was that wheel rotation would remained halted against the wall, and the LIM would flip up to the vertical position, where-after the power to the motors would immediately be turned off.

In the first round of testing, the acrylic wheels which were left bare, simply skid. This indicated that the build did not have sufficient traction. At this stage in the testing, it was thought that the climbing motion was more important than ensuring the wheels stopped when making contact with a stair as this was thought to be easily remedied. The test was repeated with the front wheels held fixed the ground as close to the point at which they contacted the ground. This was done in order to forcibly halt wheel rotation such that the LIMs flipping capabilities could be examined. Running directly off the 12 V power supply, the robot was not able to complete the climbing motion - both motors stalled without the LIMs lifting off the ground.

Haskel noted in his report that Theseus' LIMs managed to flip but that they couldn't raise the body up to complete the climbing motion. Due to this knowledge, the Mark 1 LIMs were swapped out for the Theseus LIMs and the test was carried out again expecting different results. The same results were produced so the Theseus LIMs were put back on the Theseus body. Theseus then underwent the same test as Mark 1 to determine whether Haskel's results could be produced - they could not at that time. The Theseus LIMs' inability to flip was assumed to be due to the gradual degradation of the parts over time while being stored. It was not discovered why Theseus' LIMs did not flip and it was not tested after that point.

A third round of testing of Mark 1 indicated that the LIM mechanisms were 'trying' to flip. This testing was done by placing the robot body on a small box such that the LIMs were hanging over the ends of the box and not touching the ground. While locking the front wheels and supplying power to the motors, the LIMs did flip in the desired direction. Since the second round of testing showed that the LIM design produced the correct motion, it was concluded that the second round of testing had failed due to a lack of torque being supplied to the LIMs through the drive shaft and that a significant increase in torque would likely flip the LIMs. It was also concluded that the traction on the wheels needed to be increased significantly.

Later, when Mark 1 was subjected to the same testing as in rounds one and two, it was noticed that - rather than the motor torque rotate the LIMs - the motor torque instead rotated the *body* of the robot in the opposite direction. This was realised to be due to an insufficient amount of counter torque on the body to keep it in place. This was noted as something that needed to be solved in Mark 2.

The build's regular horizontal movement along the ground was satisfactory at this stage of development.

Lastly, after prolonged testing, it was found that the high torque that the drive shaft transmitted wore down the holes of the acrylic spacers and gears enough for the shaft to rotate mostly independent of them. The purpose of the D-profile was to transmit torque but this was negated by the stripped gears. It was thought that this problem could be mitigated by accurately machining the D-profile but, instead, the D-profile of the shafts was made more extreme in the following build iterations in an attempt to solve this while still maintaining the ability to rapidly prototype.

4.3 Mark 2: improved torque transmission, gearbox reshaping and minor functional changes

Mark 2 was built with significant increases in torque, a gearbox with decreased space wastage and better shaft support, a tail to provide counter-torque to the body and other minor improvements to make operation smoother or assembly quicker.

4.3.1 Design

The LIM design did not change significantly in Mark 2 except for some minor changes to the assembly process. This decision was made because there were no significant failures or faults seen in the LIMs from Mark 1. Furthermore, it was concluded that the LIMs had not received enough torque in previous testing to expose the flaws of Mark 1. Lastly, it was thought unwise to make changes to the LIM before building the next iteration of gearboxes that tripled the torque output.

However, one change to the outer support frame was thought to be necessary in Mark 2. A single 6 mm diameter hole was drilled through the centre of the outer support frames such that the drive shaft could be supported over a larger distance in the LIM. Furthermore, allowing the drive shaft to pass right through the LIM allowed for an M3 nyloc to be fastened on to the far side of the LIM to prevent it from falling off or loosening during operation. This was the only change made to the outer frame.

The gearbox was redesigned with three main features in mind: increased torque output, increased shaft support, and general compactness. Furthermore, greater care was taken when assembling and securing the parts of the gearbox to ensure the uprights were kept vertical.

Due to the low torque abilities of the gearbox from Mark 1, changes were made to the gear ratios in order to satisfy the minimum torque requirements for the flipping motion to be carried out successfully. These minimum torque requirements were based off of the force body diagram in Figure 4.19. However, this was later learned to be incomplete due to the addition of the tail (which was only included in Mark 2). The calculation to find the gear ratios needed to satisfy the minimum torque requirements are included below.

The torque applied by the LIM gearing was expressed by Equation 4.5 and was thought to be the only effect the motors had on the LIM. This was later discovered to be incorrect.

According to Equation 4.6, for a positive net torque to be applied to the LIM, $T_{arm} > mgd_1$. Therefore, relating it to Equation 4.5, the following expression was reached that dictated the minimum torque requirement.

$$T_{motor}\frac{N_{drive}}{N_{motor}} \times \left(1 - \frac{N_C}{N_A}\right) > mgd_1 \tag{4.7}$$

Note that the mass of the Mark 1 robot was measured to 1,235 kg, distance d_1 was designed to be 90 mm and the rated motor torque was 0.196 Nm. Based on these values and the equation, it was calculated that a 3:1 drive gear:motor gear ratio would easily satisfy the minimum torque requirements of Mark 2

The ratio of drive gear teeth to motor gear teeth was therefore designed to be 3:1 based on these calculations, which was implemented as 20 and 60 teeth on the motor gear and drive gear, respectively. However, given that these calculations did not take into account the addition of the tail - which was found to make a significant contribution to the LIM's torque - they were not valid.

Figures 4.20 and 4.21 found below, show the change in gear ratio between the gearboxes of Mark 1 and Mark 2 respectively. These figures are side views of the corresponding Solidworks models. The outer supports have been hidden to reveal the gears.

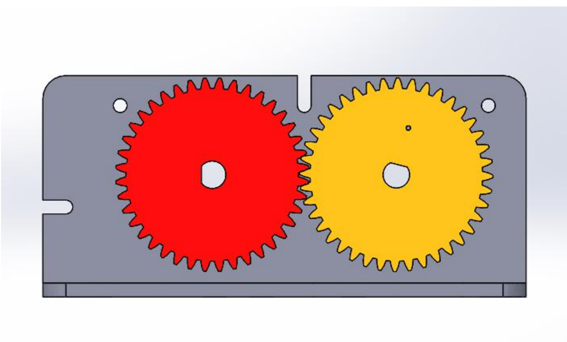

Figure 4.20: Mark 1 gearbox: both motor gear (red) and driver gear (orange) with 30 teeth.

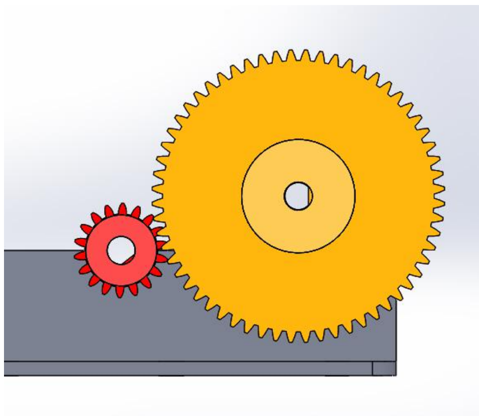

Figure 4.21: Mark 2 gearbox: motor gear (red) with 20 teeth and driver gear (orange) with 60 teeth.

Due to the drive shaft slipping in the housing of the master gear of the Mark 1 LIM, the D-profile was made more extreme in an attempt to prevent the loss of torque transmission created. This was done by increasing the width of the flat section of the shaft from 3.7 mm to 4.5mm; the shaft was also modelled smaller to account for the laser cutting beam thickness. The Mark 1 and Mark 2 D-profiles are compared in Figures 4.22 and 4.23.

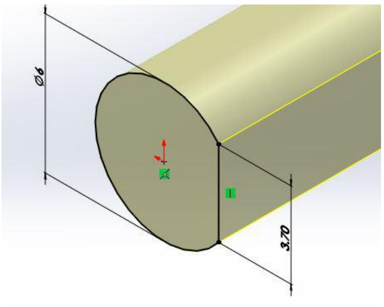

Figure 4.22: The dimensions of the D-profile of the Mark 1 drive shaft.

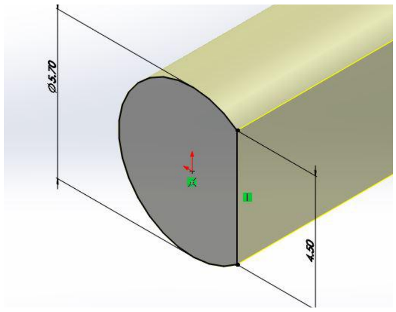

Figure 4.23: The dimensions of the D-profile of the Mark 2 drive shaft.

It was noticed during the design stage of the gearbox that a high amount of torque was being applied on the gears. With enough force, it was thought to be possible to snap off a gear tooth, however it was not known how much force would be needed to do so. In order to mitigate this problem before it occurred, the motor and drive gears of Mark 2 were designed to be 6 mm thick.

The spacers to be positioned on either side of the Mark 2 gearbox drive gear were designed to provide a clearance between the gear teeth and the gearbox uprights to prevent the problem that Mark 1 faced with gear teeth cutting into or being obstructed by the uprights. The designs of the gearbox of Mark 2 are shown in Figures 4.24 and 4.25 following, to indicate the changes in upright distances and spacer usage.

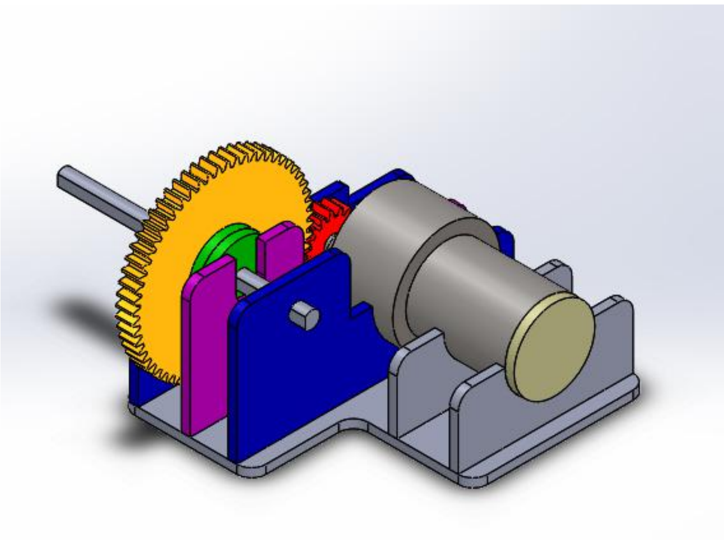

Figure 4.24: The Mark 2 gearbox configuration with drive shaft spacers shown in green (Isometric view).

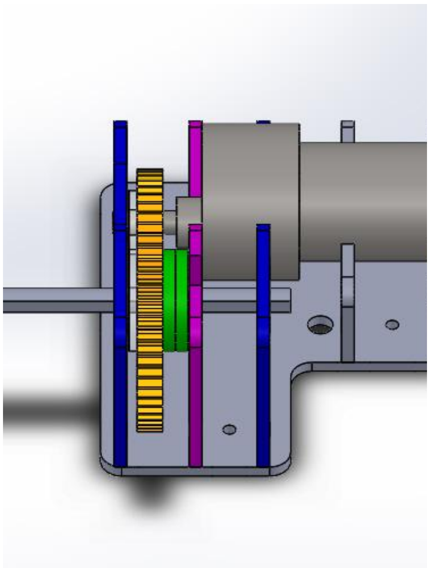

Figure 4.25: Closeup of the gearbox configuration (Top 45°view).

The gearbox uprights that house the drive shafts (referred to as the drive shaft uprights) are shown in blue, the gear spacers are shown in green and a third upright in purple (which is referred to as the centre upright). By increasing the distance between the drive shaft uprights as suggested by the findings of Mark 1, spacers would have been needed over a distance of 22 mm - the distance from the drive gear face to the right-hand drive shaft upright (as shown from the perspective of Figure 4.25). This was thought an unnecessary amount of redundant parts that may have made the assembly process more cumbersome. Instead, the centre upright, which was initially much shorter, was extended past the drive shaft as shown such that the drive shaft passed through this upright. This meant that the spacers only had to span as far as the centre upright (6 mm away) as opposed to the drive shaft upright on the right-side which was 22 mm away.

Notice the slot size of the centre upright - the slot is small enough such that the spacers are kept between the gear and the upright but large enough to not interfere with the drive shaft in any way. The thought process that determined this design was the following: if the slot was the same width as the drive shaft diameter, a slight misalignment of any one of the three uprights would have produced a big problem. However, with the Mark 2 design, slight misalignment of the holes or slots in the uprights *may* have been remedied relatively easily.

Spacers were an important part of ensuring gears aligned properly as well as preventing being obstructed by other parts of the robot which would have significantly deceased the efficiency of the gearbox torque transmission. However, trying to insert drive shafts through drive shaft uprights, a gear *and* multiple spacers was found to be extremely cumbersome while assembling Mark 1 since the clearance allowing the spacers to be inserted between uprights was very small - sometimes the spacers would slide off the shaft if one wasn't careful. An attempted spacer design intent on making this process simpler and quicker is shown in Figure 4.26, below. This spacer design was referred to as the 'square spacer' and is shown in green in the figure.

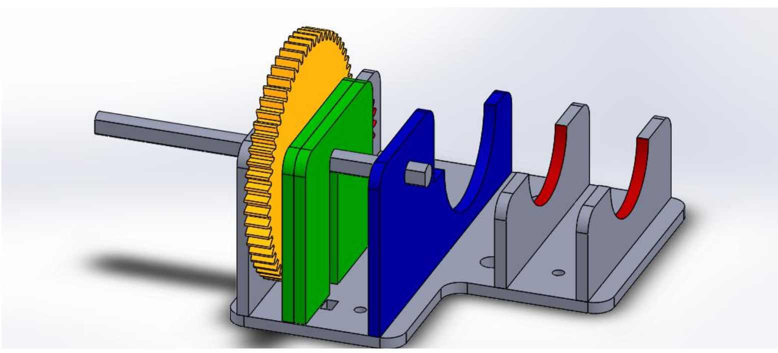

Figure 4.26: The 'square spacers' designed to make gearbox assembly quicker (shown in green).

The idea was to assemble the gearbox without spacers - a much easier task - and then slide the square spacers over the shafts where spacing was required. These spacers would then rest on the gearbox's base. The conclusions surrounding this design are detailed in the implementation section following. As these spacers were experimental, the gearbox was designed with the to incorporate regular, round spacers if the square spacers were to fail. If the square spacers had been a success, they would have been properly accommodated in the design of Mark 3.

Two obvious solutions to the problem of shaft housing tolerance were regarded as a) decreasing the size of the hole and b) to cut an additional 'ruler' with slots cut out of it that could be placed on top of the uprights while gluing to keep the uprights vertical; its intended use can be seen in Figure 4.27 below where the ruler is shown in turquoise. Note that these are view from the back of the gearbox. It was designed such that once each of the uprights had been slotted into the gearbox body, the ruler would be placed on top of them to ensure they were the equivalent distance apart at the top in comparison to the bottom i.e., vertical.

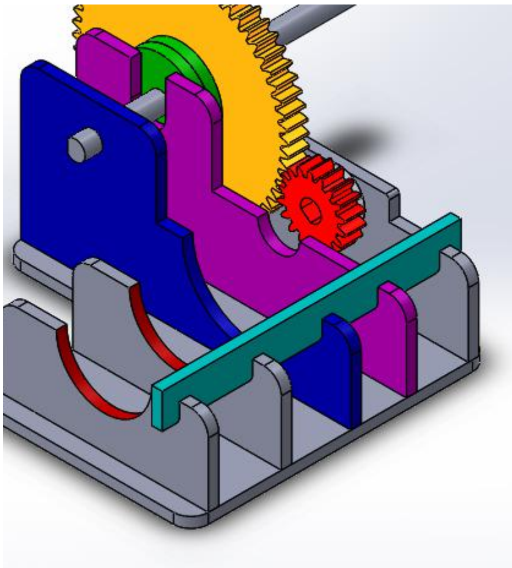

Figure 4.27: The gearbox ruler positioned on top of the uprights to maintain correct spacing.

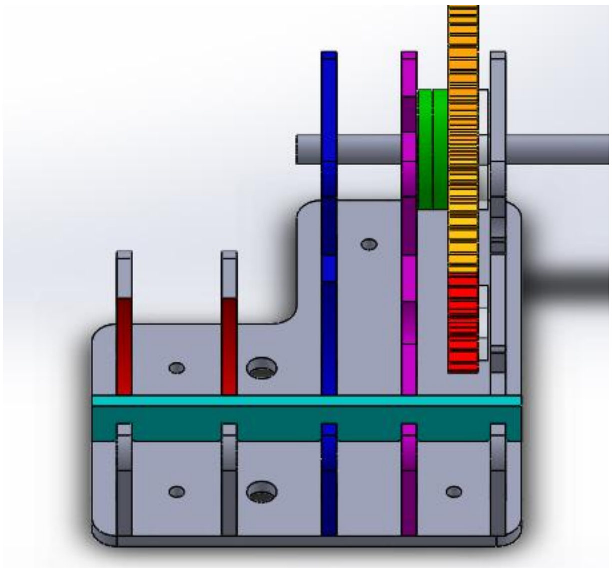

Figure 4.28: Closeup of the gearbox ruler.

It was decided to use the second solution - the ruler - as the distances between slots was already known and these could be mimicked in the ruler design. It was thought that the first solution would be the more accurate solution (since the ruler slots would experience the same clearance error as the gearbox slots) however, it did not seem worth the trial and error to find the 'perfect' slot width that would accommodate 3 mm material. therefore, this 'gearbox ruler' was manufactured along with Mark 2.

The full Mark 2 robot assembly is shown from different views in Figures 4.29 to 4.33, below to provide a better understanding of the shape of the full robot build.

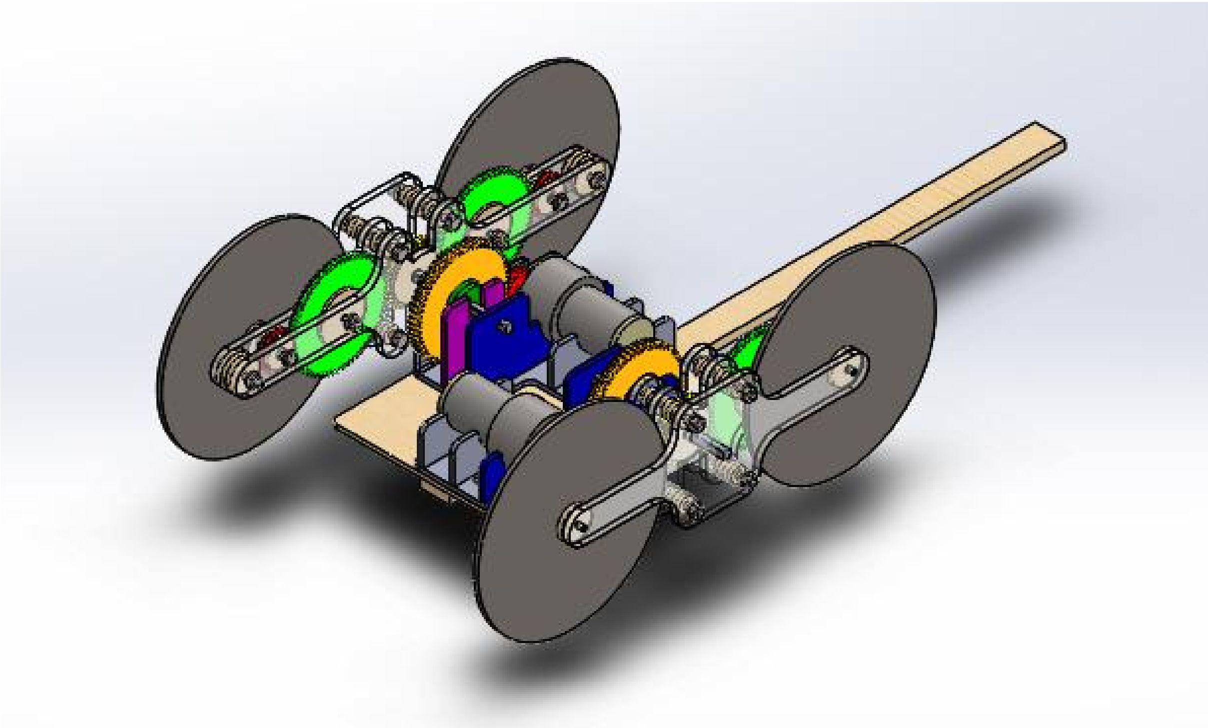

Figure 4.29: Isometric view of Mark 2 assembly.

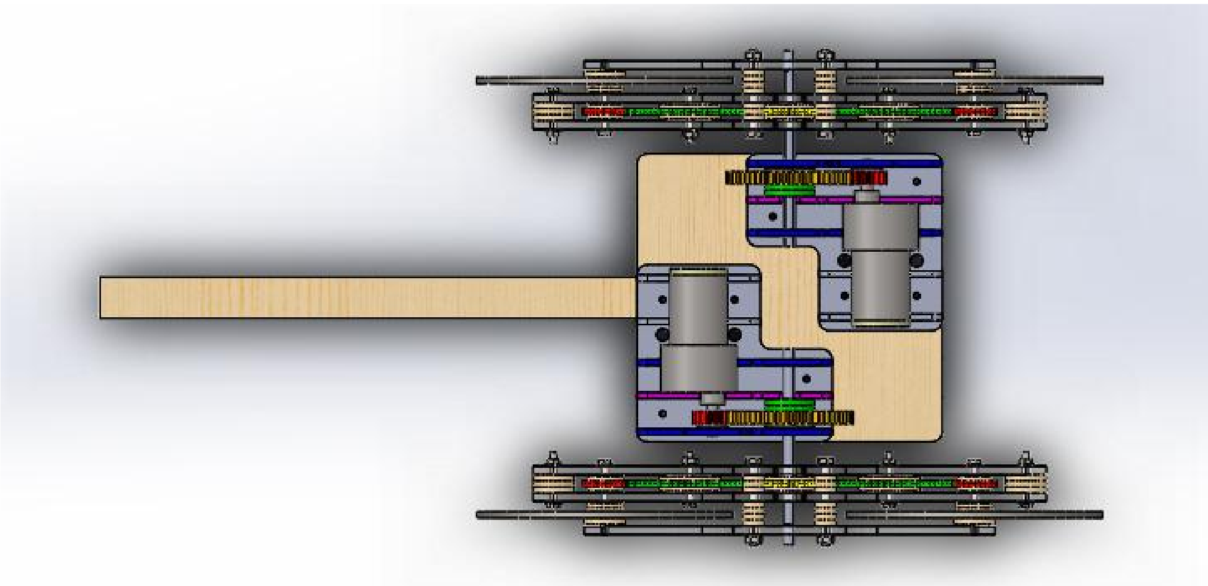

Figure 4.30: Top view of Mark 2 assembly.

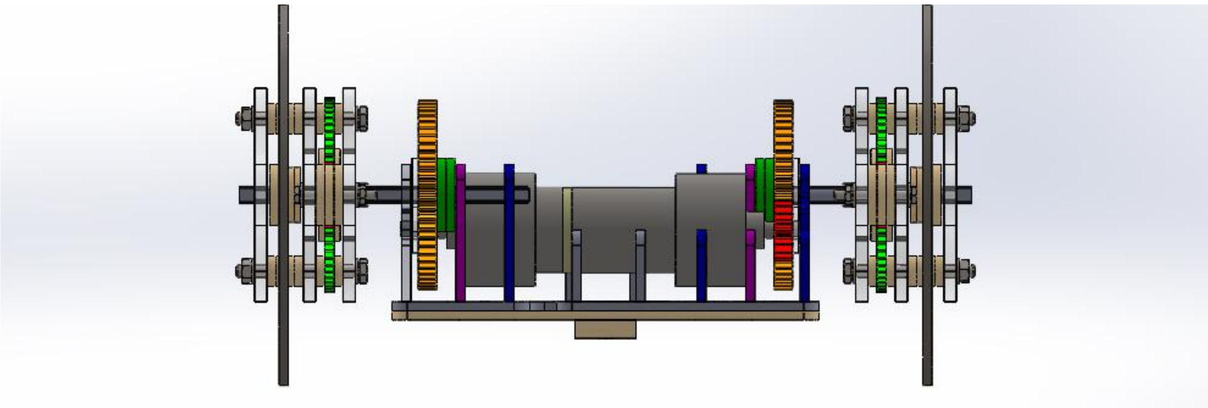

Figure 4.31: Front view of Mark 2 assembly.

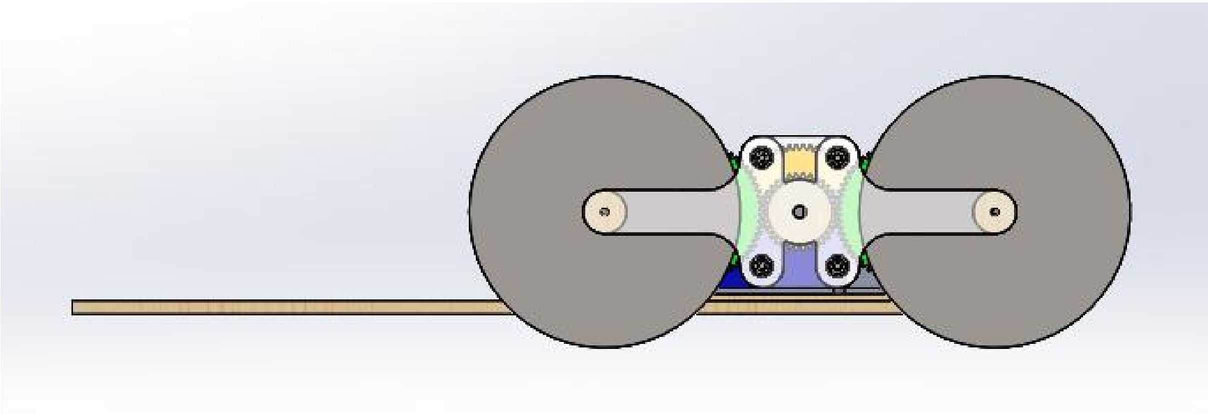

Figure 4.32: Raised side view of Mark 2 assembly.

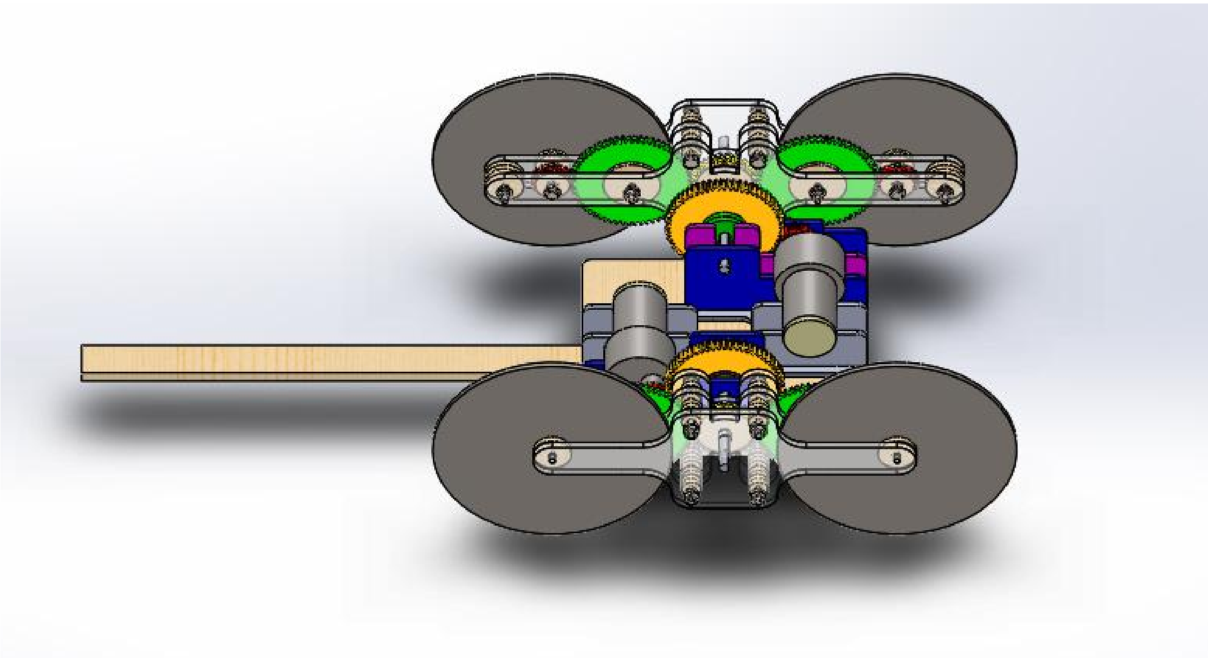

Figure 4.33: Raised side view of Mark 2 assembly (transparent gearbox upright to show gearbox gears).

4.3.2 Implementation

The gearbox ruler was found to help immensely when assembling the gearbox and gluing the uprights in place. However, it was noted that with only one ruler, it was difficult to keep all the uprights vertical. Furthermore, the ruler could not be positioned on top of the tall sections of the uprights without falling off. A shorter one needed to be made specifically for the section with tall uprights.

The Mark 2 assembly shown in Figures 4.34 and 4.35 was weighed to be 0.810 kg without motors and motor fasteners and 1,222 kg with the motors fastened in place.

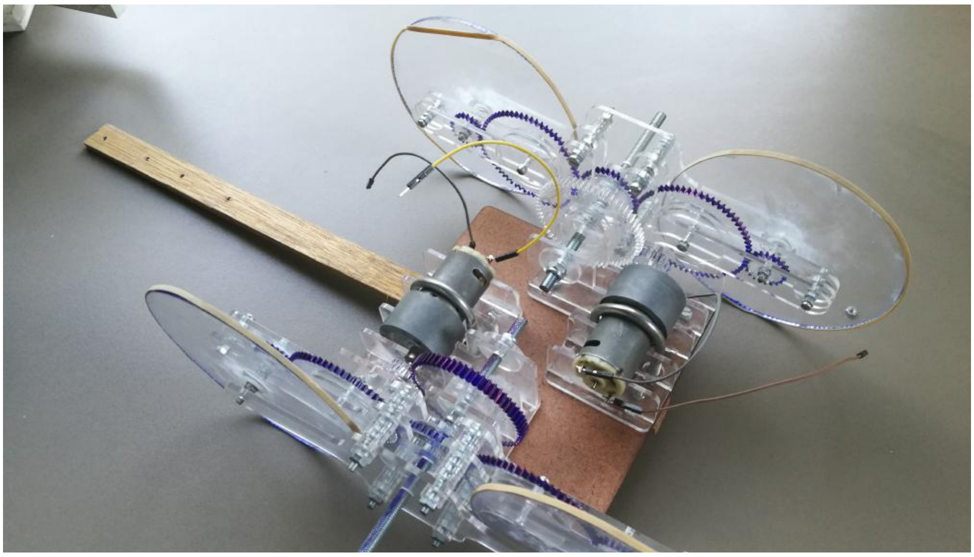

Figure 4.34: Full Mark 2 build.

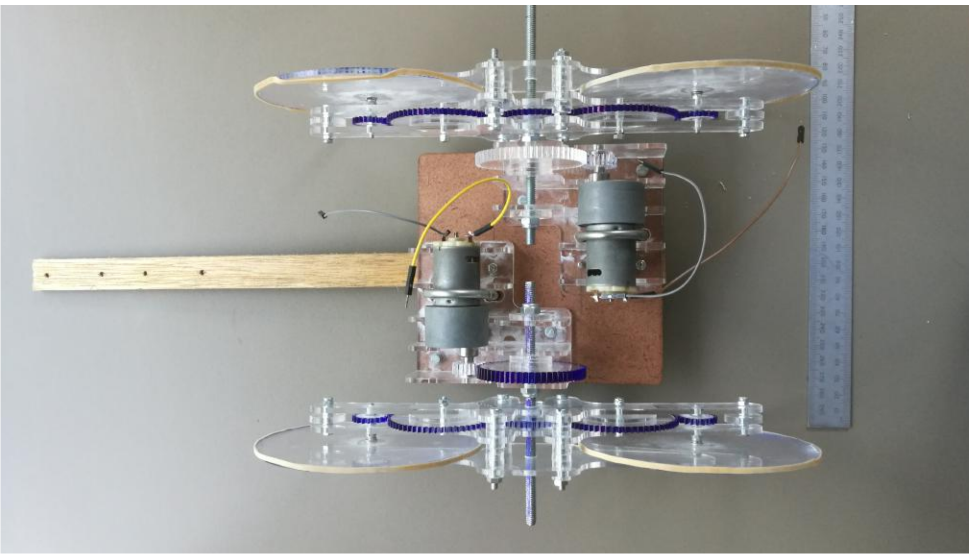

Figure 4.35: Full Mark 2 build (30 cm ruler for scale).

4.3.3 Testing and Analysis

This section details the testing that Mark 2 underwent as well as analysing its strengths and weaknesses. These are then discussed and conclusions are made which influenced the following build iteration. Neither the motors, nor any parts were replaced between tests unless explicitly indicated. All tests made use of a 12 V ATX power supply to power the motors; this was done by connecting the supply directly to the motors - no control systems were used.

The spacers first used in the testing process were the square spacers. These made it much simpler and quicker to assemble the gearbox. However, while the drive shaft was rotating, the friction between the spacers and gear was enough to rotate the spacers such that they eventually loosened and fell off the shaft. In another test, one of the spacers obstructed the drive gear teeth which left deep teeth marks in the acrylic material - there was also an incident where a square spacer obstructed the drive gear to such a degree that it actually halted rotation of a motor. Due to the previous results, the square spacers were considered a failure and since there posed problems, they were discarded. Testing then continued after dismantling and reassembling the gearbox using the regular round spacers.

The testing of Mark 1 showed evidence that the D-profile of the drive shaft needed to be more profound to prevent stripping of the gears and spacers. After the adjustment of this profile for Mark 2 and updating the gears and spacers to reflect the changes, it was noticed both the gears and spacers fitted over the shafts better and had less rotational play in them. No noticeable stripping was found after the testing of Mark 2 and therefore, this D-profile was considered a success. The profile could have been made even more extreme, however this would have required significantly more work when filing down the drive shafts. It should be noted that the D-profile's likeliness of stripping decreases with its level of extremity. However, since the forming of profile effectively weakened the shaft, there would have been a point at which the profile became so extreme that the shaft may eventually twist or snap completely. This point would have depended on the torque applied to the shaft which, however, was not in the scope of the project.

The increased distance between the drive shaft uprights significantly decreased the amount of play from the horizontal. When the motors were run without the LIMs, it was noticed that the drive shaft rotated more truly about the intended axis in comparison to Mark 1. It was also noticed, however, that a small yet noticeable clearance existed between the drive shaft circumference and the concentric holes in the drive shaft uprights that accommodated it. It should be noted though that too large a clearance may have produced the effect shown in Figure 4.36 where the shaft is only supported on a small section of the hole. This may cause the shaft to rotate unevenly - especially when the flat section rotates past the bottom section as seen in Figure 4.37. Since it was too difficult to take a photograph of the hole clearance with the drive shaft inside, the figures are of a Solidworks recreation - the object in green shows the drive shaft and in the blue is a drive shaft upright.

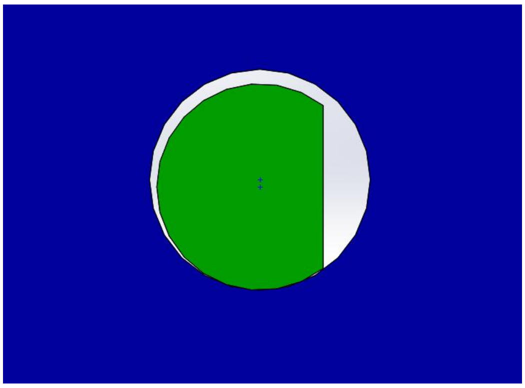

Figure 4.36: Not coaxial: drive shaft rests on bottom of hole when clearance too large.

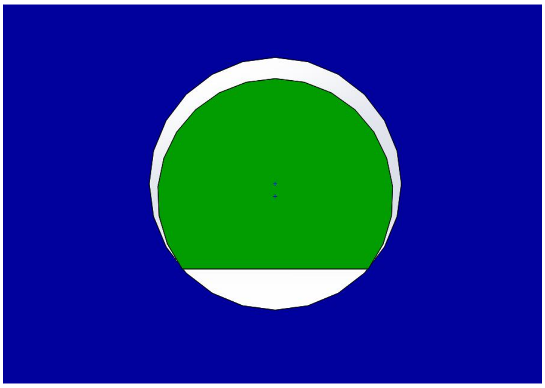

Figure 4.37: Issues with large hole clearances when accommodating D-profile.

It was assumed that by decreasing the hole clearance slightly, the amount of play would be decreased even further thus allowing the shaft to run even smoother. However, since the amount of play did not present any sort of problem at that time and further adjustments could have caused unforeseen problems, it was decided not to attempt to decrease the shaft hole sizes.

Testing of Mark 2 was carried out by placing the robot on the ground with the front wheels against a wall but still touching the ground. The motors were then connected to the 12 V ATX power supply simultaneously. All LIM wheels kept spinning on the floor with the front two spinning against the wall. It was noted that there wasn't enough friction between the wheels and the ground or wall to halt the front wheel rotation. Before making traction improvements to the robot, the test was repeated by holding the front wheels to the ground and halting front wheel rotation. Instead of the LIMs flipping, the body of the robot simply rotated opposite to the intended flip direction of the LIMs. Repeating the test and holding the body as horizontal as possible resulted in the LIMs flipping instead of the body - it appeared that more counter-torque needed to be provided to the body such that the gearboxes rotate the LIMs instead of the body. Haskel had mentioned that Theseus needed a 'tail' to function although it was not stated to what extent this helped. This made it difficult to comprehend the details of the problem and its causes. Furthermore, not fully understanding the problem meant that the Haskel's solution would be difficult to critique or improve upon. therefore, it had been decided to not use Haskel's tail solution and rather understand the scale of the problem from first principles. However, upon witnessing the effects of no counter-torque on the body, Haskel's tail was understood and implemented.

A 600mm-long piece of scrap meranti wood was used as the tail as it was readily available, light, easy to cut shorter and easy to fasten to the robot's body. The slight flexibility of the wood was thought to be a benefit too. The tail was cut such that the length could provide significant leverage against the body but not too long that it may drastically decrease the robot's potentially small turning circle. Initially, the tail was longer but it was cut shorter so that the full robot could fit into a backpack. This was decided due to the practical element of being able to transport the robot to various labs, consulting staff members, and the laser cutting room. Incidentally, it was realised that being able to fit the robot in a backpack would be of great advantage in Urban Search and Rescue environments.

The tail was fastened to the body using the pre-existing holes in the gearboxes and robot body base. The 12 mm M3 screws that secured the gearboxes to the body's base were replaced with slightly longer ones such that they could extend through holes drilled into the tail. The tail was strong and light but flexible and easily replaceable.

Testing restarted after the addition of the tail was complete - the front wheels still had to be held to the ground to prevent them from spinning. With the addition of the tail, when the motors were powered and the front wheels held, both LIMs rotated in the desired flipping motion until they were vertical against the wall. The test was repeated multiple times to determine the consistency of this motion occurring. Out of a total of five attempts, the LIMs flipped in three tests. In the other two tests, the motors simply stalled - one with the LIM at ground level and one which stalled with the LIM at roughly a 30 degree angle to the horizontal.

At this point, testing was halted to make improvements to the wheels. By using Haskel's method of gluing elastic bands onto the wheels, the friction between the robot wheels and the ground was increased significantly - the extent of this was later investigated by repeating the same tests as previously but without holding the wheels to the ground. Given the elastic nature of the bands, attaching them around a circular object with a depth of only 3 mm proved unnecessarily and, at times, embarrassingly challenging as they often slipped off while trying to glue the underside to the the wheel. The process was not quick even though the idea seemed simple. During testing, there were instances when the elastic bands also detached from the wheels.

It should be noted before going further that these tests were repeated days after the tests with the tail. With the elastic bands on the LIMs did not flip as they did previously - the motors simply stalled. After repeating this test multiple times and analysing the robot's systems, it was noticed that the front wheels had disconnected from the drive shaft. Since these had only been held onto the shaft using a combination of nylocs, round washers and spring washers, it was decided that a more effective method was needed to secure the wheel to the drive shaft such that both rotated together even when the wheel experienced a resistive torque. The wheels and combination of threaded nuts and nylocs were super glued onto the shaft in an attempt to do this.

After a number of hours, testing resumed again however, the LIMs did not flip. Upon inspection of the shafts, it was noticed that super glue had spread down the M3 threads. Some of the shafts - previously with clean surfaces that ran smoothly in the LIMs' outer frames - had now become contaminated with glue. Picking up the robot and slowly spinning the wheels by hand was noticed to be slightly more difficult than previously - it could not be determined whether the glue was the cause of the problem though that was the assumption. It was decided that the method of gluing the complicated configuration of nuts, washers and nylocs to the shaft and wheel was not a good solution. A more efficient and effective design was needed to secure the wheels to the shafts - this was explored in the design of Mark 3. In the unlikely case that the LIMs had not flipped due to the super glue, it was decide to revisit the gear ratios calculations. These were also used in the designing of Mark 3.

4.4 Mark 3: mass reduction, torque increases and minor optimisations

Mark 3 was designed to give the LIMs as much torque as was possible with the available motors and space limitations. Furthermore, it was known that by decreasing the overall weight of the robot, the minimum torque requirement to lift the robot would be reduced. therefore most components - particularly the large components - underwent severe mass reductions. It was attempted to further decrease the gearbox size to prevent the body from making contact with the stair while the robot was climbing as it was thought that this would prevent the robot from lifting itself up to the top of the step.

4.4.1 Design

The gearbox output torque was increased as much as possible without the motor gear becoming problematically small or the drive gear becoming so large that it may interfere with the size constraints of the robot. The drive shaft torque was determined by the following ratio between the gearbox gear teeth numbers:

$$T_{drive} \propto \frac{N_{drive}}{N_{motor}}$$

N determined the number of teeth on a gear. The motor gear's number of teeth was decreased to 18 which was thought to be a very low but safe number of teeth. It was expected that decreasing the size of this gear too much would result in it snapping under the high torques applied. The motor gear's diameter became 15 mm (between teeth) with a module of 1. The minimum distance between the gear circumference and the drive shaft hole was measured to be 4.824 mm which was thought to be sufficiently strong to not fail under full torque. However, this fail point could not be calculated so only intuition was used to make that assumption.

The drive gear size also needed to be increased to raise output torque levels however, there was a size limitation that constrained the number of teeth. The Solidworks toolbox feature that created gears required the number of teeth and the module as input to the programme - this then produced a gear with a diameter that needed to be measured by the user to determine it. This process was repeated until the maximum 'comfortable' gear diameter was reached. The Mark 3 drive gear was designed with 70 teeth and a module of 1, measuring roughly 67.5 mm in diameter (between teeth).

After a consultation with Pierre Le Roux of the UCT Mechanical Engineering department, the free body diagram (FBD) was better understood and included the effect of the tail. This produced the additional FBD shown in Figure 4.38.

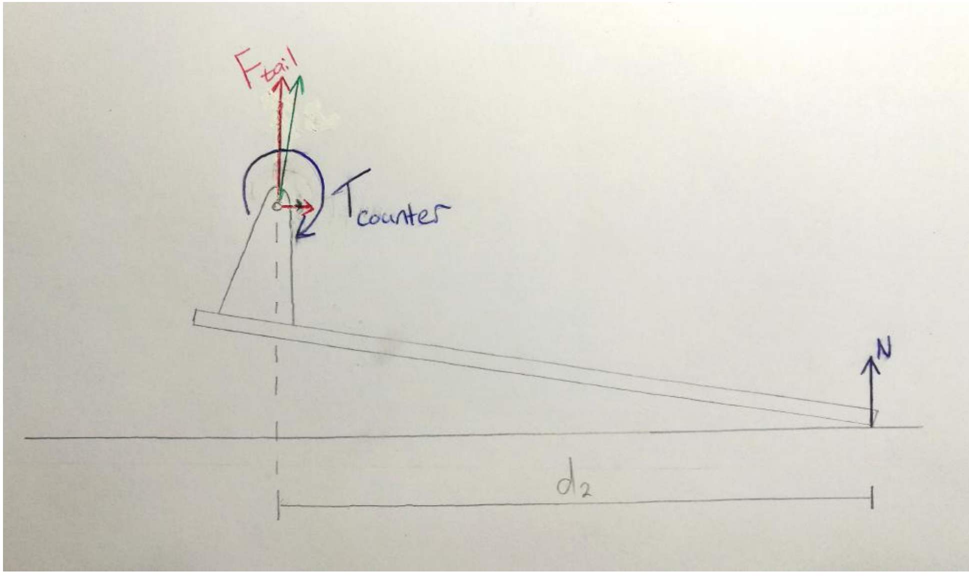

Figure 4.38: The free body diagram of the tail.

The torque that the body exerted on the tail - labelled $T_{counter}$ was halted by the normal force N which produced a net force perpendicular to the tail, labelled F_{tail} at a distance d_2 from the end of the tail. However, as understood by the consultation with Pierre Le Roux, $T_{counter}$ was equal to the amount of torque that would normally be exerted on the wheel but reversed and exerted on the body instead. Therefore the value could be expressed by working backwards from the wheel torque. This produced the following expression, Equation 4.8:

$$T_{tail} = \frac{T_{drive}}{d_1} d_2 \tag{4.8}$$

This was because, T_{drive} was first converted to a force F_{tail} at a horizontal distance d_2 from the end of the tail, and then converted into a torque around the arm, T_{tail}, at a distance d_1 from the centre of the front wheel.

Following this, the LIM free body diagram was updated as shown in Figure 4.39.

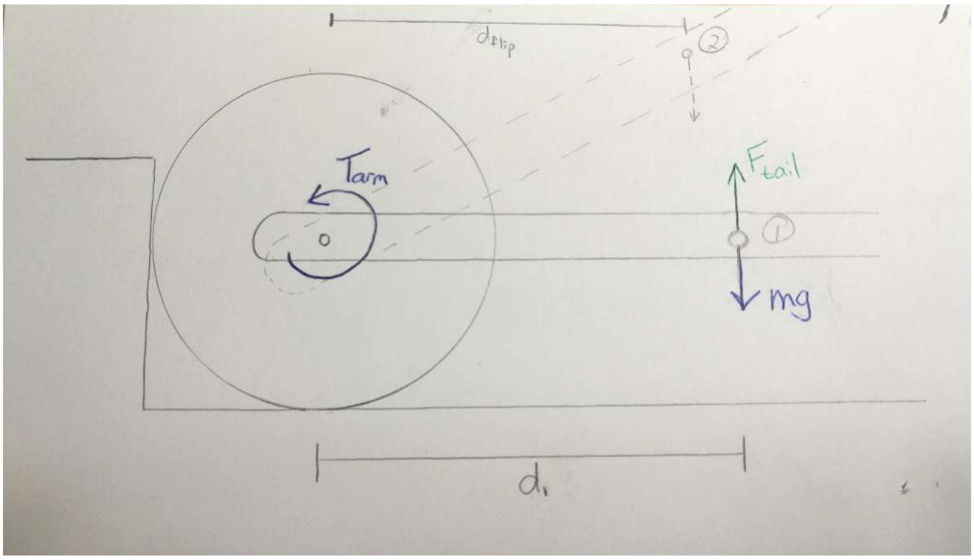

Figure 4.39: The update free body diagram of the LIM with the included effect of the tail.

This more complete understanding of the torques acting on the LIM led to the changes in Equation 4.6 to produce the following expression:

$$T_{net} = T_{arm} + T_{tail} - mgd_1 \tag{4.9}$$

Note that since there were two LIMs, $m = \frac{Mass.of.robot}{2}$.

This was further expanded to produce the following expression:

$$T_{net} = T_{drive}\Big(1 - \frac{N_C}{N_A} + \frac{T_{drive}}{d_1}d_2\Big) - mgd_1$$

This produced the final expression that modelled the net torque on the LIM arm and which was used in determining the minimum torque requirement for the LIM to flip.

$$T_{net} = T_{motor}\frac{N_{drive}}{N_{motor}}\Big(1 - \frac{N_C}{N_A} + \frac{d_2}{d_1}\Big) - mgd_1 \tag{4.10}$$

Where: $d_1 = distance.between.wheel.centre.and.drive.shaft = 90mm$.

And, $d_2 = \sqrt{(drive.shaft.to.end.of.tail)^2 - (drive.shaft.height)^2} = 375mm$.

Assuming Mark 3 mass to be 1 kg - based on Solidworks estimations - Equation 4.10 was used to design the following gear ratios for Mark 3: The LIM follower gear tooth number was decreased to 18, and the LIM master gear tooth number was increased to 54. Furthermore, the motor gear was changed to 18 teeth and the drive gear to 60 teeth.

It should be noted that the changes to the build based on Equation 4.10 later produced a successful Mark 3 climbing motion. Secondly, by substituting in the values of Mark 2, Equation 4.10 produced a negative torque which implied that the LIM torque was not enough to lift the weight of the robot - as was found in the testing section of Mark 2.

Given the large diameter of the drive gear, a slot was designed in the bottom of the gearbox and body bases for the drive gear to protrude through slightly - this is shown in Figures 4.40 and 4.41. Additionally, by lowering the height that the motor was mounted above the base in comparison to Mark 1 and Mark 2), the entire robot body could be lifted up by 12mm. This extra clearance between the body and the ground was thought would slightly help in preventing the robot from beaching during normal drive operation.

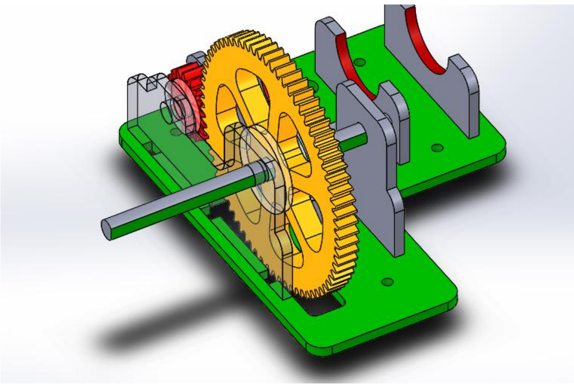

Figure 4.40: Isometric view of gearbox showing slot for drive gear in gearbox base (green).

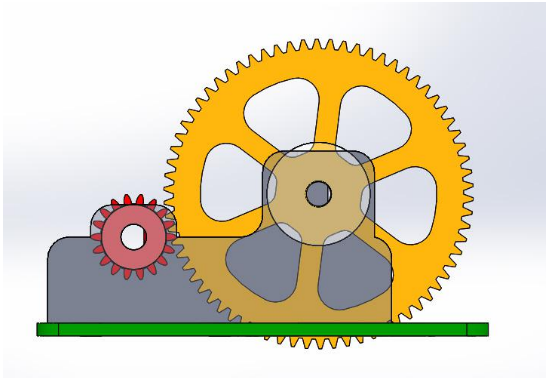

Figure 4.41: Side view of the gearbox showing the drive gear protruding through the gearbox base.

Based on Equation 4.10 included earlier, reducing the mass of the robot build would make a significant difference in the minimum amount of torque required for the LIMs to perform the climbing motion. therefore, many parts of the Mark 2's build underwent mass reductions in the developing of Mark 3.

Notice how sections were removed from the drive gear in an attempt to reduce its weight - previously shown in Figure 4.41. Being a physically large part of the robot *and* given that the gear was 6 mm thick, this gear was one of the heaviest parts of the robot build until the mass was decreased. Care was taken to not remove too much of the gear that it corrupted its structural integrity to the point where it might fail under load torque.

The following parts also underwent mass reductions: inner and outer frames, wheels and were the following. They are listed alongside their earlier versions from Mark 1 and Mark 2. The wheels underwent the most extreme mass reductions since their convenient circular shape of large diameter allowed it. Furthermore, the wheels were not parts that would typically subjected to high counter-torques and so they did not need to be near as strong as the drive gear for example.

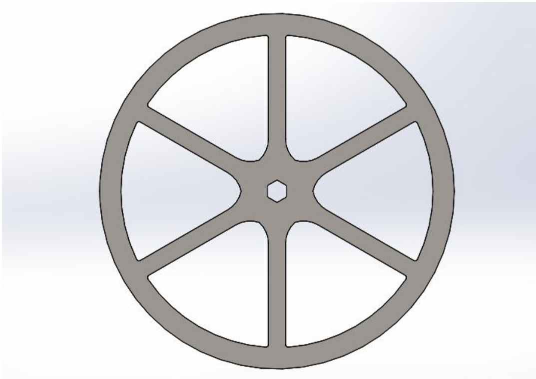

Figure 4.42: Improved wheel design - from Mark 3 (side view).

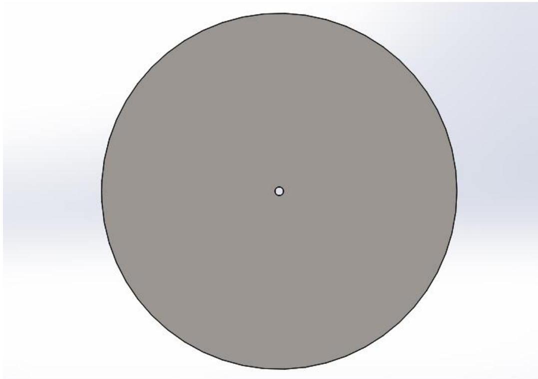

Figure 4.43: Earlier wheel design- from Mark 1 (side view).

Multiple other parts had seemingly minor mass reductions implemented too. Generally speaking, where a shaft hole occurred, at least 5 mm of material surrounded it to maintain its strength - this distance was generally larger for holes with larger diameters or if it would typically have many internal forces occurring near it.

The inner and outer support frames were one of the parts adjusted to reduce mass. The elongated sections that supported the wheel and idle gear shafts were referred to as the LIM support frame 'arms'. In Mark 3, the height of these arms had been reduced to 15mm. Some of the material from the centre of the support frames was also removed. There wasn't a significant amount of material that was removed from the inner and outer support frames but since six support frames were needed per build, this resulted in a collectively significant mass reduction.

The support frames were also redesigned because of the difficulties faced when assembling the LIMs of Mark 2. This was detailed in the preceding section *Mark 2* but, in short, the spacers were cumbersome to keep in place while inserting the drive shaft and largely inaccessible after the assembly had been completed. This was mostly because there was limited space to operate tools and also largely due to the outer frame completely blocking access to the LIM's master gear and spacers. therefore, the inner and outer frames were redesigned with accessibility in mind. The Mark 3 inner support frame is compared to the original Mark 1 design in Figures 4.44 and 4.45 below.

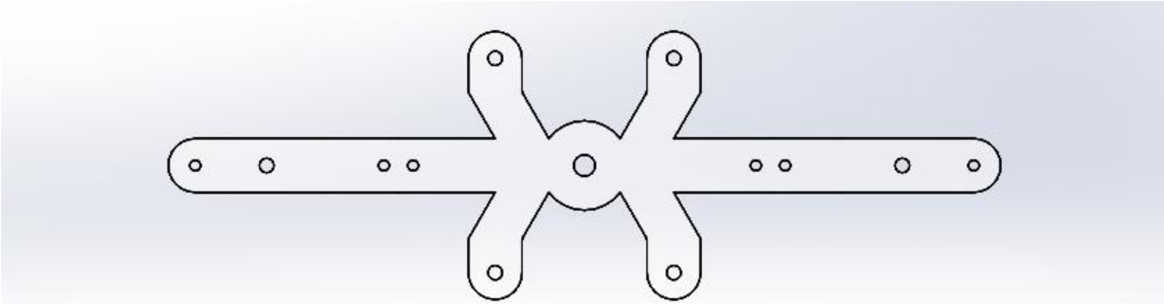

Figure 4.44: Mark 3 inner support frame design (side view).

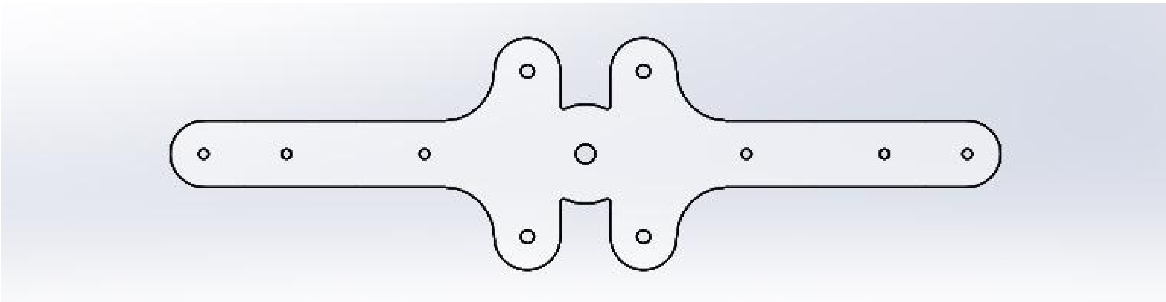

Figure 4.45: Mark 1 inner support frame design (side view).

Furthermore, the only difference between the outer and inner frames of Mark 3 was that the inner frames were slightly longer such that they could be fastened together at their ends. This was also decided with the intention to eventually feature only one support frame design in a build because having repeated parts in a build would mean that fewer unique parts would need to be manufactured per robot. This would also mean that in a situation with only one spare support frame available, if one of the robot's support frames were to be damaged or fail, it would not matter which one it was as they could all be replaced by the same spare part.

During testing of Mark 2, it was noticed that the body of the robot may interfere with the stair the LIMs are trying to climb due to it being longer than necessary (measured from the front end to the back end of the robot). therefore, the gearbox was redesigned to decrease its length - these changes can be compared in Figures 4.46 and 4.47 below.

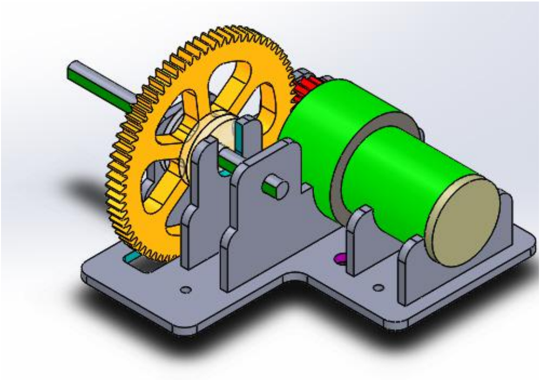

Figure 4.46: Improved gearbox design of Mark 3 (Isometric view).

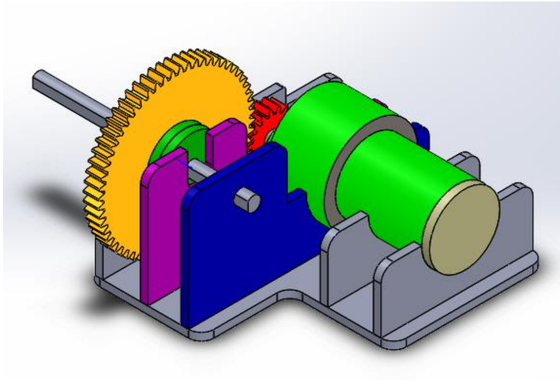

Figure 4.47: Earlier gearbox design from Mark 2 (Isometric view).

Minor mass reductions can also be noted from these figures: each upright was shortened towards its loading points e.g. the small uprights that supported the thinner diameter section of the motor were shortened towards their centre arc. At least 10 mm of material surrounded each shaft hole to maintain the strength to support the properly. The base of the Mark 3 gearbox was extended outwards past the drive gear because it was concerning how little strength might remain in the base after the slot for the drive gear was cut out of it. This was not experimented with as it was not of high priority so it was thought best to ensure that the gearbox base maintained enough strength - even if that meant extending it a little further than necessary.

As was evident in the Mark 2 gearbox, the motors caused most of the elongation of the gearbox due to the orientation they were chosen to be positioned in. It was therefore decided to rotate the motor 180 degrees such that the motor shaft would be situated on the edge of the gearbox allowing the body to be tucked in towards the centre of the gearbox, closer to the drive shaft. This change in orientation can be seen comparison between the Mark 3 and Mark 2 gearboxes can be seen in Figures 4.48 and 4.49, following.

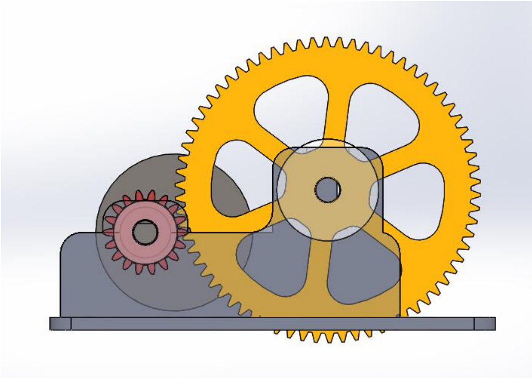

Figure 4.48: Gearbox design of Mark 3 showing new motor orientation (Side view).

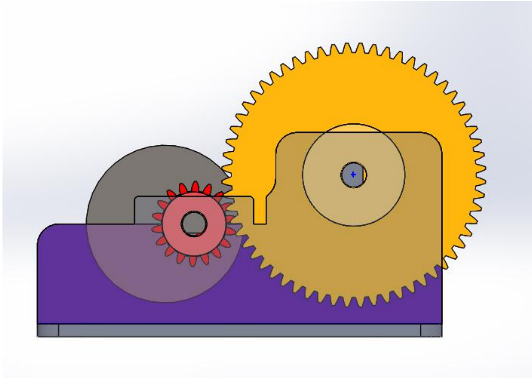

Figure 4.49: Earlier gearbox design showing motor orientation from Mark 2 (Side view).

The width of the gearbox of Mark 3 was measured to be 105 mm (from the left of the gearbox base to the right) which was almost exactly the same as the width of Mark 2. The same was found with the body base of Mark 3 versus Mark 2. It was realised beforehand that the limiting factor of the width was the mounting of the gearbox gears - particularly the motor gear. If the motor gear were positioned lower down and to the right - from the perspective of Figure 4.48 - this would decrease the width further. However given that this would be a maximum distance of roughly 5mm, it wasn't thought worth the effort. It should be noted that while neither the gearbox nor the body base dimensions were decreased, it was an achievement to keep them the same while also accommodating a significantly larger dive gear.

Mark 2 experienced problems with the wheel not rotating with the wheel shaft - it dislodged and the torque transmission failed. This prevented the wheels from locking up and hence, the LIM was never engaged to climb. The wheels of Mark 3 were designed to accommodate M4 hex nuts the centre of the wheel. It was intended that gluing M4 nuts onto the wheel shaft - previously M3 thread but changed to M4 for this reason - would act in the same way that the D-profile of the drive shaft did, successfully transmitting torque. It was decided to change the wheel shaft to an M4 thread because the M4 nuts were larger and were thought to be less likely to strip the hex hole in the wheel as opposed to M3 nuts which were significantly smaller.

The full Mark 3 robot assembly is shown from different views in Figures 4.50 to 4.54, below to provide a better understanding of the shape of the full robot build.

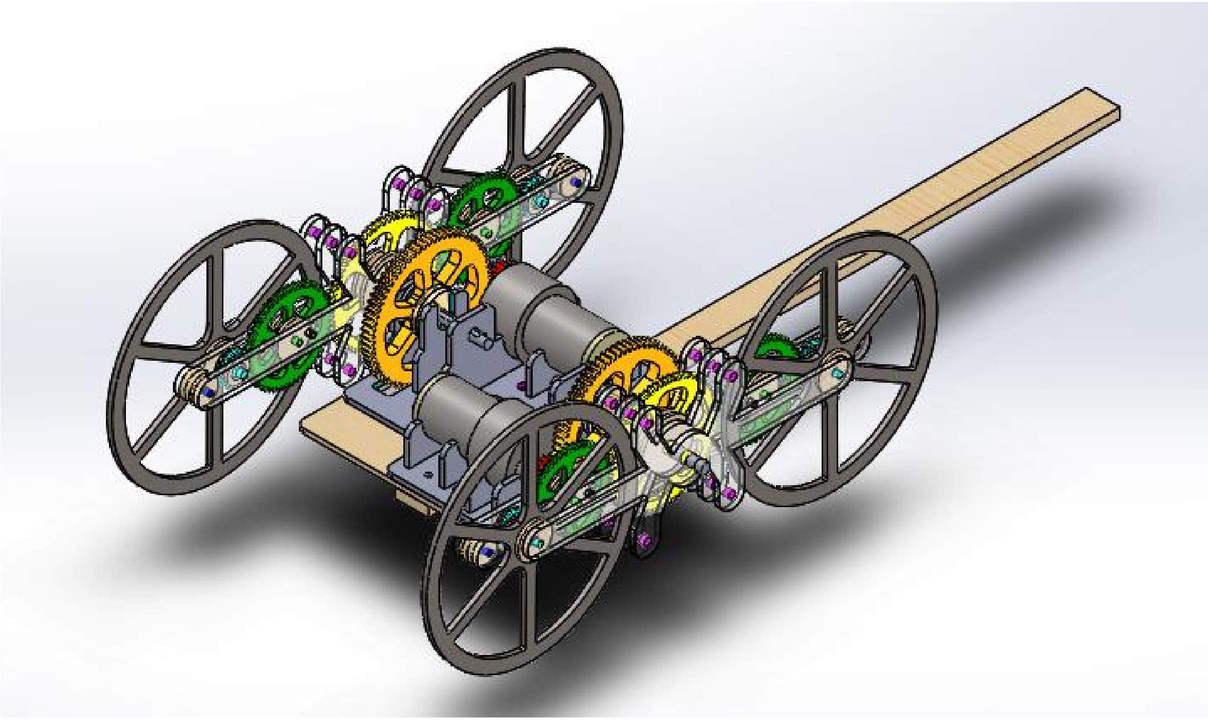

Figure 4.50: Isometric view of Mark 3 assembly.

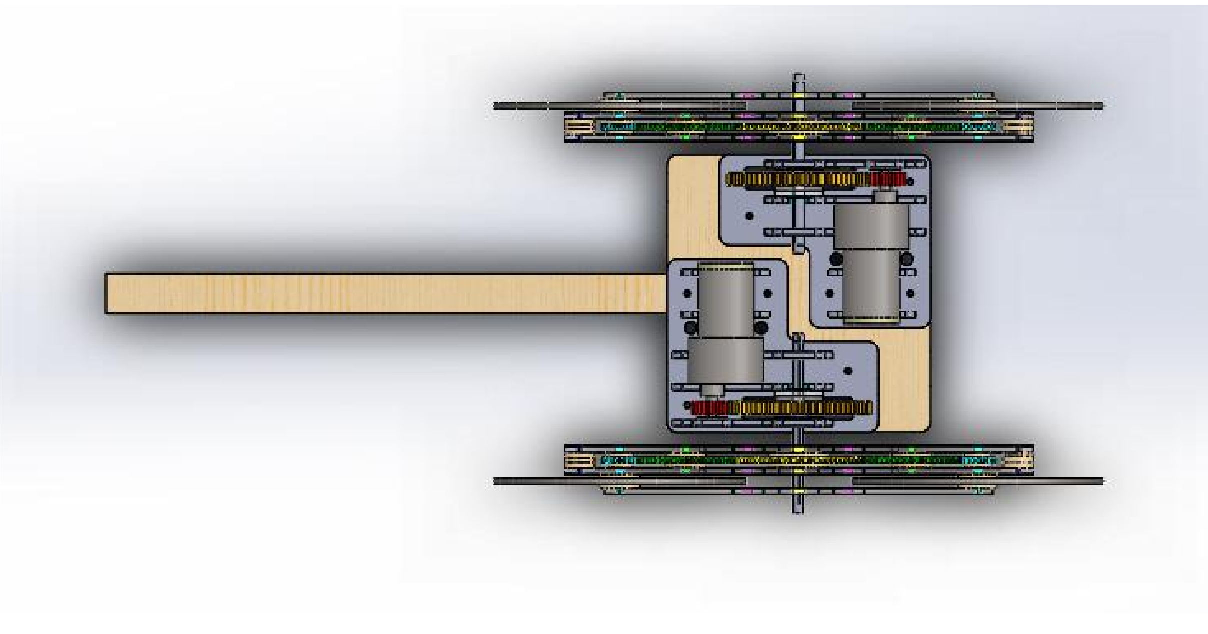

Figure 4.51: Top view of Mark 3 assembly.

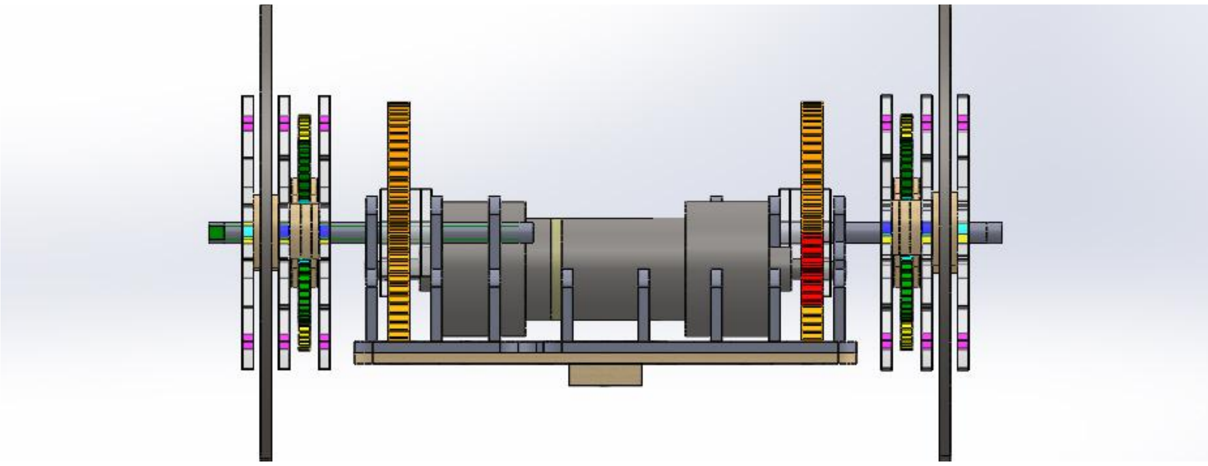

Figure 4.52: Front view of Mark 3 assembly.

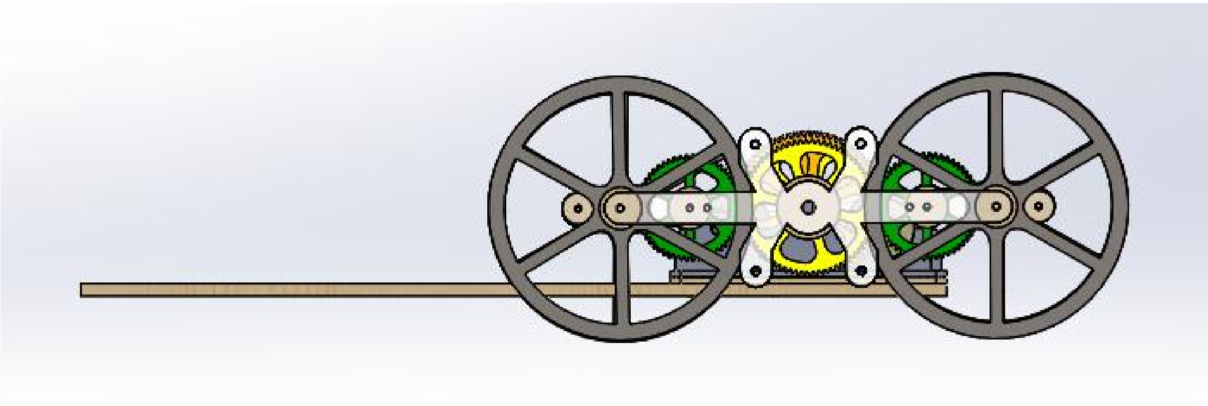

Figure 4.53: Side view of Mark 3 assembly.

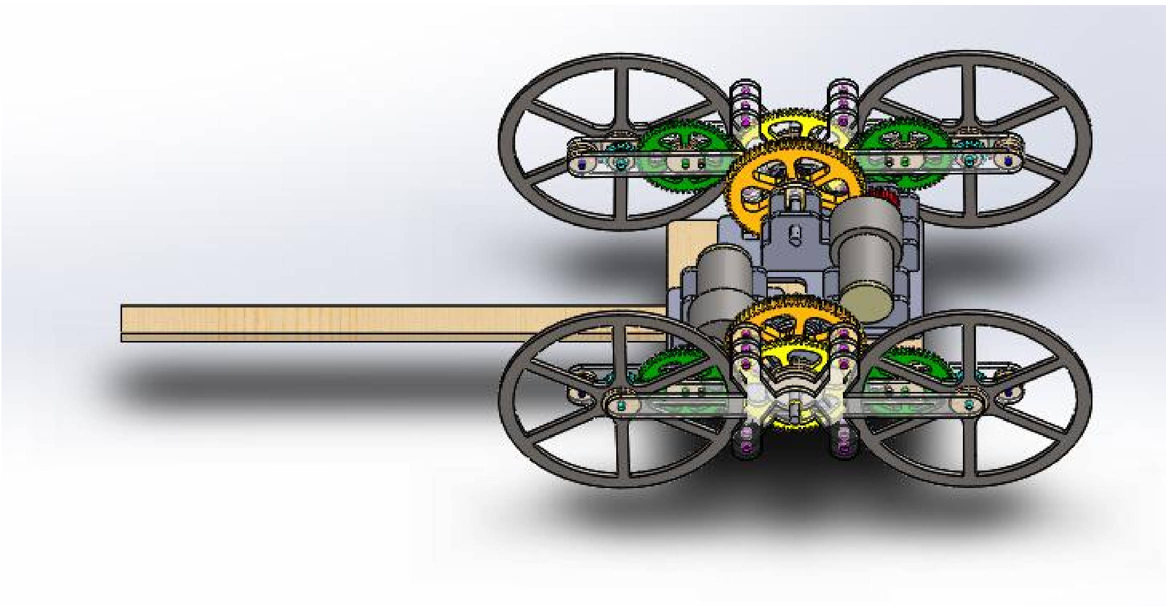

Figure 4.54: Raised side view of Mark 3 assembly.

4.4.2 Implementation

In the Mark 1 implementation section listed earlier, it was mentioned that the clearance between the gear spacers and inner support frames of the LIM was too large such that gears would wobble excessively to the point where gears might have disengaged from adjacent ones or some gear teeth may even snap off from the excessive force applied over a small area a tooth. This was remedied by replacing some inner support spacers with M3 nuts which were slightly thinner. However, this was much slower and would add a noticeable cost to the robot if it were produced on a large scale compared to the original plan of using acrylic parts as spacers.

This clearance problem was solved by making inner support frame spacers out of both 3 mm and 2 mm thick acrylic. This also decreased the number of M3 nuts used by more than half and was felt to be more accurate than relying on the mass-produced M3 nuts to be the same thicknesses - particularly since their faces were already been found not to be perpendicular to their central axes, as is discussed in a following paragraph. The clearance between gear spacers and the inner support frames after assembly was found to be small enough such that the gears were not at risk of losing contact with each other but large enough that there was an amount of play available that suggested the gears experiencing very little resistance to rotation which is imperative for this robot - indeed, most systems using gears.

Implementing the new method of ensuring that the wheels were locked to the wheel shaft was relatively simple and incidentally easier than it was designed to be. This was because it was realised during assembly that the M4 nuts being used were 3 mm deep. This changed the original plan of gluing two nuts up against each other on the shaft. Instead, three nuts were threaded onto the wheel shaft with an M4 washer between each (two washers per wheel shaft); the wheel was positioned over the centre nut between the two washers. In clarity, the order of the parts placed over the shaft was the following: nut, washer, nut, wheel (placed over previous nut), washer, nut; a small amount of super glue was placed over the thread on the adjacent washer before threading the next nut to the desired position on the shaft. An acrylic washer had been cut and placed either side of the three-nut configuration. This method worked out much better than expected as it was simple, effective and seemed very permanent. The only downsides were that the method's degree of permanence discouraged changes to the LIMs.

However, a minor issue that was noticed was that that hexagonal faces of some of the nuts were not machined to be exactly perpendicular to the its centre axis as this product does not require this feature. therefore, some of the washers also sat skew on the shaft, causing the wheel to be misaligned. It was noted that this should likely have been remedied in future versions although it was not known what difficulties would occur from this or how significant or problematic they may be; therefore, this was thought necessary to change until a problem presented itself.

The Mark 3 assembly was weighed to be 0.572 kg without motor or motor fasteners and 0.984 kg with the motors fastened in place. It is shown in the Figures 4.55 and 4.56.

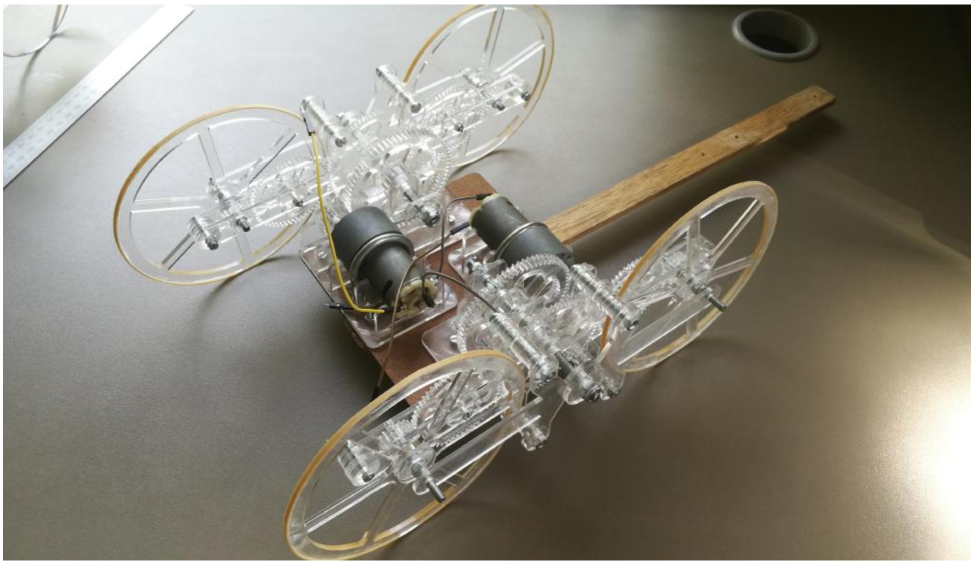

Figure 4.55: Full Mark 3 build.

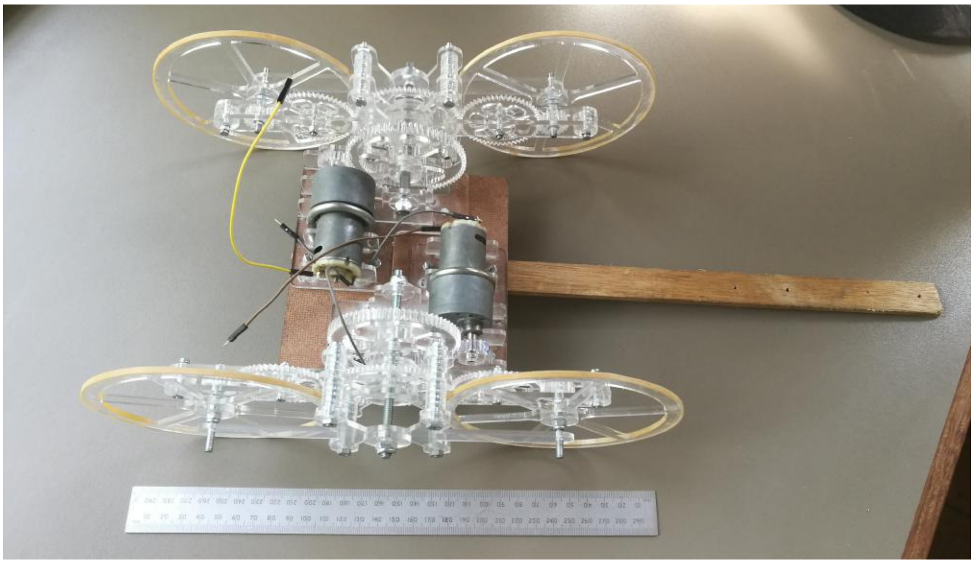

Figure 4.56: Full Mark 3 build.

As seen in Figure 4.57, it was also considered to be man-packable which was one of the objectives as outlined in the introduction chapter.

Figure 4.57: The full Mark 3 build fit comfortably in a regular backpack without any dismantling required.

4.4.3 Testing and Analysis

This section details the testing that Mark 3 underwent as well as analysing its strengths and weaknesses. These are then discussed and conclusions are made which influenced the following build iteration. Neither the motors, nor any parts were replaced between tests unless explicitly indicated. All tests made use of a 12 V ATX power supply to power the motors; this was done by connecting the supply directly to the motors - no control systems were used.

The testing procedure that was carried out for Mark 3 was the same as the testing procedure for the previous prototypes. Mark 3 was positioned on the ground facing a wall with the two forward-most wheels in contact with the wall. The motors were then simultaneously connected to the 12 V ATX power supply. The robot's LIMs immediately began the intended climbing motion with ease. Once the LIMs had flipped until upright against the wall, the power was disconnected as the test was over. This test was repeated five times over and, in all five tests, the LIMs flipped up to the vertical position without any difficulties. Based on these results, it was concluded that the LIM was receiving enough torque to overcome the first phase of climbing.

However, during the third iteration of this test, the power was not properly disconnected from the motors after the LIMs had reached the vertical position. With the LIMs attempting to continue the climbing motion after the vertical position, they eventually overcame the traction on the elastic bands that prevented the bottom wheels from slipping out. The bottom wheels then slid backwards and the LIM continued its flipping motion causing the LIM arms to drastically accelerate their rotation - and that of the wheels that were elevated at the time. This resulted in the front wheels being accelerated heavily towards the ground. The sudden impulse caused by the wheels colliding with the ground snapped off one of LIM arms near its centre. It was evident that decisions to decrease the weight of the LIM arms had undermined their structural integrity an ability to withstand load torques and forces. As it was a clean break, the broken part was repaired with super glue; the part did not fail for the remainder of the testing phase.

The second test was designed to determine whether the Mark 3 design was suited to the second phase of climbing: pulling itself up onto the above step. This test partially tested torque abilities and partially tested the suitability of the Mark 3 body shape to the task. Before the test, the robot's front wheels were put onto the top face of a box of height 120 mm with the back wheels resting on the ground. The front wheels were placed against the box the box while still resting on the ground.

The test was started by simultaneously connecting the motors to the 12 V ATX power supply. A successful test would have seen the robot pull itself onto the top of the box with no external help. What had been expected to happen was for the LIMs to rotate again, lifting the body up in an arcing motion but, in each of the successful tests, the robot wheels simply pulled the body up in the shortest path possible thus passing the test. All ten of the tests were passed at a height of 120 mm.

The final test was a combination of the two previous tests - essentially, this tested the robot's ability to climb a stair with no external interference. In preparation for the test, the robot was placed on the ground in front of the box - the same 120 mm high box as used in the previous tests - with the front wheels in contact with the box. This is shown in the top left frame of Figure 4.58 which shows the process of Mark 3 climbing the step. The test began by simultaneously powering the motors. The expectation of a successful test was that the LIM arm would flip; the back wheels - having rotated with the arm - would come to rest on top of the box, gain traction, and pull the robot up the stair. 6 of the 10 test were passed - a video example can be seen *here*. The remaining 4 tests were to concluded to have failed due to the body being interfered with by the step. This is explained in the following test where the phenomenon occurred to a more extreme degree.

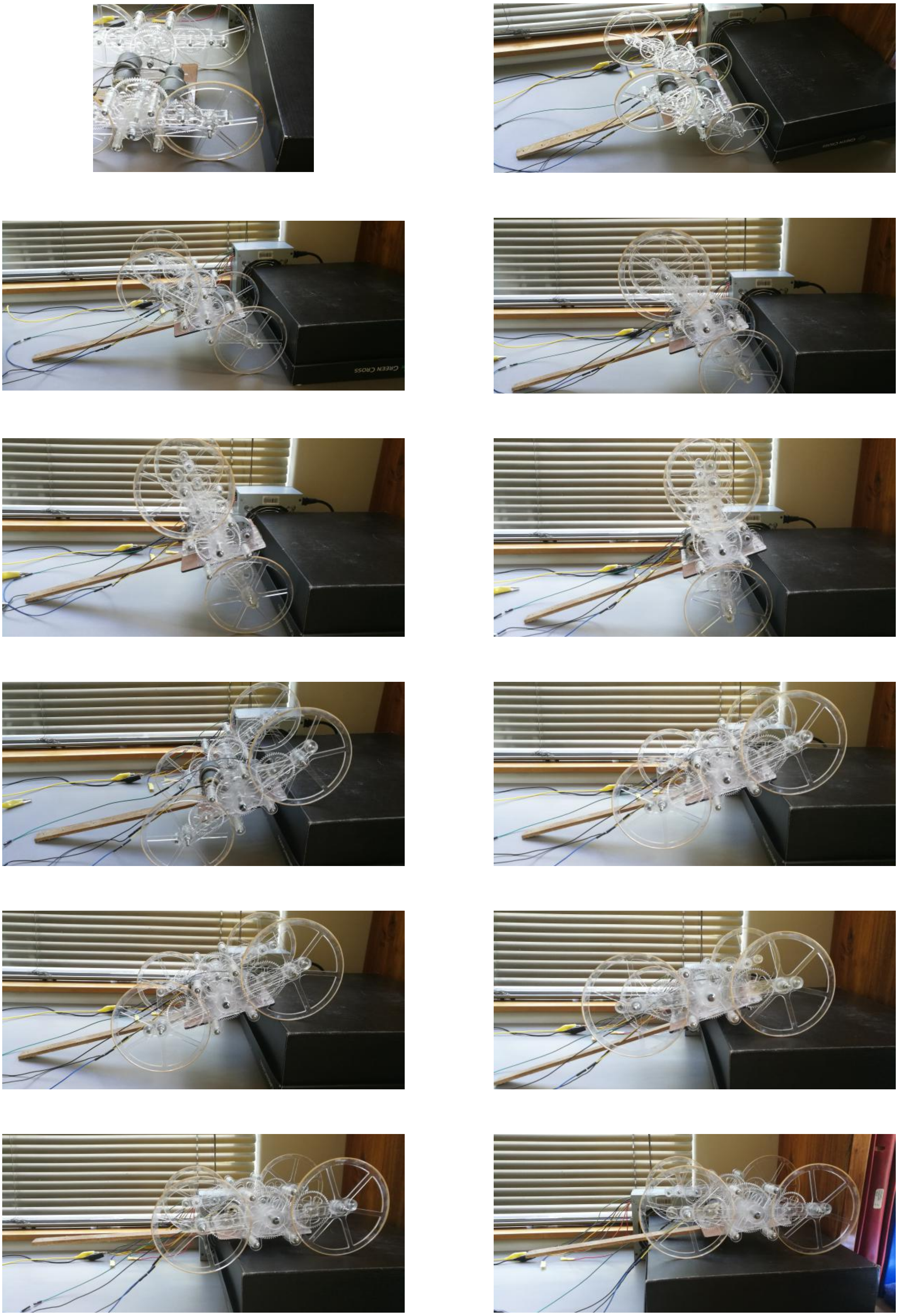

Figure 4.58: Showing the multiple stages of a typical Mark 3 step climb.

Upon increasing the step height to 140 mm, only 2 of the 10 tests were passed. The cause of failure was noted to be the same as above: the robot body was being interfered with by the step, causing the body to temporarily lodge itself on the box edge (referred to as beaching). Upon beaching, the LIMs would spin quickly due to not supporting the weight of the robot until the front wheels collided with the top edge of the box. This also occurred when testing a step height of 120 mm, however the wheels gripped the top of the step and pulled the robot up more often than not. With a step height of 140 mm, the spinning LIMs collided with the top of the step more firmly which dislodged the body but subsequently caused the entire robot to fall back off the step to the starting position. It was concluded that distance between the front of the body and the drive shaft was too large and was the root cause of the failure.

Overall, Mark 3's ability to climb a 120 mm box led to the conclusion of its success and ability of the system to be adapted to real-life USAR solutions. However, it was concluded that distance between the drive shaft and the front face of the body needed to be reduced to at least as small as the drive gear to avoid its interference with steps.

4.5 Torque comparisons of Mark 1, 2, and 3

The LIM arm torque contributions in each prototype are included in Table 4.2, below. Equations 4.4, 4.5 and 4.8 were used in determining the LIM, gearbox and tail torque contributions, respectively. The relative LIM arm torque values represent the LIM arm torque in terms of rated motor torque. All decimal values are listed in terms of motor torque with the exception of LIM arm torque values as these were absolute values of the torque applied to the LIM arm according to Equation 4.10. It should be noted that the resistive moments acting on each LIM due to the weight of the robot calculated to be the following based on the mass and distance between the centre of mass and centre of the wheel:

1. Mark 1: 0.545 Nm
2. Mark 2: 0.539 Nm
3. Mark 3: 0.434 Nm

	Gearbox contribution	LIM contribution	Tail contribution	Relative LIM arm torque	LIM arm torque (Nm)
Mark 1	1.000	0.460	N/A	0.699	0.137
Mark 2	3.000	0.460	1.332	2.098	0.411
Mark 3	3.889	0.667	2.800	6.347	1.244

Table 4.2: Indicating the gearbox and LIM torque contributions to the climbing motion of the robot in terms of rate motor torque.

These calculations - only understood after the implementing of Mark 2 - indicated that Mark 1 and Mark 2 would not climb. Furthermore, it was calculated that the net moment that acted on the LIM arm of Mark 3 - when the wheels were halted - was positive, indicating it would climb. This agreed with all results and was thus assumed a correct method for calculating the minimum torque requirements.

Chapter 5

Discussion

This chapter discusses the results from the tests performed on Mark 3 and is also a reflection of the design process of the robot.

5.1 Discussion on design process

Overall, the design process was thought to be an effective and efficient method of developing a capable robot. Using the four steps as noted by Mark Rober - research, prototype, sensitivity analysis, and final build - proved very useful in determining which directions to explore for solutions to a problem. However, it was realised that being able to run computer simulations to test the each of the prototype designs before building them would have resulted in a more time-efficient sensitivity analysis phase. Assembling, troubleshooting and fixing unforeseen issues with the prototypes sometimes took up to four days. Issues dependent largely on the dynamic operation of the robot e.g. minimum LIM arm torque, effect of weight, distribution thereof, and tail length could all have been investigated without needing to assemble one of the builds. Furthermore, the ability to run computer simulations would have allowed for real-time analysis of the build followed by immediate adjustments that could be simulated immediately thereafter. A large limitation on the design process was the inability to optimise Mark 3's various parts - a limitation that could have been mitigated with computer simulations.

5.2 Discussion on design choices

The choice to drastically decrease the amount of material used in Mark 3 was believed to make a large reduction in the torque requirement of Ascender (to climb a stair). It was unfortunate that this change led to the breaking of one of the LIMs of Mark 3 when care was not taken during the management of the Mark 3 prototype. However, this failure of the leaner support frames led to better understanding of the internal stresses placed on the robot's various parts.

The removal of material from the gears and wheels resulted in the Mark 3 build weighing 28% less than the build of Mark 2 (without motors or motor fasteners). However, with the motors fastened to each build, the mass reduction from Mark 2 to Mark 3 was calculated to be 19.5%. This made a significant difference to the counter-torque placed on the LIM by the weight of the robot.

The gearbox, LIM gear ratios and tail affected the torque applied to the LIM arm while wheel rotation was halted. As seen from Table 4.2, the decision to change gear properties in both the gearbox and LIM made a substantial difference to the robot's ability to climb. The gearbox torque output increased by 29.6% from Mark 2 to Mark 3 and the change to the gear ratios in the LIM contributed a 45%. Furthermore, the changes in the gearbox and LIM also increased the tail torque contribution by 50.2%.

In total, the calculated increase in LIM arm torque (when the wheel was halted) was 206.68% from Mark 2 to Mark 3 (according to the Table 4.2). While the mass reductions made a considerable difference to the ease at which the LIMs flipped, the torque adjustments made a much larger difference. The improved understanding of the tail's contribution to the climbing motion of the gearbox was the final factor needed to produce a successful stair-climbing prototype of Ascender.

The choice to significantly increase the LIM's master gear diameter was based on Equation 4.4 which stated that a larger master gear - in relation to the follower gear - would increase the torque output to the arm significantly. While it was thought that this was a necessary change to ensure that the LIMs could climb stairs, the byproduct of this torque reduction was that the robot's regular travelling speed along the ground was greatly increased. This would certainly decrease the controllability of the robot from a tele-operation perspective - particularly when trying to make fine movements and turns.

The use of elastic bands on the wheels was the difference between the drive shaft torque spinning the wheels and halting wheel rotation to transfer the drive torque to the LIM arm. The change between the two tests was surprisingly large. It was originally though that a material with a much higher coefficient of friction would need to be implemented but this wasn't strictly necessary. It should however be noted that super gluing the elastic bands onto the 3mm edge of a circular shape is extremely cumbersome because a) the elastic band kept slipping off the edges, and b) having to super glue around the whole circumference of the wheel and carefully position the elastic over it while waiting for the glue to try was time-inefficient.

5.3 Discussion on test results

5.4 Strengths

The Mark 3 prototype is a very low-cost, specialised robot given its complex function and ability. With knowledge gained, Ascender has the opportunity to incorporate the tele-operation and live video streaming functionality investigated by Haskel [13] to become a fully operational - but completely expendable - urban search and rescue robot. The Mark 3 build features repeated parts that would enable search and rescue teams to reduce the number of unique spare parts that would be needed to repair the robot (if repairs are possible). Furthermore, repeated parts cause the decrease in manufacturing costs for mass-production.

The simplicity of the man-packable robot design gives it the ability to be rapidly deployable. Secondly, given the LIM mechanism's complex gear chain, this reduces the number of commands that an operator may need to typically give other stair-climbing robots i.e., as long as the motors are sufficiently powered (and the obstacle is within the robot's range of capability), the robot will climb without extra commands from the operator. This significantly decreases the amount of training that an operator may need to control the robot.

5.5 Limitations

Limitations of the Mark 3 design included being relatively fragile to falls, the amount of time required to assemble a single build and the materials with which it was made. Furthermore, the build would not be able to manoeuvre in spaces with a ceiling height lower than 130mm. The robot has only been tested in a laboratory environment where a power source was available and where the surfaces that it came into contact with were flat and unobstructed; these surfaces were also not dusty or slippery which helped provide more traction to the robot's wheels. These surfaces do not represent the environment of typical urban environments which feature dusty surfaces like cement.

The robot was also only operated in a straight line due to the lack of the tele-operation functionality. Turning was only possible by fully powering one motor without the other however this was a severe limitation on the possible turning circles that could be recreated. The ability to manoeuvre through small spaces was also not tested.

Repairs to the robot were relatively simple to carry out, however replacing a part such as a LIM gear would require dismantling of most of LIM to do so. This may require more time than is sometimes available in disaster zones.

Chapter 6

Conclusions

This investigation set out to design a low-cost urban search and rescue robot that had the specialised ability of ascending stairs. It was specified that the robot build should remain small so it could manoeuvre through small spaces and be ma-packable, however, it should be able to accommodate necessary electronics to give it tele-communication functionality in the future. Lastly, the robot was to be designed without the use of high-torque motors which are typically expensive, heavy and large.

It was concluded that the Mark 3 robot was capable of climbing a step of height 120 mm due to the results of the testing phase. Furthermore, since a staircase is simply a repeated number of stairs, it was reasonably thought that the robot would be able to ascend a staircase once a control system was built for it. However, the large increase in ground movement speed of Ascender from Mark 2 to Mark 3 was concluded to be too high to control properly.

The cost of the robot development was kept well within the R1500 budget assigned by the UCT engineering department and the cost of the Mark 3 production was concluded to be well within the low-cost requirements of the build. The robot was manufactured using low cost, readily available materials - acrylic and hardboard - that were significant contributors to the low cost. The design could certainly be manufactured quickly, however the assembly procedure was thought to be too cumbersome to assemble en masse without machines with fine control. As such, it was concluded that the design was not simple enough to be mass-producible while maintaining its low cost.

The size of the robot was much smaller than that of Wilson's [5]. It also maintained the size of Haskel's [13] Theseus robot such that the electronics that Haskel developed might be implemented in a future version of Mark 3. This creates an opportunity to test the Ascender's Mark 3 build with tele-operation functionality and other typical USAR capabilities such as live video feeds. The build dimensions and light weight allowed the robot to be comfortably transported with the use of a backpack. The unexpected need of a tail, incidentally provided a comfortable method of holding the robot which could be useful when moving it into position.

The robot functioned successfully with relatively low-torque motors of 0.196 Nm while maintaining size constraints. This also minimised the cost of the overall project which was concluded to be a great achievement given the challenge of using low-torque motors to carry out the desired task.

The completion of a working prototype allows further research to be done on the optimisation of the LIM design such that it may result in finer control of the robot. Furthermore, the introduction of more compact gear systems - perhaps such as that of the gearbox - would allow the robot's size to be further decreased such that it may fit inside even smaller spaces than designed.

It was, however concluded that Mark 3 was not sturdy enough to withstand the harsh environments typical of disaster zones as the build broke in lab environments to the point where it could not ascend a stair without external input. It was admitted that more work needed to be done on this aspect of the design before Ascender was integrated with the electronics of Theseus.

Drawing on the details of Mark 3's operation, it was concluded that the LIM design by Wilson [5] was a very elegant solution to stair climbing as the kinetic calculations were relatively simple to understand and manipulate, and the general design was relatively simple to implement - albeit sometimes slow and cumbersome for smaller builds.

It was further concluded that the equations derived from the free body diagrams of the robot's generalised design were correct as the results matched the equations' solutions - particularly important was that of Equation4.10 which expressed the total torque acting on the LIM arms and could be used to calculate the minimum torque requirements.

Chapter 7

Recommendations

Based on the content of previous chapters - most notably the discussion and conclusion chapters previously - the following recommendations were made for any future projects that wish to continue or improve on this work.

7.1 Further testing

Before further improving Mark 3, it is recommended that the build be recreated - possibly multiple times - and tested further to better understand the limitations of the Mark 3 robot. Some features to test are included below.

It was not tested whether Mark 3 was capable of ascending a staircase - each with acceptable step height 120 mm - and this should be tested in future before making further prototypes.

The maximum weight that the robot can continue to climb stairs with should be investigated to determine the limitations for any potential payloads.

The strength of the Mark 3 build should also be further tested; specifically, the build needs to be tested to its breaking point(s), improved and then tested again. This should be repeated multiple times to mitigate the number of unacceptably weak points in the robot structure. Improvements should start with increasing the strength of the LIM support frames.

Testing Mark 3's capability when traversing over rough surfaces that resemble typical disaster environments should also be tested.

As the motors were only tested with 12 V ATX power supply, it is suggested that investigation be done into using different power configurations as this may determine some specifications for a battery if one were to be installed in future.

7.2 Further research using simulation techniques

The most highly encouraged recommendation that can be given is that of using computer software to accurately simulate the robot as it was concluded that the developer would achieve a better understanding of how the different features of the robot build affect its suitability to climbing stairs. Furthermore, computer simulations would drastically decreased development costs and wasted material. Lastly, having accurate kinetic models of the robot design would allow further research into implementing a stair-climbing solution that is optimised for factors such as strength, low-cost, small size, weight-carrying capability, fine motion control, mass production and rapid assembly, and in-field repair-ability.

7.3 Suggested improvements and alternative designs of Mark 3

The first and most highly encouraged recommendation is to improve Mark 3 such that it is sturdier. It is suggested to copy the support frames of Mark 2 and appropriate them to the different shaft distances required by Mark 3 as the LIMs of Mark 2 were noticeably stronger and provided better support for gear shafts.

It is also recommended that Mark 3 be redesigned with the entire body situated *behind* the drive shaft. This would result in a body that could never get in the way of a stair or other obstacle which is expected to increase the climbing success rate of the robot significantly. However, it is advised that careful thought be taken to choose how to position the motors such that the robot remains balanced.

The tail was an integral part of the robot's functionality and it is suggested to further investigate the optimum length for the tail - keeping in mind that a longer tail may inhibit turning in small spaces. Therefore, it is further recommended to investigate a tail that can be made flexible or rigid at the control of the operator - this will allow the robot to manoeuvre more easily in cramped spaces with many bends.

It was concluded that the method of increasing wheel traction through the super gluing of elastic bands to the wheel circumference was too cumbersome. It is suggested that the wheels be 3D printed with grooves around their circumference that a rubber O-ring could be fitted into, to serve as the wheel's 'tyre' that provides the necessary traction. This concept would allow the rubber O-rings to be easily replaced when damaged. Secondly, due to the design's ease of replacement, different types of rubber - or completely different materials - could be investigated.

It was also concluded that the gearbox took up too much space on the robot. A more compact gearbox solution should be investigated to make room for more electronic systems and other potential payloads.

It is recommended to investigate the effectiveness in using recycled materials in rescue robots that might decrease the costs of a developing country such as South Africa that may have a very limited budget for development of USAR technologies.

Lastly, it was concluded that Mark 3 was not thought suitable for relatively fine movements and thus the controllability of the robot should be improved. It is suspected that finer control can be gained by reproducing the LIM gear ratios similar to that of Mark 2 as the LIM gear ratios of Mark 3 enhanced the robot's speed to a point where it was thought to be too quick for proper control. It is recommended to analyse Equation 4.10 to further develop Ascender such that it satisfies the torque requirements to climb stairs but is not too fast during regular ground movement that it becomes difficult to control.

Lastly, it is recommended that this prototype be further developed with the intention of producing a capable, low-cost USAR robot with features such as fine-control teleoperation, live video streaming, reliability around climbing stairs and traversing other obstacles typical of disaster zones, such that the harm to and loss of human life be prevented as far as technology allows.

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