Hybrid locomotion for agricultural robotic platform

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Abstract

The New Zealand dairy industry is an important component of the New Zealand economy with an annual income of 14 billion dollars. Due to its significance it is important that new technology is developed to further the industry and increase efficiency. Many precision agricultural robots and prototypes were reviewed in this thesis and the topic of hybrid locomotion was discussed. Using methods of hybrid locomotion, a design of a prototype with non-complex mechanisms has been presented in this thesis.

Hybrid locomotion is a popular field among robotics where researchers and engineers design robots that has more than one mode of locomotion. By incorporating hybrid locomotion, it allows the robot to tackle unique terrains which most single locomotion style robots cannot. The prototype presented in this thesis uses the track leg hybrid locomotion style. This design allows the robot platform to get much closer to the ground which will allow the platform to carry sensors that needs to be within proximity to the ground to operate. The design allows the prototype to have two modes of locomotion, track mode and leg mode.

IoT is the new trend in the world that can be used to remotely monitor and control devices. IoT in agriculture was also reviewed in this thesis and an IoT gateway circuit was designed and presented. A prototype was manufactured, which uses the cellular network and can receive data from sensors connected via 6 ADC inputs and the RS485 communication method which will allow the platform to carry various different sensors for data acquisition.

The final product is intended to be used in a typical New Zealand dairy or life stock farm to gather parameters such as grass health and soil parameters which will be useful to researchers for data analysis and develop new fertiliser and grass types for animals in a farm. The IoT gateway prototype in this thesis will allow the robot to be fully autonomous and will allow the prototype to be operated remotely. The final prototype is intended to have bidirectional communication where the user can send commands and receive data remotely. This concept has the potential to be a very useful tool to agricultural researchers and scientists in agriculture.

The preliminary testing showed promising results, but also suggested that more development and testing is necessary to further validate the design concept. The tests and results are presented and discussed in this thesis.

Acknowledgements

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Chapter 1

Introduction and project overview

Over the past few years farming has had a huge influence on the New Zealand economy. Amongst all farming areas such as beef farming, sheep farming etc. dairy farming brings the most revenue to New Zealand. Dairy farming contributes about 2.8% of New Zealand's GDP (Gross domestic product) with an export revenue of about $14 billion a year [1]. Since this is the leading industry in New Zealand and is responsible for a large proportion of the revenue of the country, it is important that technology is developed to maintain, monitor and improve the quality of work for the workers and the well-being of the animals of farms.

Since agriculture, specially farming, is an important industry in New Zealand, placing a mobile robot on a farm will have benefits such as autonomous data gathering for fertilizer analysis, autonomous crop maintaining, autonomous heard management, crop health monitoring, life stock monitoring etc.

This research and development project will investigate a way in which a mobile robot can be placed on a farm and the design of such a platform. The full project overview is given in section 1.1.

The current project presented in this thesis will investigate a robot platform that can be placed in a farming environment. Farms consists of rough and harsh terrains. It can also be wet and muddy during the winter seasons [2] which can introduce issues for a robot's operation. Therefore, a non-complex design was explored in this project. All components will be chosen according to their price vs features. As an example, how many features will a brushless DC motor driver have and is it worth for the price will be considered.

Most products and agricultural robot prototypes reviewed had robots with a large ground clearance. A design that allows the robot platform to get closer to the ground which can carry sensors that require to be in proximity to the ground was explored and presented in this thesis. The design was inspired by robot prototypes that used the hybrid locomotion design concept. A hybrid systems consists of two or more locomotion methods for travel [3]. Methods consists of:

- Leg wheels (LW) – This method of locomotion combines the flexibility of movements using legs and the efficiency of wheels. The disadvantage of such a system is the complex algorithms and complicated mechanical designs.
- Leg tracks (LT) – The method combines the flexibility of movements using legs and gives the robot more traction to travel in more rougher environments. The use of tracks will have reduced efficiency than a wheeled robot.
- Wheels tracks (WT) – This method of locomotion is suited for uneven and soft terrains. The use of wheels will make the system more energy efficient. However, the complex mechanical designs are required in a system.

- Legs wheels tracks (LWT) – This locomotion method will combine all the three methods of locomotion. It can be operated in different environments. The disadvantage of such a system is the complexity of design.

Figure 1: Mantis a LW robot [3]

Figure 2: CHIMP a LT robot [4]

Figure 3: Helios IV a WT robot [5]

The design presented in this thesis uses the leg track locomotion method. This design allowed the robot to have a low ground clearance and travel through rough terrain. The design was inspired by a leg, track and wheel robot named Azimuth [6] by the University of Sherbrooke, Canada.

Figure 4: Azimuth LWT Robot [7]

Figure 5 below shows the fully assembled prototype and Figure 6 shows the prototype's leg.

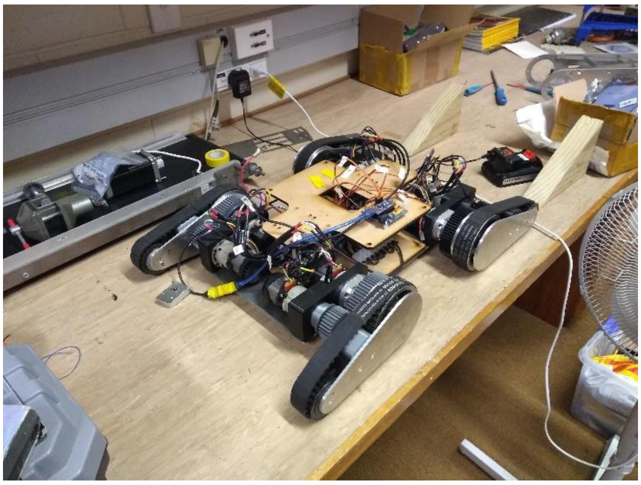


Figure 5: Fully assembled prototype

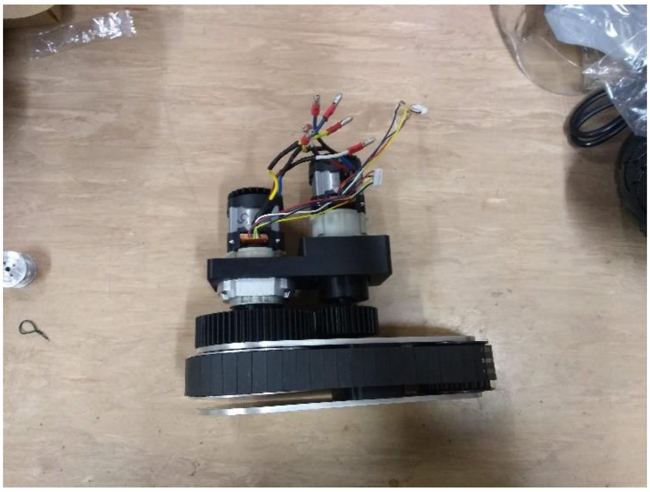


Figure 6: Prototype leg design

Furthermore, an IoT (Internet of Things) gateway method which can be used for communication is also presented in this thesis. The PCB design allows 6 ADC inputs and a RS 485 input for sensors. The PCB also carries a cellular modem which can be used to connect to a remote server to send and receive data. The final product is to be fully autonomous and can be operated by a user via the internet.

1.1 Project overview

Upon full completion at least the following points should be investigated for this project. This thesis will investigate some of these points which are shown in section 1.2. As the project continues more key points maybe added to this list but it was decided that these points must be addressed for the completion of this project.

Literature review

- Preliminary research into existing farm robots and their functions.
- Research into locomotion methods.
- Research into current rough terrain robots and their design principals
- Current IoT technologies used in agriculture

- IoT options for robots
- Sensors that can be incorporated with the robot for farms
- Vision strategies
- Robot control strategies

Design

- Design of a rough terrain robot to be placed in a farm
- Electronics components selection
- Chosen electronics components implementation
- IoT components selection
- Embedded electronics design of IoT circuit
- IoT implementation (Web based project using web services such as AWS etc)
- Sensor options for the robot
- Implementation of chosen sensors

Experiment

- GAIT methods of the design
- Control systems for the chosen GAIT method using ROS
- Control system implementation
- Electronics for chosen sensors
- Control strategy implementation
- Vision strategy implementation
- Implement full system into a farm
- Testing of full system
- Improvements if necessary
- Data gathering for experimentation and build complex algorithms
- End of project

1.2 Current project overview

This thesis will be investigating the following aspects of the project from the overall project overview and propel the project towards its completion in the future. The main elements of the remaining chapters in this thesis are:

Chapter 2: Preliminary Survey and Research

- Preliminary research into existing farm robots and their functions.
- Research into locomotion methods.
- Research into current rough terrain robots and their design properties
- Current IoT used in agriculture

Chapter 3: Design Considerations and the proposed system

- Design of a rough terrain robot to be placed in a farm
- Embedded electronics design of IoT circuit
- Electronics components selection
- IoT components selection

- Chosen electronics components implementation
- Farm robot prototype implementation

Chapter 4: Preliminary Testing of the mechanical design

- Prototype testing
- Test results and observations
- Test discussions

Chapter 5: Conclusions and recommendations

- Recommendations for the future
- Ideas for future improvements

1.3 Current project objectives and specifications

During the preliminary research, detailed in Chapter 2, many agricultural robots and prototypes of robots that is used in agriculture was reviewed. The common theme was that they had complex designs. Furthermore, they have yet to utilise IoT methods to communicate as part of the base platform design.

The New Zealand farming environment and terrain is relatively harsh and requires robust designs of equipment to operate in it. The aim of this project will be to design a robot to operate in such environments and have a relatively simple and robust design. This project will also attempt to allow the robot to have an IoT method to connect to the internet by designing a PCB that will allow a cellular connection to communicate.

The following objectives will help achieve this project aim. Preliminary tests are done, the results are discussed, and recommendations based on the results are presented in this thesis.

- Design and prototype platform of a robot that can be placed in a farm
- Design and manufacture a protype IoT solution that can be used by the robot
- Test basic function of the mechanical design and get it prepared for the GAIT implementation
- Test basic function of the electronics design of the IoT and get it ready for the next phase of the project
- Present learnings of the tests and the strengths and weakness of the current design and provide recommendations for improvements

The GAIT generation and implementation is not in the scope of this project. This will require research and development of complex algorithms and electronics. This thesis will test only the tractor mode of the prototype and present the findings. Furthermore, only the electronics side of the IoT gateway is presented in this thesis. The server side development of this project is not in the scope of this thesis. Since the onboard sensors has not been chosen yet we cannot determine the battery specifications, therefore the battery specification is also out of the scope of this project.

The end goal for the product is to place a fully autonomous robotic platform in a New Zealand farming environment. The platform should have the ability to carry sensors that require proximity or contact with the ground to gather useful information. Therefore, the following specifications were set to help achieve this aim.

- A design that will allow the robot/platform to get within proximity to the ground. At least within 50 mm from the ground
- The prototype will also have to overcome a small obstacle such as small rocks. The robot must have the ability to ‘lift’ itself up to at least 100 mm. This will allow the robot to overcome small rocks or imperfections in a farming environment.
- A non-complex design that will allow servicing and the overall cost of the prototype low.
- The system should be able to operate from 12 V to 24 V as most sensors and equipment require this range of voltage to operate.
- Since the product is intended to operate autonomously in a New Zealand farm it would be an appealing feature for the product to cover a significant land area. Therefore, a speed of at least 0.5 m/s is desirable.
- The product should be able to carry and array of sensors (sensors not decided in the scope of this project) and maybe even a robotic arm. Therefore, the robot should be able to carry a payload of at least 100 kg.
- The electronics of the robot will have to accept an input from an analogue reading from sensors. This analogue signal input should be able to accept and reading up to 10 V.
- The system electronics has to have the ability to send and receive data/commands from a remote server.

Chapter 2
Preliminary Survey and Research

Literature research into existing technology and prototypes is a crucial step before any product development. Although we can look into all aspects of knowledge and literature on the subject, only products that are relevant to this project will be reviewed in this chapter.

This chapter will investigate the following:

- The New Zealand dairy industry and how it is doing. Current automation in farms, current robots used in agriculture, Internet of things (IoT) in agriculture, current rough terrain robots.
- Rough terrain robots and their locomotion methods and special design concepts that will be useful for a robot that can be used in an agricultural setting.
- IoT methods that can be integrated into a robot. What is IoT, what are the types of IoT and what will be the best method for this project.

2.1 New Zealand Dairy Industry

2.1.1 Herd Statistics

According the New Zealand dairy statistics [8], dairy is one of the main incomes for New Zealand's economy. In the 2017/18 season New Zealand dairy companies had processed 20.7 billion litres of milk which contained around 1.84 billion kilograms of milk solids.

The average herd size in the 2017/18 season was 431 cows. The data also showed that there was an increase in the heard size by 17 cows than the last season. The South Island has seen an expansion of heard sizes which has contributed to the average herd size increasing. The largest herd size was reported in Canterbury with 803 cows.

Although the number of cows in a herd has increased the number of herds in a farm has decreased by about 158. The 2017/18 season has an estimate of 11,590 herds.

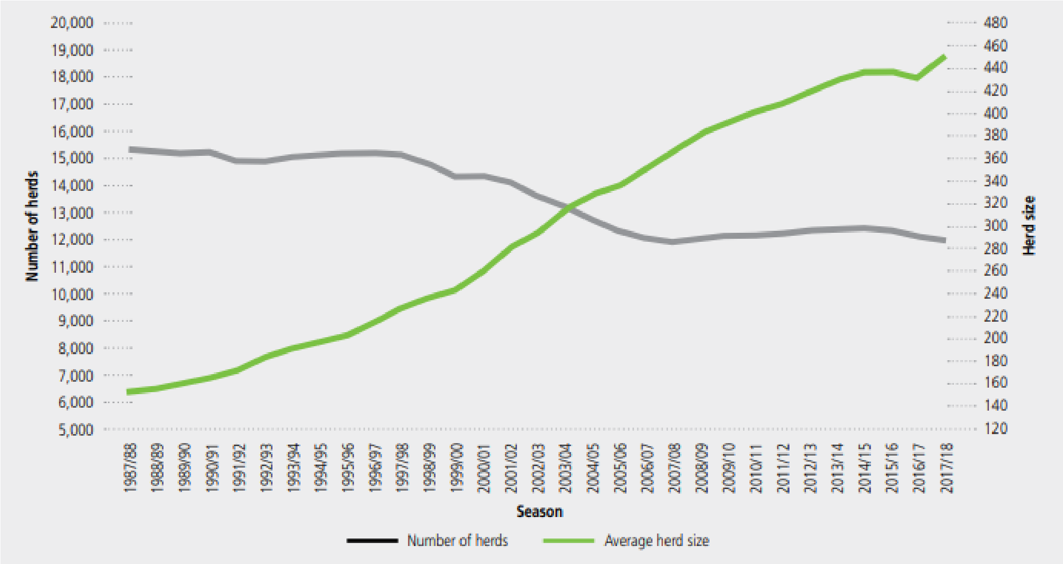


Figure 7: Average herd size vs Number of herds in NZ [8]

Data shown in figure 7 suggests that the farming industry is very important for the New Zealand’s economy. Since it is a key income source it is important that new technologies are developed to minimise the losses and to further maximise the profits. Placing a fully autonomous robot on a farm can be beneficial for stock monitoring, heard monitoring, soil monitoring etc.

2.1.2 Regional Dairy Statistics

In New Zealand most dairy herds are located in the north island (72.3%). The Waikato district holds about 22.7% of the heads and is the greatest concentration of herds in the country [5]. The 2017/18 season counted 4,992,914 cows and a total of 11,590 herds. Figure 8 shows the distribution of dairy herds by region.

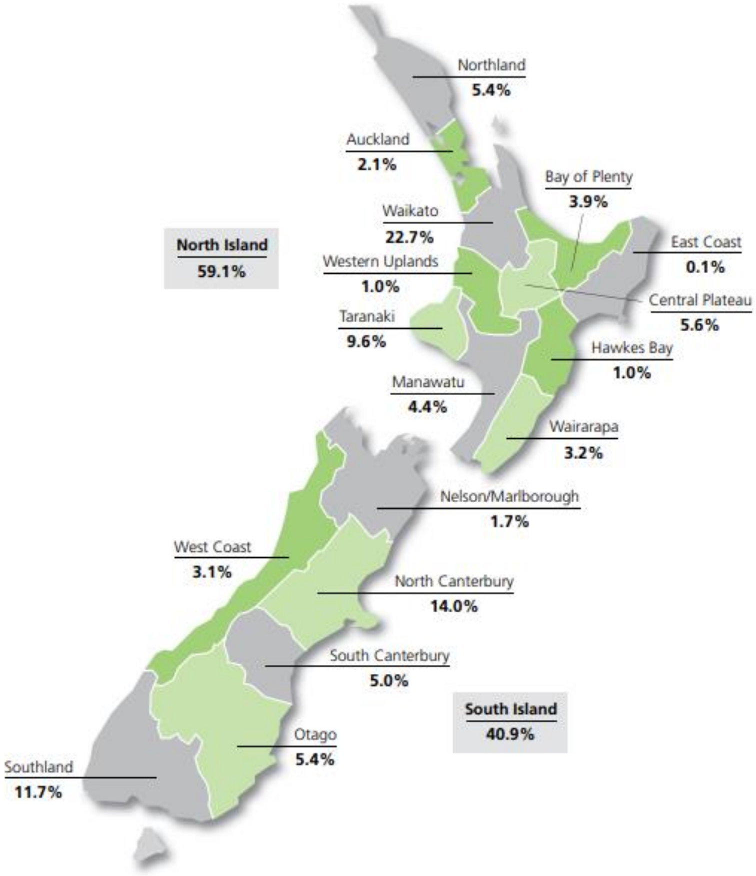


Figure 8: New Zealand farm land distribution [8]

New Zealand's terrain is mostly mountainous or steep hill country. The geology consists of hard and brittle rocks in the mountain areas. The north island terrain can turn into mush during heavy rains [2]. Land used in the dairy industry has increased between the years 2002 and 2016 by 42.4 percent. It also mentioned that sheep and beef farming land has decreased by 19.8 percent [9].

Our product will be deployed in a dairy farm because the above statistics shows that dairy farming is, by far, the most preferred farming type in New Zealand. Since the terrain is mountainous the product will take this into design consideration.

2.2 Robots in Agriculture

Agricultural robots were an interest of research in the 1980's as a substitution for repetitive work for workers in farms. Tasks such as handling heavy vegetables in harvest season to handling heavy compost bags in fertilizing season workers are required to have physical strength and skill for the job. Furthermore, these tasks are dull and repetitive [10].

One of the main problems an agricultural robot will have to encounter is the surrounding environment in a farm. Unlike a factory floor which is uniform and can be mostly controlled by design a farm cannot. The workplace in a farm is a part of nature with uneven terrain and other variables nature introduces such as mud, rocks, trees, tree roots etc. Furthermore, agricultural robots must deal with changing weather and aspects of the farm workspace after such an event such as muddy ground.

Currently there are robots in farms that can milk cows, shearing sheep, picking weed, weeding, spaying and cultivating. And with new technologies evolving these robots are getting smaller and smarter.

Agricultural robots maybe used to detect:

- Fungicides; fungi are the most common cause that damage a lot of crops in the world. Robots can be used to detect fungi and gather data which may help scientists get a better understanding.
- Herbicides; Robots can be used to detect and destroy weeds from around plants and collect them are bring them to a composting are.
- Pesticide; Robots can be used to identify and controls pests that can be harmful to crops.
- Data gathering in farms such as soil conditions for nitrate levels which can help determine the grass quality that are fed to cows in dairy farms.

Some examples of current agricultural robots are discussed below. Since our main objective is to design a ground robot, we will only investigate ground robots in this section. We will not investigate air borne robots such as drones or water-based robots. Ground robots with rollers, tracks, legs and combinations of rollers, tracks and legs will be discussed in this section.

2.2.1 Slug Bot

Slug Bot is the world's first artificial predator [11]. This robot was designed to operate autonomously in agricultural lands. The main function of this robot is to hunt and catch slugs. Slug bot uses the corpse of the hunted slugs to produce biogas which is then used as the energy source for the robot.

Deroceras reticulatum is a type of slug that is extremely destructive, slow moving and large. UK farmers spend over 20 million pounds per year on buying and spreading pesticides to destroy this pest to protect their crops such as wheat and potatoes.

The designers of Slug bot made all effort to make sure the robot uses minimum energy while operating. The robot body was constructed using materials such as carbon fibre and aluminium. Special considerations were made when designing the electronic systems, making sure they used de-centralised modern low power controls so they could shut down devices that were not used. All control strategies were designed to optimise efficiency.

An arm was used for detecting and capturing slugs. Moving an arm is more energy efficient than moving the whole robot. Figure 9 shows Slug bot and its gripper.

Figure 9: Slug Bot and its gripper [11]

A vison system was developed to identify the slugs and was then picked up by the gripper. A PIC microcontroller was used to handle all the communications between sub systems. The I^2C interface was used to connect between the different subsystems.

Table 1: Slug bot pros and cons

Pros of slug bot	Cons of slug bot
First of its king of robot being a predator robot	Requires someone to operate
Energy efficient and can also re-charge using the slugs (prey) (still in development)	Low ground clearance
On-board vision system to identify the pray	Since the robot uses wheels it can only travel in selected terrain
Carries an arm with a gripper to pick up slugs	

2.2.2 Agri Bot

Agri Bot is a project undertaken by university of Sao Paulo, Brazil [12]. Agri bot is a mobile robot platform developed for data acquisition in agricultural settings.

Figure 10: Agri Bot platform [12]

The robot has a rectangular structure with a headroom of 1.8 m. Depending on the operating field the robot consists of an adjustable gauge of 2.25 m to 2.8 m. The robot was platform is designed in separate modules,

- Main frame module:
  This module carries the engine, hydraulic oil tank, hydraulic pumps and hydraulic cylinders

- Wheels module:
  This module carries the hydraulic propulsion motor which are directly fixed into the four wheels of the robot, the steering system, the pneumatically operated suspension system and a system that can is used to control the adjustment of the main frame.

All electronics and control systems are in a refrigerated case. The weight of the full system is approximately 2800 kilograms.

The main power source for the robot was supplied by a turbocharged Diesel 4 stroke engine by Cummins which provides 80 horsepower at 2200 RPM. Characteristics such as complete autonomy and operation time of 20 hours continuous and quick refuelling was the main reason that this system was chosen.

Variable propulsion axial piston pumps with electronic proportional control solenoids were used for the hydraulic system for the robot and this system was designed by Bosch Rexroth AG.

All the sub systems, from the engine to the guidance devices, were communicated via CAN (Controlled Area Network) with a data transmission rate of 250 Kbits/s. Figure 11 below shows the electromechanical schematic.

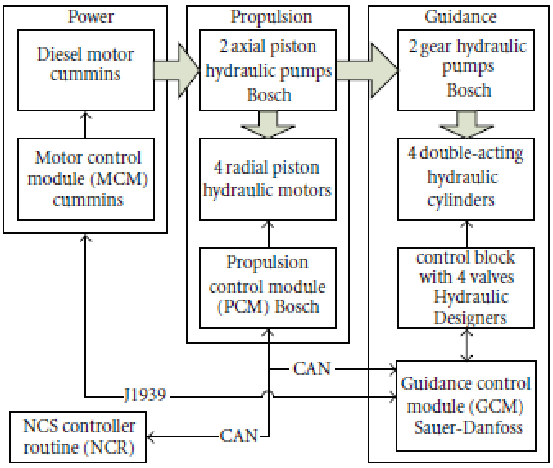


Figure 11: Agri Bot electromechanical schematic [12]

Table 2: Pros and cons of Agri Bot

Pros of Agri Bot	Cons of Agri Bot
Fully autonomous, uses radar technology for guidance	Larger size
Can operate up to 20 hours before requiring to re-charge	Weight
Large platform	Uses a diesel engine, emissions are not environmentally friendly
All systems are well protected and cooled when necessary	Uses only wheels therefore limiting the operating environments.

2.2.3 Horti Bot

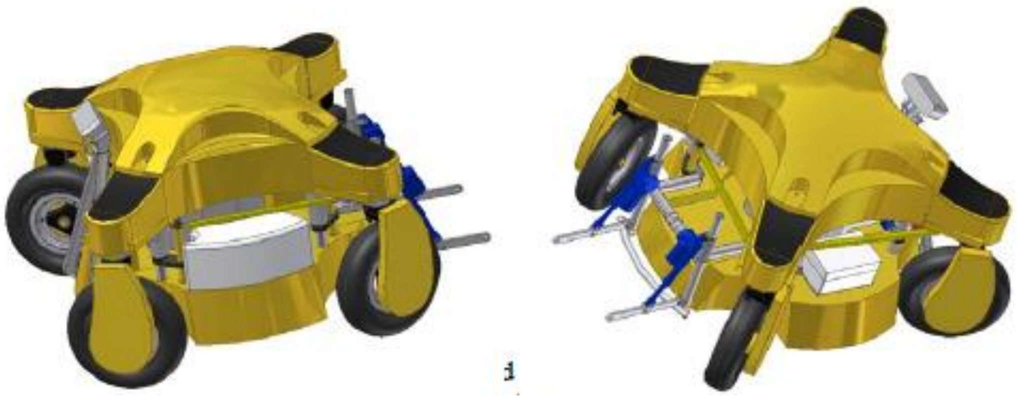


Figure 12: CAD model of Horti Bot [13]

Horti Bot is an agricultural robot developed by the Department of Agricultural Engineering and the institute of Agricultural Sciences in Denmark [13]. The motivation for this robot is to cut down on the 50-300 hours spent per hectare by workers on weeding in carrot and onion gardens. This is an expensive but a necessary task to ensure that the output of the produce is within the projected income of the farms in the growing season.

The Horti bot is based on the Spider ILD01 which is a slope mower produced in the Czech Republic by Dvorak Machine Division and is used to mow lawns in uneven terrain with slopes up to 40 degrees gradient.

The platform's four wheels are powered by a central hydraulic motor and is steered by a central DC motor. The platform is operated remotely by an operator.

The orientation of the Spider could not be controlled because the heading of the device was changed by turning all the four wheels. Therefore, the Horti Bot was modified to carry four hydraulic motors for propulsion, four DC motors for steering, with speed and angle sensors for each wheel.

All the modules of the robot were communicating with each other via CAN bus. The full system is shown in the figure 13.

Table 3: Horti Bot pros and cons

Pros of Horti bot	Cons of Horti bot
Utilises an already designed product from the market	Low ground clearance
Low centre of gravity which allows it to travel in terrains with high slopes	Needs an operator to control it
Four-wheel drive and steering	Uses only wheels limiting the ground it can be used on

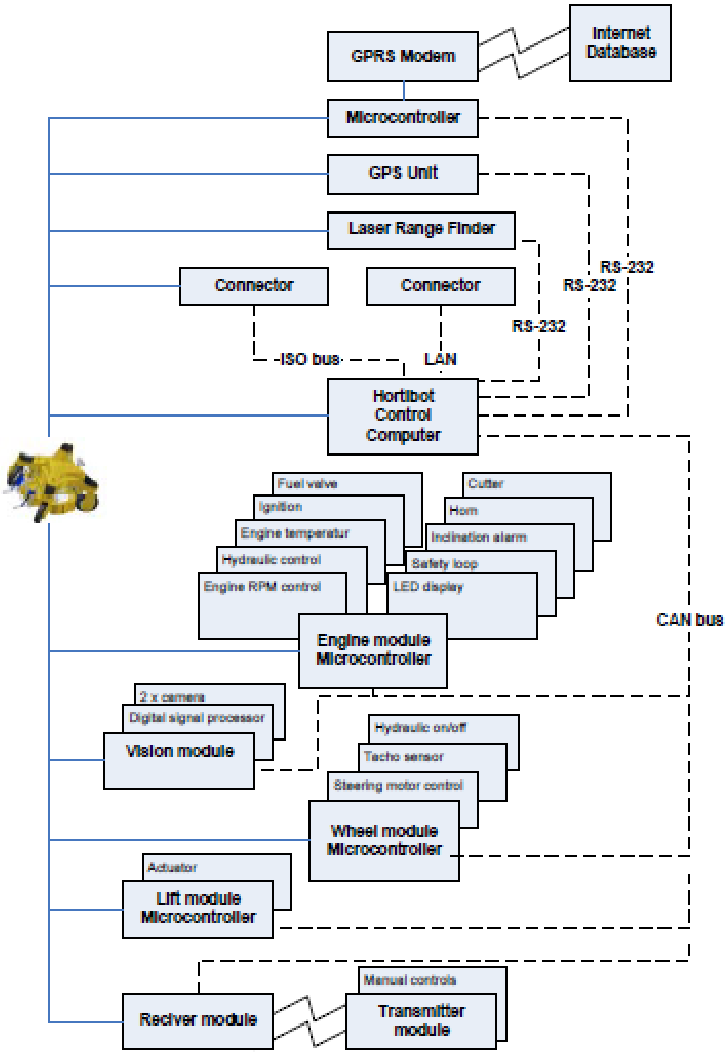


Figure 13: Communication schematic of Horti Bot [13]

Several other experimental precision agricultural robots were also reviewed.

The technical university of Denmark has designed a weeding robot which is consists of four-wheel drive as well as four-wheel steering by using hub motors [14]. This also had the capability of driving in the weeded crops to be disposed. This robot could operate for 2-4 hours before requiring a re-charge. The robot was also consisted of GPS, encoders, compass and tilt sensors. A real time operating system was developed using Windows 98 by the designers.

This prototype also used off road wheels which means it could only travel in selected terrain. It has a high centre of gravity. An onboard autonomous system was developed by the designers to attempt at a fully autonomous system using Windows 98 which is quite old operating system.

Figure 14: Weeding robot prototype by the technical university of Denmark [14]

A project from the university of Denmark designed a similar device but incorporated tracks instead of wheels called Armadillo [15]. It had features to adjust the height and width of the vehicle. The tracks approach was used instead of a four wheeled drive and steering method because of its reduced complication. The tracks allowed good traction but had a noticeable impact on softer soil as the tracks dug into it and occasionally mud and dirt were mentioned during their trials. Further design changes were to be implemented.

Figure 15: Armadillo track assemble and during operation [15]

Another project looked into mechanical weeding operations in sugar beet fields [16]. The designed system consists of a diesel engine which had an output of 31 kW. The design allowed for the system to be a four-wheel drive system or a two-wheel drive system. The two modes could be switched remotely and the thinking behind it was to switch to the two-wheel drive mode when moving between working fields. The vehicle could move at 6.5 km/hr and was 1250 kg. The platform was 1.5 m wide and 2.5 m long. The robot consisted of a GPS (RTK: Real time kinematic) system which was used by the software. The system has a ground clearance of 50 cm to avoid damaging crops.

Figure 16: Weeding robot developed for operation in sugar beet fields [16]

Similar four wheeled robots such as the Skinny boy [17], BoniRob [18], and weedy robot [19], have similar characteristics to HortiBot [13]. The only difference being Skinny boy was only two-wheel drive steering. All robots were designed to handle tasks such as weeding and crop planting.

Most robots apart from HortiBot, weedy bot and Armadillo have a high ground clearance and carry sensors on the robot body or has an arm with sensors on it which allowed them to get closer to the subject to be tested. The robots such as weedy robot, hortibot and Armadillo had lower ground clearance because of the application of weeding. These robots were tested relatively on a flat ground and used wheels or tracks for locomotion.

2.3 Commercial precision agricultural robots.

Although there many agricultural robots being designed and researched into, there are only a few robots that consumers can buy as a full unit in agriculture. The main reason being that these systems are relatively new to the market and the initial investment of these units and the cost to maintain and the cost to repair them are high. But as more and more consumers see the benefits of such systems, the demand may increase making maintenance and repair cost and the costs of units decrease in the future.

Autonomous tractor corporations (ATC) Spirit tractor uses tracks for mobility [20]. This was developed as a mowing system that can be used in farms. The vehicle has four wheels and a track that runs over the wheels. The wheels are powered by electric motors. The vehicle also carries diesel generators onboard to generate power for the motors. Different configurations are available from the company for their customer’s needs. This is a consumer product currently available for the public from prices ranging from US $150,000 to US $750,000.

Figure 17: ATC's spirit tractor [20]

Armadillo [15], as mentioned above, is a system developed by the University of Denmark. Since then Kongskilde Industries and conpleks Innovation has made an improved version of it nicknamed the product Vibro Corp Robotti [21]. This is designed to carry multiple tools on its platform and can be configured to different kinds of work such as seeding, crop cleaning and weed removal.

Harvest automations HV-100 [22] is another commercialised agricultural robot that can be used for collecting and planting potted trees. This system requires a more controlled setting than the others and operates via battery which has and work time of 4-6 hours.

Figure 18: Harvest automation HV-100 [23]

Grizzly by Clearpath Robotics [24], is and automated vehicle that can be used as a tractor. It can carry up to 600 kg and is operated via electric motors. This system has a run time of about 10 – 12 hours. The system can operate in harsh environments such as snow.

Figure 19: Clearpat robotics Grizzly [24]

Rowbot [25] by United States of America that can navigate itself in corn fields using GPS (global positioning system) and dispense nitrogen fertiliser to crops, it also carries onboard sensors to collect data for experimentation and data analysis.

Kinze Manufacturing [26] are an agricultural equipment producing company based in the United States of America. Alongside Jaybridge Robotics they have commercialised a system that uses video cameras, radar, laser sensors and GPS which are used to alongside software developed by the company for obstacle detection and avoidance. This system can be retrofitted into a machinery such as combine harvest machines and farm tractors. When fitted the tractor/harvester can operate autonomously in a farm.

Green Tech Robotics [27] is a New Zealand based company that develops weeding and seeding robots. The Seed spider is a seeding robot that is currently being used in North America by mesclun farmers. It can seed as well as harvest the crops and the system is fully autonomous. The weed spider is a fully autonomous weeding robot that is guided by GPS and can identify a number of different kinds of weed types and remove them. It uses a vison system and software based around it for object identification.

University of Sydney has developed Lady bird [28] and RIPPA [29]. These robots are solar powered and are used in the horticulture industry. The robots carry several sensors which can gather data from test subjects and can be used for weeding operations.

This section has investigated various types of precision robots that are currently in development or commercialised. All robots either used tracks or wheels to move from place to place. They are relatively new to the market and require a large sum of investment to implement them into a farm. Furthermore, the cost of maintenance is also high and skilled technicians are required to do repairs and maintenance.

Most of these common commercial agricultural robots are expensive to acquire and expensive to maintain. They are large and heavy. Most of these machines used either track or wheels for locomotion. These machines may not be suitable for New Zealand farmlands.

As an example, the spirit tractor uses tracks for locomotion, because of its weight it will damage the ground specially during the rainy season when the ground is muddy.

Locomotion methods that consist that combines these methods together will be more beneficial for the New Zealand terrain. Common locomotion methods and methods that combines two or more locomotion methods are discussed in section 2.4.

Most of these commercialised systems uses tracks or wheels for locomotion. These designs seem to be relatively simple designs. Although some of these may work in some New Zealand farming environments, they will have issues when avoiding large objects and the muddy grounds. Therefore, more locomotion systems that uses more than one method are reviewed below.

2.4 Locomotion systems of ground robots.

The above section talked about some of the precision agricultural robots that are being used in agriculture today. Most of them used wheels or tracks for locomotion. This section will investigate locomotion systems that are currently being used and systems that have two or more locomotion methods combined to move around (hybrid systems). The advantage of such systems will also be discussed in this section.

Although there are variety of different hybrid locomotion methods that may allow robots to work in environments such as water or air, to keep within the theme and scope of this research project we will only investigate ground robots.

According to L. Bruzzone and G. Quaglia [30] ground robots can be classified into the following.

- Wheeled robots (W)
- Tracked robots (T)
- Legged robots (L)

A category named as hybrid robots that contain two or more of these methods is also mentioned. These methods include:

- Leg wheels (LW)
- Leg tracks (LT)
- Wheels tracks (WT)
- Legs wheels tracks (LWT)

2.4.1 Wheeled robots

Wheeled robots can reach high speeds at a low power consumption. The disadvantage of a wheeled robot is that it will struggle overcoming obstacles. Complex solutions using software will need to be implemented to maneuverer around obstacles.

Lady bird [28], RIPPA [29], Rowbot [25], Harvest automations HV-100 [23] and Clearpath Robotics [24] are a few examples discussed above that uses wheeled locomotion systems to travel with in an agricultural setting. These wheeled robots have been designed for weeding and data gathering operations. Most of them have a low ground clearance. They are operating in flat ground and has less obstacles. Lady bird and Rippa uses solar panels and batteries to operate.

Figure 20: Lady Bird [28]

Figure 21: Rippa [29]

RT Mover [31] is a concept of a four-wheel mobile robot designed for rough terrain. The target environment for the robot was forest floors, uneven indoor floors and outdoor terrain with an uneven ground. The mechanical design consisted for four wheels mounted on two independently moving axels that can be moved in various angels to travel on different terrain types. The systems were powered by a 24 V battery. The concept carried encoders and current sensors for each motor and a posture angle sensor.

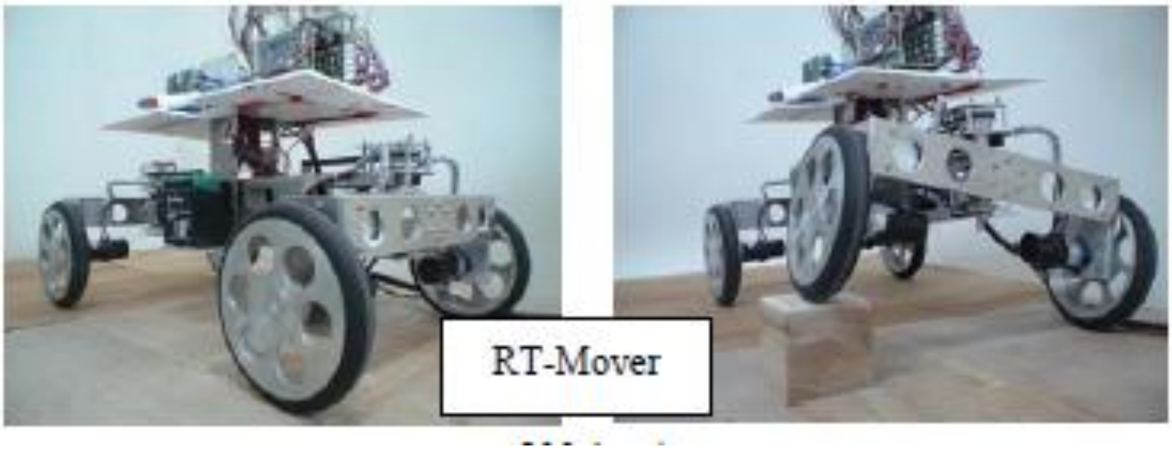


Figure 22: RT-mover [31]

The Scarab rover by Carnegie Mellon University in the United States of America [32] is a robot designed for drilling on the lunar surface. The scenario would be to land the robot into a shadowed crater (Figure 24) and will be drilled to find water ice. A passive kinematic suspension system with the ability of lowering the robot to the ground for drilling operations was shown and the robot consisted of four off road wheels. The robot mass was approximately 280kg and special consideration were made to sustain the trust created by the drill when is operation on the moon because of the gravity differences. It was stated that the drilling operation was expected to generate a trust of 100 – 200 N.

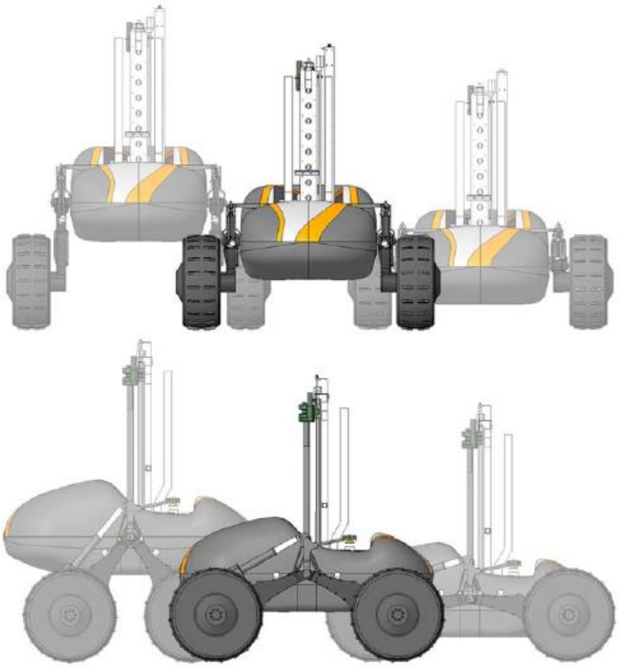


Figure 23: Scarab rover [32]

Figure 24: Shadow crater of the moon [32]

Shrimp by the Swiss Federal institute of Technology [33] is a wheeled rover designed with the ability to climb and steer while maintaining ground clearance and stability. The robot can travel over obstacles which is twice the size of the diameter of its wheels. The robot's main purpose was to overcome obstacles rather than avoid them, which will reduce the travel time and, in some scenarios, maybe is the only way of reaching the target. The design allowed the robot to change its ride height which allowed it to move over obstacles. The changing height also changes the centre of gravity of shrimp and this was used to stabilise the platform. The designers intend to use shrimp as a planetary exploration or terrestrial applications such as mining, agriculture or construction.

Figure 25: Shrimp [33]

Most of these examples above used wheeled locomotion method for movement. It was clear that most of these robots are designed to operate in flat hard ground surfaces. They can also reach higher speeds and can be operated using a few active degrees of freedom. Wheeled robots will not drop performance when they meet obstacles. Stability of a wheeled robot can be increased by adding more wheels [30].

2.4.2 Tracked robots

Tracked robots have a large contact footprint with the ground and therefore are suitable for tasks that require a higher traction. Depending on the ground clearance, tracked systems may overcome obstacles on uneven grounds as well as soft terrains. The disadvantage of such systems would be limitations to its speed and vibrations caused from the tracks to platforms which may cause failure of onboard systems. This could be overcome by implementing a suspension system [30].

The spirit tractor [20] mentioned above is an example of a tracked robot already used in agriculture.

The Nanokhod [34] exploration rover is an example of a tracked robot designed by the European Space Agency. Its intended task was to carry a scientific payload on a planetary surface. It was designed to have a small robot mass allowing it to carry a larger payload. The robot can operate up to 50 m around the lander. The mass of the rover is 2.95 kg and can carry a payload up to 800 g. It has two tracked locomotion units which are connected via a tether bridge. The payload cabin is attached to the other end of the locomotion unit via two leavers which allows it to have two degrees of freedom movement. It was noted that special care was taken when choosing for components to make sure they work in extreme low temperatures. The control electronics such as the motor drivers were designed to place inside the locomotion unit. It carries sensors to monitor voltage, currents and temperatures which are connected to a central ADC unit.

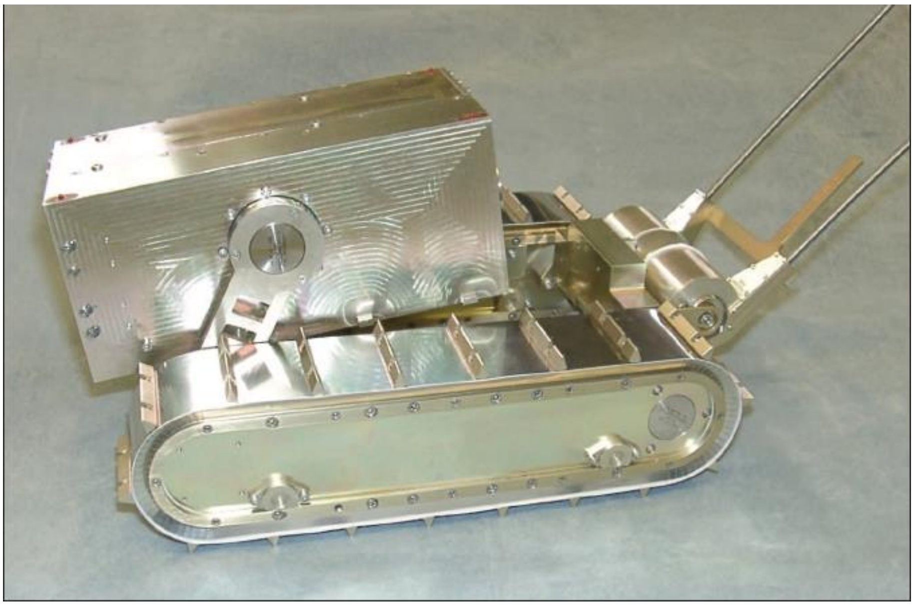


Figure 26: Nanokhod Rover Prototype [34]

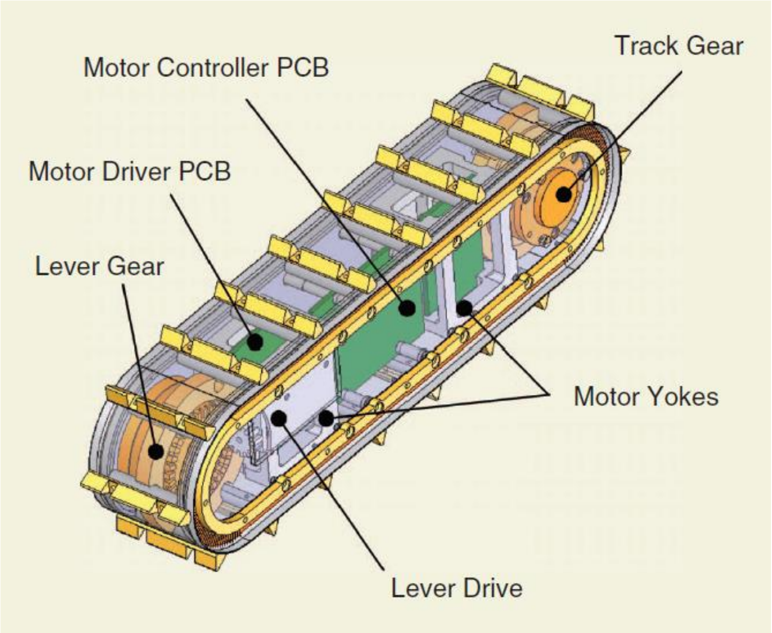


Figure 27: Nanokhod Rover track assembly [34]

2.4.3 Legged robots (L)

Legged robots are versatile, therefore can be used to tackle tasks on uneven environments as well as controlled environments. Legged robots are complex and require many actuators, sensors and complex control systems to operate. The development of legged robots has scientist and engineers looking into biological specimens. Legged robots are slow and require considerably more power to operate. There are legged robots that have two legs which are inspired by humans, four legs inspired by quadrupeds and multilegged robots inspired by insects. Important characteristics of legged robots are their gait. There are two types of gait; static and dynamic. Static gait is when the robot is always balanced. A dynamic gait is when the robot is not balanced ex, running, trotting or galloping. A dynamic gate requires more complex control systems [30].

Big Dog is a quadruped robot developed by Boston Dynamics in United States of America [35]. It was designed to tackle rough terrain that a tracked vehicle or a wheeled vehicle cannot reach. Big dog is 1 m tall and 1.1 m wide and weighs about 109 kg. It carries a 15 hp internal combustion engine which is water cooled. The engine acts as a power supply to operate a hydraulic pump that pressurise hydraulic liquid which is used to operate the legs. Each leg has 4 hydraulic actuators that is used to power the legs. Big dog carries 50 sensors which includes force sensors, gyroscopes etc which are controlled by a central computer. Big dog is capable of various different locomotion behaviours. It can sit, stand, squat down walk with a crawling gait that lifts just one leg at a time, trot and run. It can trot with a speed of 1.6 m/s and run with a speed of 2 m/s. A human operator in a control unit controls big dog via IP radio signals.

Figure 28: Big Dog trotting in snow [35]

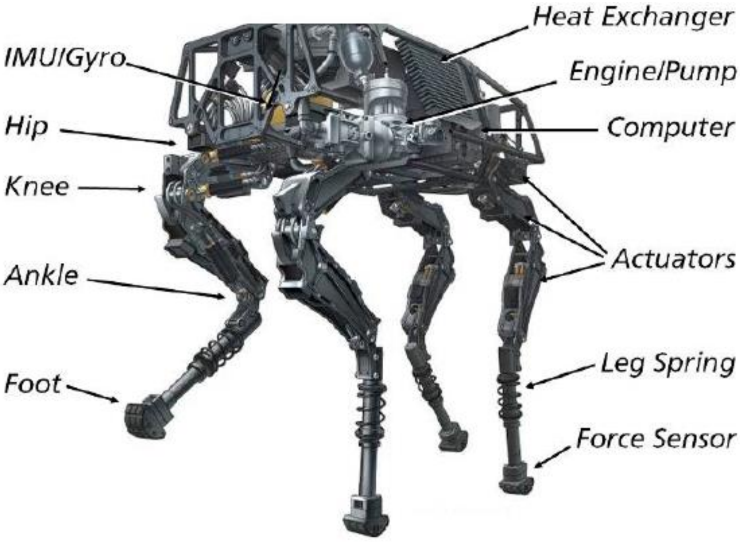


Figure 29: Big dog structure [35]

SILO6 by the industrial automation institute in Spain [36] is a six-legged robot designed for detection on land mines. The robot carries a specially developed sensor head to detect mines. The robot is operated semi automatically and uses technologies such as GPS for localisation. The six-leg design is an advantage in operating in rough terrain and it can maneuverer over obstacles better than a tracked robot. A six-legged robot (hexapod) design was also chosen because it can achieve higher speeds than a quadruped robot and is also more stable. The control system of SILO6 is an operator station and an onboard computer on the robot. The operator station is a PC based computer which runs windows XP and the robot controller was a half-sized PC that runs QNX which is a UNIX based real time operating system. The two systems communicate via radio ethernet. The system uses batteries and weighs 80 kg with all systems included. The designer’s intention is to reduce the human involvement in removing landmines.

Figure 30: SILO6 six-legged robot field testing [36]

Humanoid robotics platform 4 (HRP-4) by AIST [37] is a lightweight and slim body biped robot. It has 34 degrees of freedom which includes 7 degrees of freedom of freedom for each arm to facilitate object handling. The robot is 151 cm tall and is 39 kg. The design was optimised to have a lightweight and slim body, a lower price, a lower power consumption, an improved object manipulation and expandability. A lightweight body design and a slim body has reduced the overall weight of the robot therefore reducing the overall power consumption. The robot carries a 48 V DC Ni-MH battery as a power source. The design considerations have allowed the robot to operate with just 80 W per hour. HRP-4 will be further developed to operate in a home environment and do day to day housekeeping tasks.

Although a legged robot will be ideal for operation in a New Zealand farm environment it will require complex software algorithms to operate and complex design and will be costly to build. They will also require more sophisticated sensors and motors to operate. Unlike a wheeled system or a tracked system, a legged robot will require logic and electronics to stand still as well as moving. Computational power to run these systems is expensive. Furthermore, a legged system will need to be maintained and regularly monitored to ensure precise operation.

2.4.4 Leg wheel hybrid (LW)

Leg wheel hybrid robots combine the efficiency of wheels and the operation flexibility of legs. These two locomotion methods can be combined as such,

- Fitment of a wheeled robot with legs connected to the robot body
- Placing the wheels on the leg links (At the end of the leg)
- Designing retractable modules that can be used as wheels or legs

Research suggests that the method of attaching wheels to the leg is the most effect way for this method of locomotion [30].

Armadillo [38] by the Osaka University is an example of a leg wheel hybrid system that uses a mechanism that can be used as a wheel and can convert into a leg when needed. This design mechanism was inspired by the armadillo's natural retracting defence mechanism. The developed concept is shown below. When in wheeled mode as a result of its large wheel diameter, armadillo can climb single step or a single gap obstacle. When the leg is in leg mode it can tackle rough terrain. The diameter of the wheel of the prototype was 100 mm and the width of the wheel was 45.5 mm (which is also the footprint size of the leg). The prototype weighed 1577.2 g. The system was battery operated.

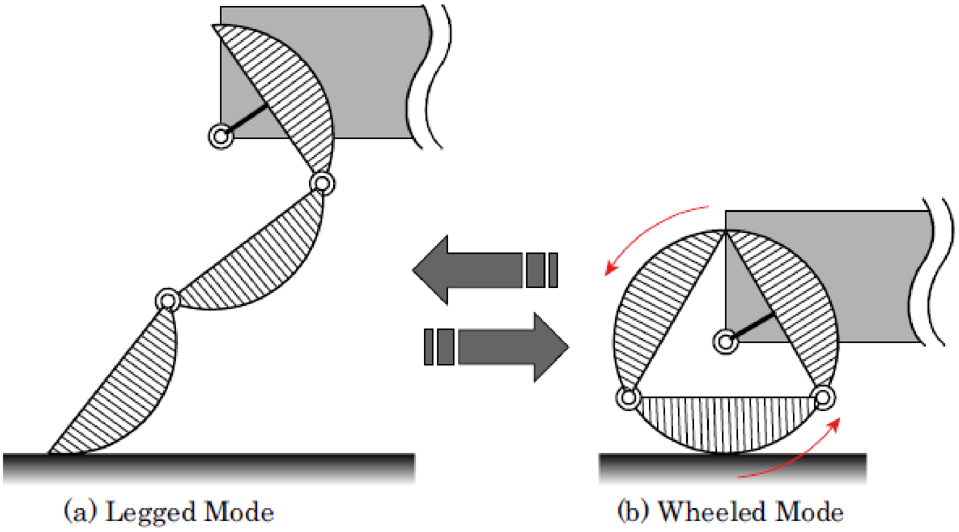


Figure 31: Armadillo's leg wheel design concept [38]

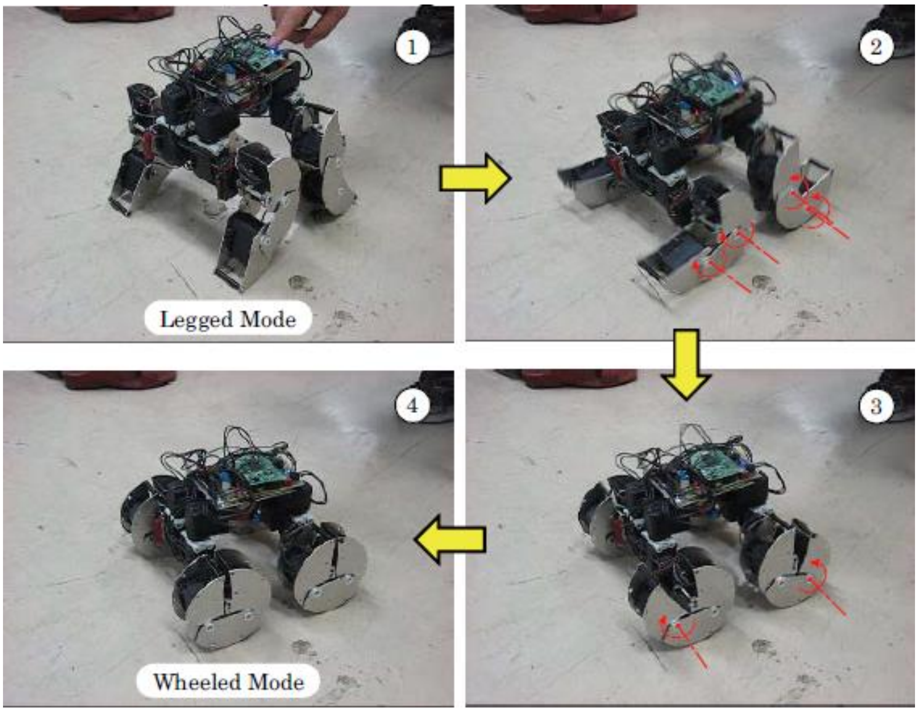


Figure 32: Armadillo's conversion from legged mode to wheeled mode [38]

Mantis [3] is a hybrid leg-wheel robot designed by the University of Genova. It has the design which incorporates the method of fitment of legs into a wheeled robot. Mantis was developed as a surveillance and an inspection robot. The design consists of two driven wheels and two legs inspired by the praying mantis legs. These legs can rotate. The overall dimensions of the robot with the legs in its rest position (shown in image below) are 355 mm x 298 mm. The prototype has a weight of 3.2 kg including a camera for surveillance and the 2600 mAh LiPo battery. This prototype's testing showed it was effective in rough terrain and could overcome obstacles when needed. Further development is being done to the robot to increase its surveillance capabilities.

Figure 33: Mantis in action [3]

Momaro [39] is another wheel leg prototype built for the DAPRA (Defence Advanced Research Projects Agency) robotics challenge. This follows the design concept of a wheel fitted at the end of a leg strategy. Momaro's long term goal is to be used in the search and rescue sector. It is a quadruped robot with four steerable wheels attached at the end of the leg. In addition to the locomotion system the robot also carries two 7 degrees of freedom manipulators that has dexterous grippers at the end. The legs of the robot have three pitch joints hip, knee and ankle which allows it to adjust the wheel position of the robot according to the terrain plain. This design allowed the robot to travel omnidirectionally and step over obstacles. Carbon fibre was used to construct the leg making it strong and lightweight. Robotics Dynamixel actuators were used which offered good torque to weight ratio. Control of Momaro is done by an Intel Core i7-4790K CPU with 32 GB ram. A Netgear Nighthawk AC1900 WiFi router was equipped for communication with the robot. The robot was powered by a replaceable six cell LiPo battery with 16 Ah capacity, this allowed the robot to have an operation time of 2 hours. The temperature of the actuators, position and applies torque was constantly monitored by the control system. Because of the use of light weight material Momaro was approximately 57 kg.

Figure 34: Momaro in an obstacle course [39]

Most of the above examples have complex designs. Although some maybe be in the research or prototype phase their complex design does not look robust enough for the New Zealand farming environment. These designs will not cope with muddy environments. As an example, Armadillo may have issues if operated in muddy environments by getting mud in the complex mechanisms and may cause it to fail.

2.4.5 Leg track Hybrid (LT)

When speed and energy efficiency is not critical a leg track hybrid system can be a viable solution. It is well suited for very difficult terrains and environments. Currently this type of robots is are used in security sector doing surveillance and explosive detection. A common way of achieving a leg track system is to combine two or more tracks together [30].

CHIMP developed by the Carnegie Melon University [4] uses the leg track hybrid locomotion system. It was developed for the robotics challenge by DAPRA. CHIMP is designed to work in dangerous, degraded, human engineered environments. The robot has a near human form, strength and dexterity to work in these mentioned environments. Using the sensors mounted on the head of the robot it can construct a 3D representation of the environment its being used in. CHIMP has 39 degrees of freedom which allows it to operate effectively in engineered environments. Rather than legs, tracks were used to minimise the dynamic stability issues. The track leg hybrid system allows the robot to drive as a tank, on its knees or in a standing position. The robot was operated via an operations trailer. The power to the robot was supplied via cable alongside the network and computing used to control the robot therefore restricting the robot to a limited workspace.

Figure 35: CHIMP and its features [4]

A mobile robot which is equipped by four legs and tracks have been developed by a research team in Japan [7]. The legs can also be used as manipulation arms which was used to retrieve a target object during testing. The robot's body was 390 mm in length, 420 mm in width and with a height of 180 mm. The weight of the robot is 10 kg. It can move with a velocity of 500 mm/s. The legs have 4 degrees of freedom. The design also allows the robot to use the legs as manipulator to pick up objects in front of it. The robot was developed to work in disaster area such as an earthquake zone. The legs can remove obstacles such as small stones in front of it if needed. The robot also can move on a gap and move along a roof.

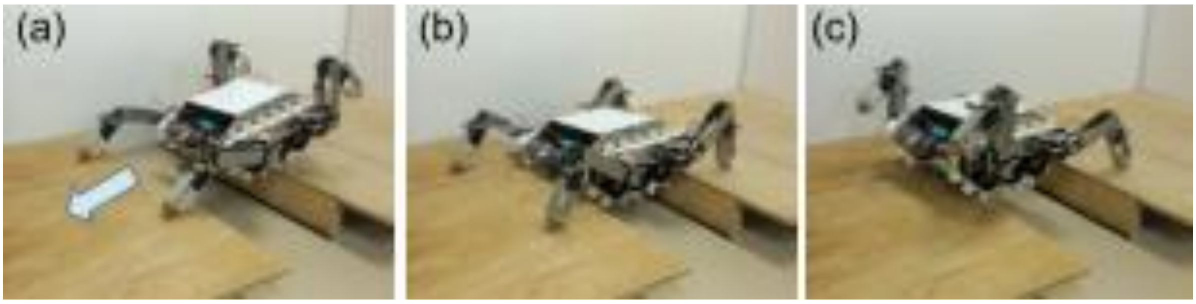


Figure 36: A track leg robot prototype tackling a gap [7]

A research group has designed and built a prototype of a rough terrain robot which uses the leg track hybrid locomotion system [40]. It uses a combination of a crawler mechanism and a track mechanism. The mechanism has two links with tracks and two rotational joints. Each unit has four motors and there are four units in total. The robot is able to crawl over obstacles as shown in the figure 37 below.

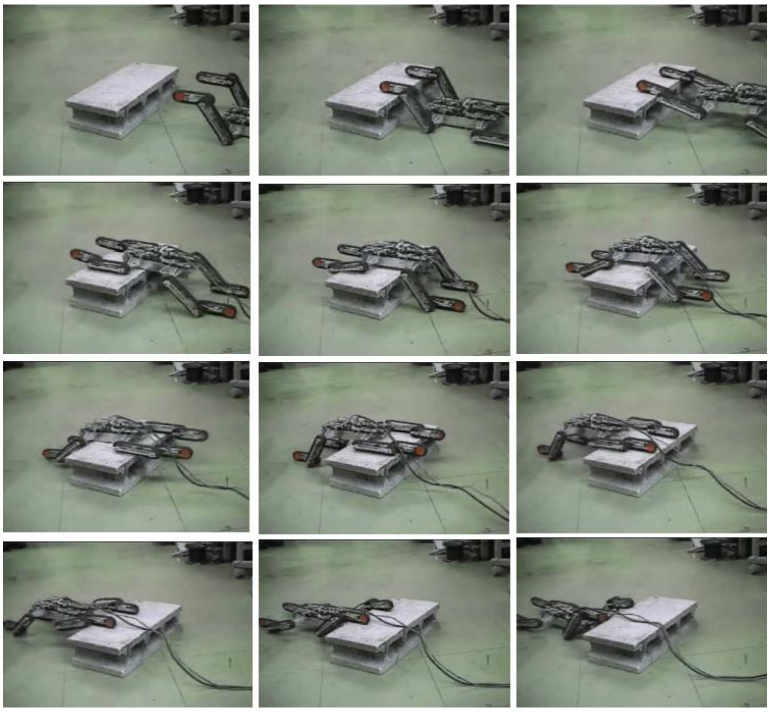


Figure 37: Leg track robot obstacle tackling [40]

The leg track locomotion method shows traits which can be used to design a system for the New Zealand farms. The tracks will be useful for muddy terrains and the legged locomotion will be useful for obstacle avoidance and to get out of harsh environments. The systems detailed above have complicated designs (e.g. CHIPM), designs that are not robust enough for a New Zealand farming environment (e.g. Japanese prototype [34]) and have low ground clearance (eg. [35]).

2.4.6 Wheels tracks (WT)

A wheel track system is suitable for soft terrains combined with uneven terrains. The advantage of such a system is that it can travel in soft terrain with high energy efficiency and only deploy the tracks when it is introduced to a challenging environment [30]. Following are some examples of wheel track hybrid robots-

NEZA-I [41] is a prototype robot developed to perform planetary exploration, reconnaissance, anti-terrorism and rescue. A self-adaptive track wheel mechanism is being used by NEZA-I. It uses two, wheel tracks units and each unit are operated by a single servo motor. The track assembly can transform to a wheel only mode or a track only mode depending on the terrain. The control system does not require separate sensors to analyse the terrain, in turn the mechanism can get the constraint force information by interacting with the environment directly. The design is also simple and can be de-assembled for maintenance or relocation. It is also noted that the system can only be operated via wheeled mode or track mode, it cannot be operated using both modes at the same time.

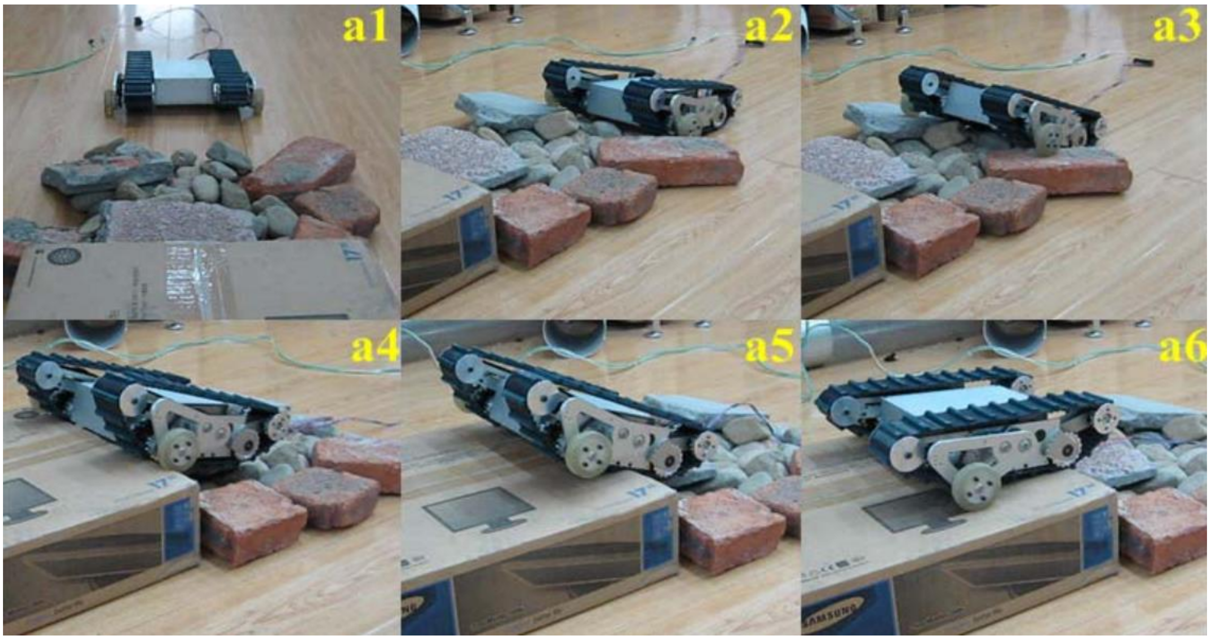


Figure 38: NEZA-I using tracks for uneven terrain and wheels for flat surface [41]

RHMBot [42] is a wheel track mobile robot which is based on the watt II six bar linkage (See figure 39) . It has three locomotion modes which includes wheel mode, tracked mode and climbing mode. A deformable track is used alongside the watt II linkage system to configure the different modes. The belt was developed using material such as latex and polyamide which allowed the belt to have good elasticity at a lower cost. The tooth profile track layer and the transmission layer were developed separately and bonded together. Special considerations were made to make sure the two belts had constant length at the bonding stage. The maximum belt length was 1395 mm. The test found that on grass surfaces and hard terrains the robot could run efficiently using the wheeled mode and when an obstacle is introduced the robot will change into the tracked mode. When RHMBot encounters a larger obstacle, it can use roll over mode. This mode will leave the track in its intended configuration and will rotate the whole track over the obstacle. It could roll over obstacles 120 mm high.

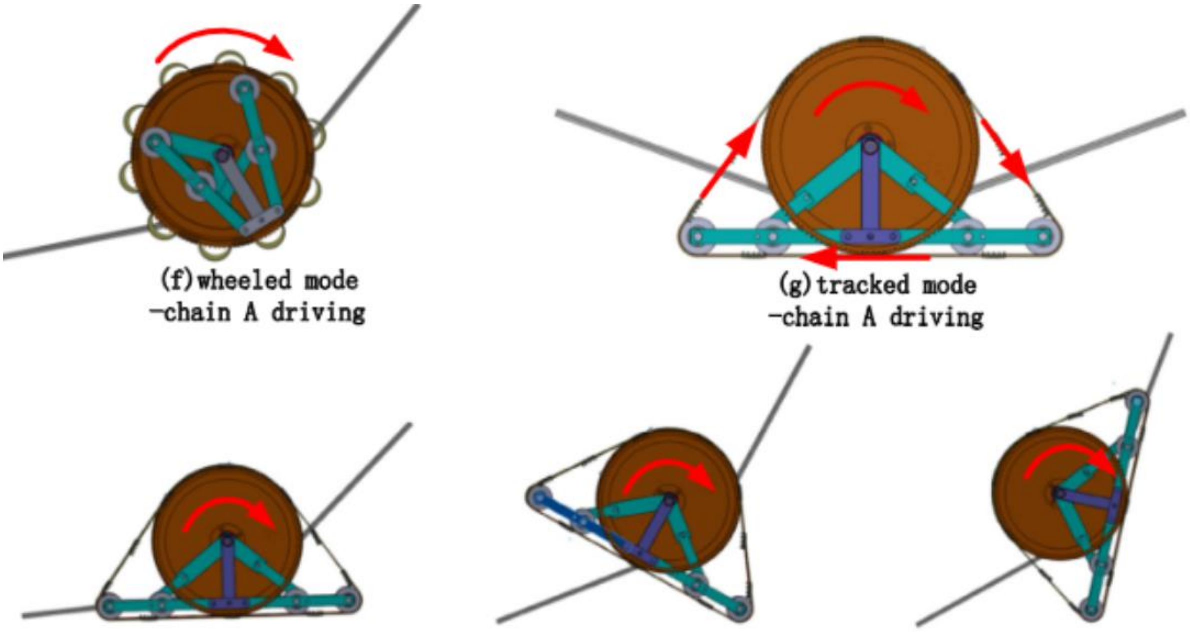


Figure 39: RHMBot wheel track configurations [42]

The HELIOS series by developed by the Tokyo Institute of Technology [43] is another system that uses the wheel track locomotion method. It was developed for off-road vehicles and powered wheelchairs to give them the ability to ascend and descend stairs and high gradient slopes. The latest in the series is the HELIOS-IV which includes a track and a movable wheel (see figure 40). The movable arm has a range of 90 degrees. The system intention is to act as solution for wheelchairs to climb up stairs with a gradient of 40 degrees and has a velocity of 70 mm/s with maximum load. The full system is 85 kg and can carry a load up to 100 kg. The system is powered by a lead acid battery (36 V/5 Ah). The full system has 6 DC motors.

Figure 40: Helios-IV stair climb testing [5]

The above examples have a low centre of gravity and some have complex mechanisms (RHMBot). The tracked mode is enough for muddy environments. But the wheeled mode will not help this locomotion method in tackling harsh obstacles such as rocks.

2.4.7 Legs wheels tracks (LWT)

This hybrid locomotion system includes all three locomotion methods which are legs, wheels and tracks. This can generate a wider variety of locomotion modes which includes climbing of obstacles and stairs and omni-directional motions. Below are some examples of robots that uses the Legs wheels tracks method.

Azimuth [6] by the University of Sherbrooke, Canada is a robot platform developed using legs, tracks and wheels. The legs allowed the robot to climb over obstacles and change its height, the tracks allowed it to travel on uneven terrain and soft surfaces and the wheels allowed efficient travel in flat surfaces. Azimuth can move up, down or straight and is also capable of moving sideways without changing its orientation. It can deal with three dimensional environments. It is equipped with sensors in its actuators so it can feedback precise data of the environment it is in. The robot has more than 2500 parts. The mechanical design was divided into the following sub systems:

- Chassis:
  This section held the robot's hardware and its battery packs. The battery packs were placed in the bottom of the chassis to keep the centre of gravity low. The PC was placed between the two battery packs.
- Bodywork:
  All body work is designed to protect the internals of the robot and also the aesthetic of the robot.
- Track wheel leg:
  This system included the track, which is a diamond profiled rubber conveyor belt, the wheel which was made with a thin rubber strip and the leg mechanism which held everything together

Once the robot is in the leg mode the tracks are locked mechanically allowing it to move. In the other modes the assembly will be moved into a set location and the wheels and tracks will both move together. The modes are shown in the figure 41. It uses ferrite SevoDisc motors for propulsion and uses standard brushed DC motors for the direction and the rotation of the articulations. The CAN bus protocol is used to communicate between the onboard PC and other electronic sub systems. The system can carry a payload of 10.4 kg.

Figure 41: AZIMUTH's wheeled mode, track mode and legged mode [6]

Another novel wheel track leg mechanism has been researched by a group in China [41]. The group of scientists and engineers has introduced a mechanism that can change itself to a wheel, a leg and a track. It uses a flexible belt and a linkage system to change the morphology of the wheels. The mechanism uses a wheel rim which is cut into four end-to-end circles which can be arranged into round circle and a flat ring as shown in the figure 42. The design was constrained by the belt which had to be in the perfect tension. Too much tension makes the transformation hard and too little makes the belt fall off the mechanism. The advantages of the systems are that the robot has excellent terrain capability to unpredictable environments, compact design, simple and light weight.

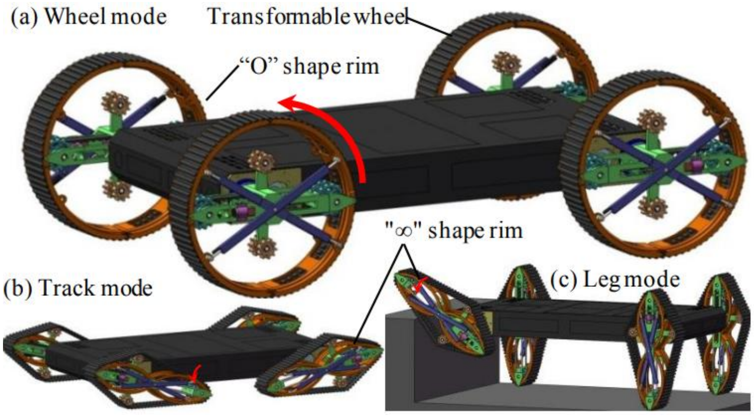


Figure 42: A leg track wheel robot design concept [41]

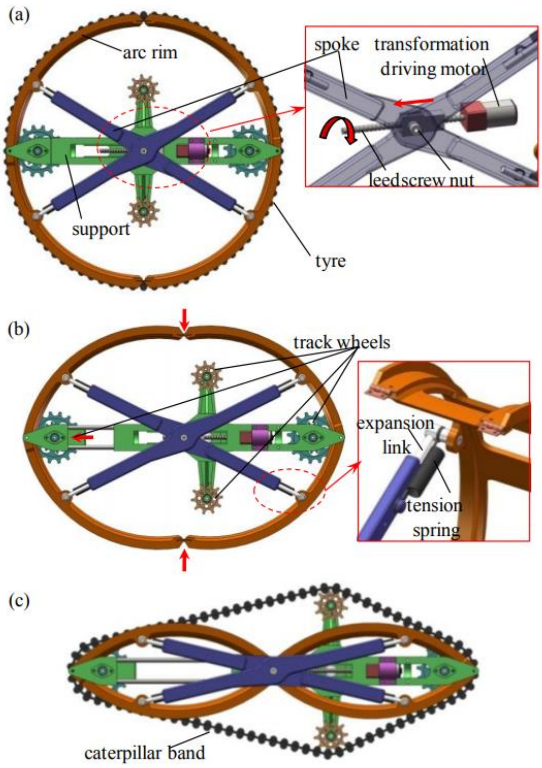


Figure 43: Leg track wheel design CAD model [41]

Most of these examples also have complex mechanisms and complex electronics to operate. The prototype by china [40] shows a unique design of a shape changing tracks. If placed in the New Zealand farm environment the mud may cause this complex mechanism to fail. AZIMUTH uses tracks, legs and wheels for locomotion. It has the ability of changing its height. This design may be sufficient for it to be placed in a New Zealand farm environment. AZIMUTH uses complex electronics and a complex gearbox to operate the track leg and wheel mechanism. AZIMUTH has also complex control algorithms to operate.

2.4.8 Section Summary

This section discussed different locomotion methods that are being used by ground robots. Legged robots are excellent at tackling rough terrains with a lot of obstacles and environments that requires climbing but requires complicated control systems to control the complex actuators and sensors to operate them. Tracked robots were effective against rough terrains. Tracked robots mostly have simple designs and does not require as complex control systems to operate. A track system is also robust. Depending on the track profile the robot may damage the ground it is working on. Wheeled robots are effective against flat obstacle free environments. It can operate with high efficiency. Generally wheeled robots cannot operate in rough terrains. This chapter also looked into robots that have combined multiple locomotion methods to gain an advantage in different terrains. The graph below (figure 44) by [30] compares all the ground robot locomotion methods. The Y axis is the mobility in unstructured environments and the X axis is the speed and energy efficiency.

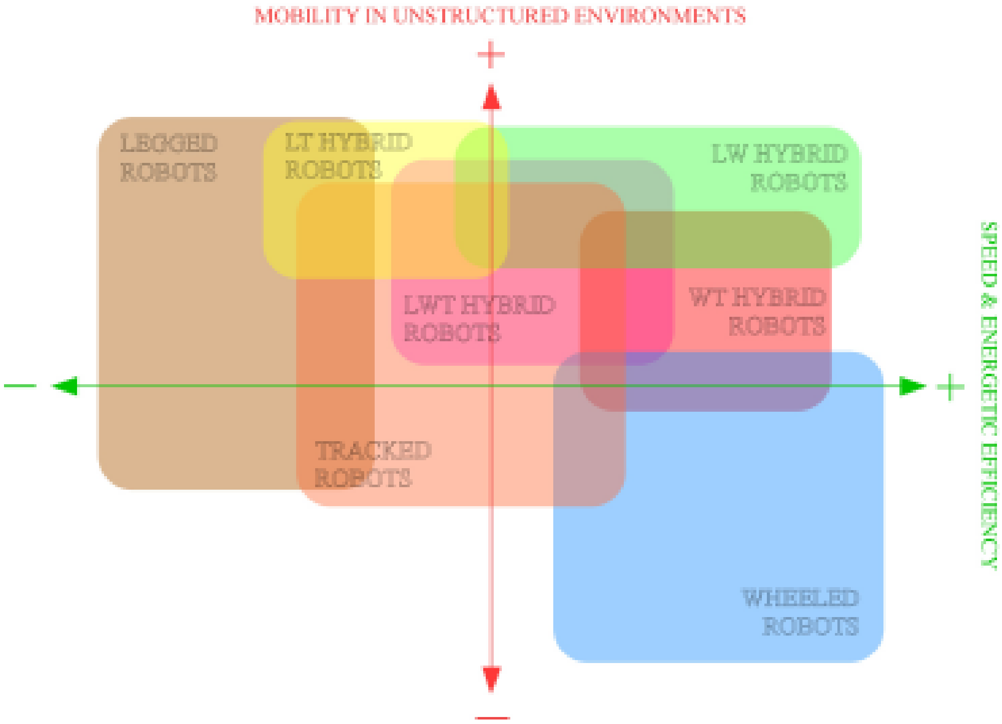


Figure 44: Mobility vs Efficiency in all the ground robots [30]

The above prototypes and products used wired and wireless methods to communicate. Some had software implemented to operate fully autonomous. Most of them required an operator to control the product. Some could be operated remotely but the operation room needed to be close by. IoT is the up and coming technology in the world and it can be a useful to place such technology in a robot. IoT technologies are discussed in the next section (section 2.5).

2.5 Internet of things (IoT)

In 1999 the internet of things (IoT) concept was derived by a member in the radio frequency identification (RFID) development community. With the increase of devices that can access the internet the concept is more relevant topic [44]. IoT is a network of physical objects such as computers, vehicles, smart phones, home appliances, toys, cameras, buildings and all communicating objects which can share information in real time. Keyur K Patel and Sunil M Patel article [44] defines IoT in these three categories:

1. People to people interacting via the internet
2. People to machine/things interacting via the internet
3. Things/machine to things/machines interacting via the internet

IoT is a mix of hardware and software technologies integrated together to process data and communicate with the internet. There are various ways of connecting devices into the internet, however because of the involvement of alliances methods such as ethernet, WiFi, Bluetooth, ZigBee, GSM and GPRS are popular and are becoming the standard protocol for

IoT [45]. Devices that uses these methods are well supported and serviceable. The IoT architecture can be divided into the following layers [44, 46]:

- Smart device/ smart sensor:
  These are the devices that will be designed according to the spec of the task such as monitoring humidity, soil temperature and such
- Gateways and networks:
  The method in with the sensor can be connected to the internet and how the data can be transferred.
- Management service layer:
  Data security, processes and analysing is done in this layer.
- Application layer:
  When the data has been processed what to with is decided in this layer.

There are various applications of IoT. From weather monitoring systems to smart home systems, IoT is becoming a very useful tool for humans. We will follow the theme of this thesis and investigate systems that are agricultural focused.

The main challenge in agriculture is cultivating produce in a farm setting and delivering the produce to the customer with the best quality [47]. In the world almost 50 percent of the produce from farms does not reach the end customer due to wastage [47]. Internet of things (IoT) allows various devices and sensors to send data over the internet in a real time manner. This data can be processed and used by researchers or farmers to monitor their produce and take quick action when necessary. In agriculture IoT is used to monitor controlling factors such as soil pH levels, soil moisture levels, temperature and humidity. Modern IoT systems send data to a server (cloud) and then processed within the server and send it back to the user, services such Amazon web services are constantly evolving making data processing within the cloud more efficient. As a result of the cloud the data can be accessed anywhere in the world by logging on the internet is another useful advantage. Now days users can access the internet not only via a PC but also a smartphone.

An implementation of a smart farm with IoT technology has been attempted by a group of scientists from the University of Science and Technology in Korea [48]. The team uses wired, Low power wide area networks (LPWAN) and Bluetooth devices were used to monitor temperature, humidity and carbon dioxide levels in a farm. The LPWAN and Bluetooth modules were interfaced using an Arduino which talked to a central device which talked to a server. The wired modules used RS485 as a serial communication module. RS485 was chosen as a communication module because most equipment installed in the farm uses this communication method. It was noted that the wired method had the least data lost via transmission than the wireless solutions.

2.5.1 Current consumer products that use IoT technology

Project farmbot [49] is an open source CNC (Computer Numerical Control) planting system that will plant produce and monitor the status of the produce. The system uses a Raspberry pi to control stepper motors and other electronics to operate the system. The Raspberry pi is also capable of communicating with the internet and provide the user with statistics regarding the produce.

Figure 45: Farmbot being used in a school [49]

Zeddy [50] is a start-up company based in New Zealand which manufactures a meal dispensing trailer to feed life stock. Based on IoT it reads RFID tags of animals and will allocate feed to each animal accordingly. All feed statistics are stored on the cloud and the farmer can access. The system is useful to identify sick animals by identifying their low feed intake during the day. The trailer can be placed in rural areas and communicates to a server via 2G, 3G cellular network.

Figure 46: Zeddy meal feeding trailer [50]

CalfSmart [51] is another system the company produces which is used to new-born calves. It also uses the RFID to identify animals and dispense milk to and nutrients accordingly. All data is recorded and can be accessed by the farmer via the internet. The system can be implemented in a farm and connects to a server via a 2G, 3G cellular network.

2.5.2 IoT networks

IoT relies on devices being connected to the internet. Many solutions in the market are wireless. IoT devices use existing technologies such as GSM, LTE, Bluetooth and WiFi to connect to the internet. New networks such as SigFox, LoRaWAN, IEEE P802.11ah (low power WiFi), Dish 7 alliance protocol 1.0, RPMA and nWanve are being used in IoT devices [52]. These networks are optimised for lower energy consumption. The aim is to use these devices using a single battery for years or even decades. The older systems relied on energy to transfer data itself but in new systems required energy to operate the sensor itself rather than the data transfer.

This section described the overview of Internet of things and looked into some examples that are already being used in agriculture. In this project we will be attempting to design a network gateway solution that can be used on a mobile robot. The system will allow analogue to digital converter inputs (ADC) for sensors and a way to connect to the internet.

2.6 Chapter Summary

While reviewing the literature regarding the current robots in agriculture it appeared that there is a lack of robots that can get closer to the ground (have a low ground clearance). All agricultural robots had a large ground clearance and carried sensors and cameras mounted on the robot body or the sensors were attached to a mechanism that allowed it to reach desired places. A robot with a low ground clearance may allow it to carry sensors and devices that needs to be in touch with the ground. Furthermore, although there were robots that had communication methods which allowed them to communicate wirelessly to a command station/operation station and transmit data, there were no IoT methods implemented on them. This gap in the market was the motivation for the current project. The current project will investigate a method for a robot that has a low ground clearance which will allow it to carry sensors that require physical contact with the ground such as sensors to measure soil temperature and humidity. A method to transfer the data via an IoT solution will also be investigated in this project. An IoT solution may introduce a method of eliminating a control point while the robot is operating.

Chapter 3

Design Considerations and the proposed System

Hybrid locomotion systems was investigated in chapter 2 and was considered when designing the following prototype. The prototype design was inspired by Azimuth, a leg, track and wheel hybrid robot designed by the University of Sherbrooke, Canada [6]. A track-leg hybrid locomotion system was chosen because of the terrain that the final product may be placed on which is the New Zealand farm environment. Also, the leg mechanism will allow the robot to lift itself up when an obstacle is introduced. According to article [53] a GAIT can be implemented to this design which will allow the robot to walk as well as climb minor obstacles. The aim of the final product is to carry sensors that requires to be in proximity or contact with the ground. The chosen locomotion method of leg track will allow for this specification.

Special considerations were given to keep the design as simple as possible with less moving parts. Complex mechanical designs were avoided to keep manufacturing costs low. Keeping the part number low was also considered to make the final product easier to maintain and keep the repair costs low.

The protype design will have four leg-track modules which will be operated via eight brushless DC motors. The motors consist of hall effect encoders which can be used for position control. Each motor will have its individual driver and can be communicated to via UART, CAN bus, USB and pulse position modulation (PPM). The track mode and the leg mode will have dedicated motors.

The current protype is designed to be placed on a flat terrain with small obstacles. With a ground clearance ranging between 25 mm and 150 mm. The prototype also consists of a 450 mm x 250 mm chassis which carries eight motor drivers, a battery, four leg track modules and the IoT circuit. This platform size can be changed in the future depending on the requirements of the sensors and computers.

The final platform will carry at least carry the following components

- A lidar system (weight approximately 3 kg)
- Hight capacity 18 V Lithium ion battery pack (approximately 1 kg)
- Intel NUC single board computer (approximately 1 kg)
- Various data acquisition sensors

In addition to the components above the platform should be versatile to carry other systems such as a robotic arm or a small cargo bed.

When deployed the final robot is intended to operate fully autonomous. Therefore, the speed of the robot is not an important factor.

The following desired specifications were decided before the designing process.

Table 4: Desired specification of the prototype

Features	Description
Ground clearance in Track	25 mm
Ground clearance in Leg mode	150 mm
Designed Max Payload	50 kg
Maximum torque	50 Nm
Maximum unloaded speed	0.1 m/s

From the specifications a prototype was designed.

The protype's design can be configured in two ways (figure 47 and figure 48).

1. Track mode:
   The prototype will have the lowest ground clearance in this mode.
2. Leg mode:
   This mode will lift the platform above the ground and will allow the robot to go over an obstacle. This mode will have the maximum ground clearance.

Track Mode	Leg Mode
 *Figure 47: Track mode*	 *Figure 48: Leg mode*

Sensors can be mounted to the bottom of the chassis and the sides. The final prototype will be fully autonomous and will have the ability to be controlled remotely via the internet. Re-chargeable batteries are to be used. An onboard computer will be used to control all the algorithms and control strategies. This will be the next phase of the project and is not presented in this thesis.

3.1 Leg design

In this chapter we will investigate the design of the leg of the prototype. Parts chosen and the thinking behind the design will also be discussed.

There are four leg assemblies in the prototype. Each leg assembly contains two brushless DC motors. One motor is used in the track mode for forwards and backwards propulsion and the other to operate the leg itself in the leg mode. Parts were also designed to be simple for manufacturing purposes. Four of these legs will bolt on to a 450 mm x 250 mm platform which will be carrying the electronics such as the motor driver's battery and computers. This platform size and design may change in the future to carry specific sensors and control apparatus. Since the leg track design is its own assembly the platform size can be changed as required.

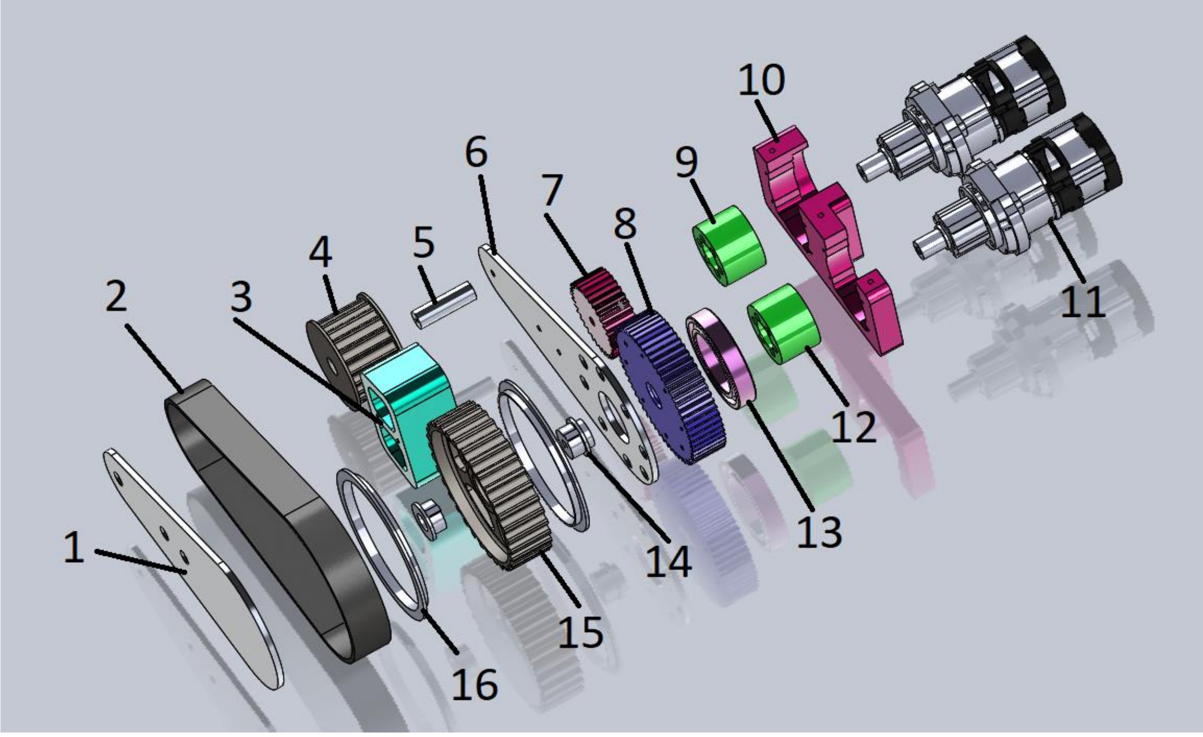


Figure 49: Leg assembly exploded view

Figure 49 shows an exploded view of the prototype leg assembly. Each part and their function are discussed below:

Outer plate (1):

This plate acts as a structural member to the leg and protects the track mechanism from mud stones and other debris from entering and jamming the wheels. The plate is 154 mm long and 4 mm thick. The prototype was made from 6061 Aluminium alloy.

Belt (2):

A timing belt used in the automotive sector was used as the track for the prototype. The belt is reinforced with fibre strands for longevity. For the prototype a timing belt was modified by cutting these fibre strands to make the belt more flexible (figure 50). The length of the belt was also shortened to approximately 550 mm. This length was chosen so it will be tensioned around the two pulleys for a better fit. The belt is 25 mm wide and has 60 teeth with a pitch of 8 mm.

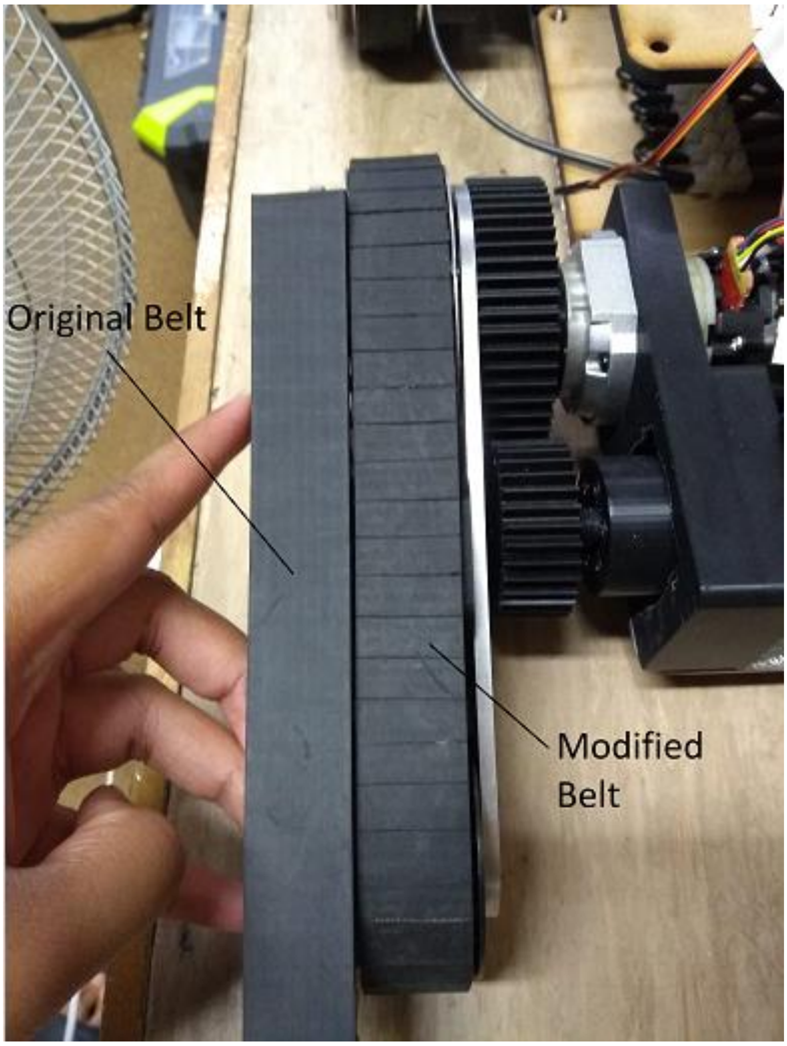


Figure 50: Modified timing belt vs original timing belt

Guide Block (3):

This part acts as a structural member for the leg. The 70 x 50 mm block holds the outer plate and the inner plate together as well as act as a guide for the track. This part of the prototype was 3D printed from PLA plastic.

Foot Pulley (4):

This pulley acts as a guide to the track. The pulley has an outside diameter of 55 mm. In leg mode this pulley will act as the robot's foot, hence the diameter size was chosen. The pulley has 22 teeth with a pitch of 8 mm. This pulley can support a timing belt with a width of up to 30 mm. The pulley was purchased from RS components and was modified by machining off some material to meet the dimension criteria.

Foot Pulley guide shaft (5):

This part holds the foot pulley in place. This has a length of 37 mm and acted as a structural member to hold the inner and outer plates together in the bottom end. Ideally this part was to be made from aluminium but for the prototype it was 3D printed from PLA plastic.

Inner plate (6):

This plate acts as a structural member to the leg. It holds the foot pulley and the guide block. The inner plate also holds the main drive spur gear. The plate is 154 mm long and is 4 mm thick. The prototype was made from 6061 Aluminium.

Power gear (7):

This spur gear is the part responsible for the leg's movement. The gear is 20 mm wide and has an outer diameter of 50 mm and an inner diameter of 44 mm. The gear has 32 teeth. This gear was 3D printed using PLA plastic. This gear is directly attached to the motor. Although there were gears with similar characteristics in the market the desired width was not available, therefore it was decided to manufacture them in house. The gear was threaded so it could attach to the drive shaft of the drill motor.

Drive gear (8):

This spur gear is attached to the inner plate and is used to move the leg assembly. The gear is 20 mm wide and has a pitch diameter of 90 mm. The gear has 60 teeth. This gear also holds a 62 outer diameter ball bearing which is used to attach the leg to the chassis mount. Because of the bearing fitment within the gear this gear had to be manufactured in house. The gear was 3D printed using PLA plastic.

Bearing mount (9 & 12):

The bearing located in the drive pully is pressed into this mount and it is the point where the leg sits. The bearing has an inner diameter of 42 mm therefore the diameter of this part was made to be 42 mm to ensure a good fit. This mount is also responsible to maintain the maximum torque setting in the gear box by pushing on the springs located within the gear box. To ensure this mount would not rotate the inside of the part was modelled to follow the drill gearbox housing structure. For the first prototype this part was manufactured using PLA plastic and was 3D printed. Only one motor needed a bearing to be mounted but it was decided that to use the same part in both motors to reduce the manufacturing part count.

Chassis mount (10):

This structural member holds the two motors and their gear boxes. This also allows the whole leg assembly to be mounted on the platform. Special considerations were made to ensure the motors are secured within the part and is not able to rotate in the mount itself. This part was 3D printed using PLA plastic.

Motors and Gearbox (11):

From the literature it was common that most robots used brushless DC motors in their design. However, a self-locking gearbox and a high torque brushless DC motors are expensive to buy. Because this project focuses on the cost aspect, a drill motor was incorporated in the design. The reason for this choice is that a drill motor requires a higher torque for the operations that they will undergo. A drill will also have a robust gearbox because of the tasks it may face during its lifetime. An 18 V Certa PowerPlus Brushless Drill was chosen for this project because of its specification and its low price of NZ $75.

Figure 51: Certa PowerPlus cordless drill

Gear box:

This is the gearbox of the brushless DC motor. It has a ratio of 60:1 and is a planetary gearbox. The maximum torque is 50 Nm at 400 rpm. There are 15 selectable torque settings and the gearbox is self-locking. Using the bearing mount the gearbox was set to its maximum torque setting of 50 Nm.

Brushless DC motor:

An 18 V brushless DC motor is used to power both the leg and the track drive in the prototype. As mentioned above the motor and gearbox is from a cordless drill therefore it is robust and is designed to be used under load in its lifetime. The encoder from the original drill will also be used in this project. The encoder has 6 hall effect sensors and can measure a minimum of 60 degrees.

Bearing (13):

A bearing was incorporated in this leg design to allow the leg to pivot. A SKF 6008-2RS1 deep groove ball bearing was chosen. This bearing had an outer diameter of 62 mm and an inner diameter of 42 mm making it ideal to allow the design to be mounted on the gearbox housing. This bearing has a static load rating of 11.6 kN and a dynamic load rating of 17.8 kN.

Coupling (14):

This part was designed to hold and attach the drive pulley to the drive shaft of the motor. The coupling was designed in two parts as seen in the figure below (figure 52). The coupling part that attached to the drive shaft was threaded with a UNF (unified national fine) ½" 20 threads per inch thread which matched the drills drive shaft thread. The other side of the coupling was tighten using a special screw with a reverse thread (clockwise to loosen, anti-clockwise to tighten) with the same thread pattern. This will ensure that the drive pully would not come loose when driven in both directions.

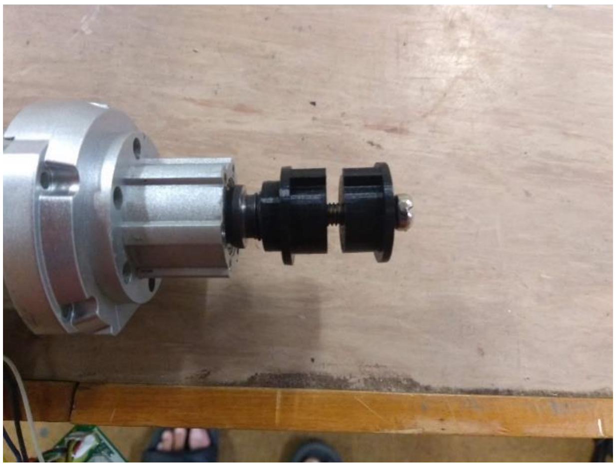


Figure 52: Coupling design attached to the drill

Drive Pulley (15):

This is the main drive pulley for the track. It is a 100 mm outer diameter cast iron pulley and is originally used in a car engine as a CAM shaft pulley. The pulley has 33 teeth with a pitch of 8 mm. The pulley can support a timing belt of 25 mm width.

Guide rings (16):

Two rings were made from 6061 Aluminium with an inner diameter of 90 mm and an outer diameter of 110 mm. The purpose is to hold the track in place during operation. Two per wheel were used in the prototype.

3.2 Theoretical calculations

3.2.1 Max torque calculation

In this section the max theoretical torque the system output is calculated. All relevant data are based on the datasheet provided by Certa.

The drive pulley is directly connected to the drive shaft of the motor via a coupling. The maximum driving torque is calculated below.

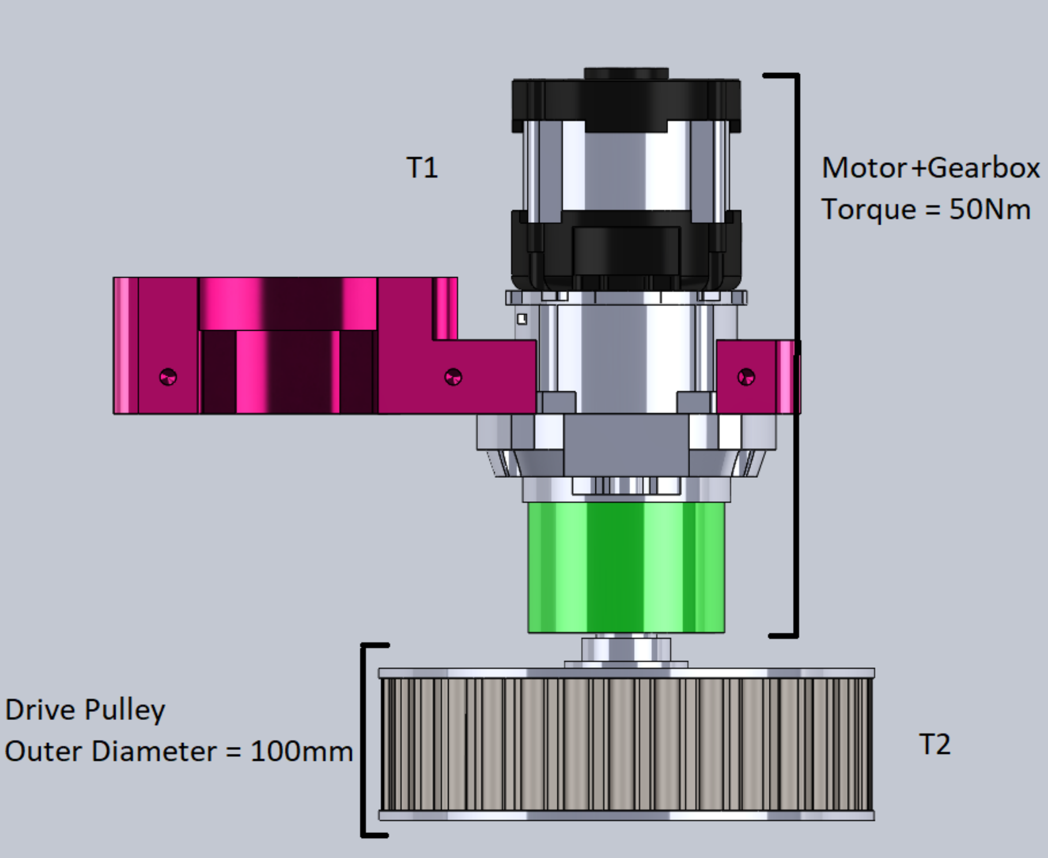


Figure 53: Drive pulley and motor setup

$$\tau_1 = 50\ Nm - From\ the\ datasheet$$
$$\tau_2 = 50\ Nm\ (Toque\ of\ the\ same\ shaft\ are\ equal)$$
$$Outer\ diameter\ of\ the\ drive\ pully$$
$$d_2 = 100\ mm = 0.1\ m$$

Each leg module has its own drive motor therefore the maximum torque is calculated below.

$$\begin{aligned}\tau_{Total} &= 50\ Nm * 4 \\ &= 200\ Nm\end{aligned}$$

The maximum calculated torque before stalling is **200 Nm**.

As the value calculated above is a theoretical one which may include human error and other assumptions a safety factor will be used for the final specification.

3.2.2 Maximum Payload calculation

Each leg is controlled by its own motor. The motor is powering a simple spur gear gearbox to increase the torque value. The following calculation assumes the gearbox is a perfect one therefore assuming 100% efficiency.

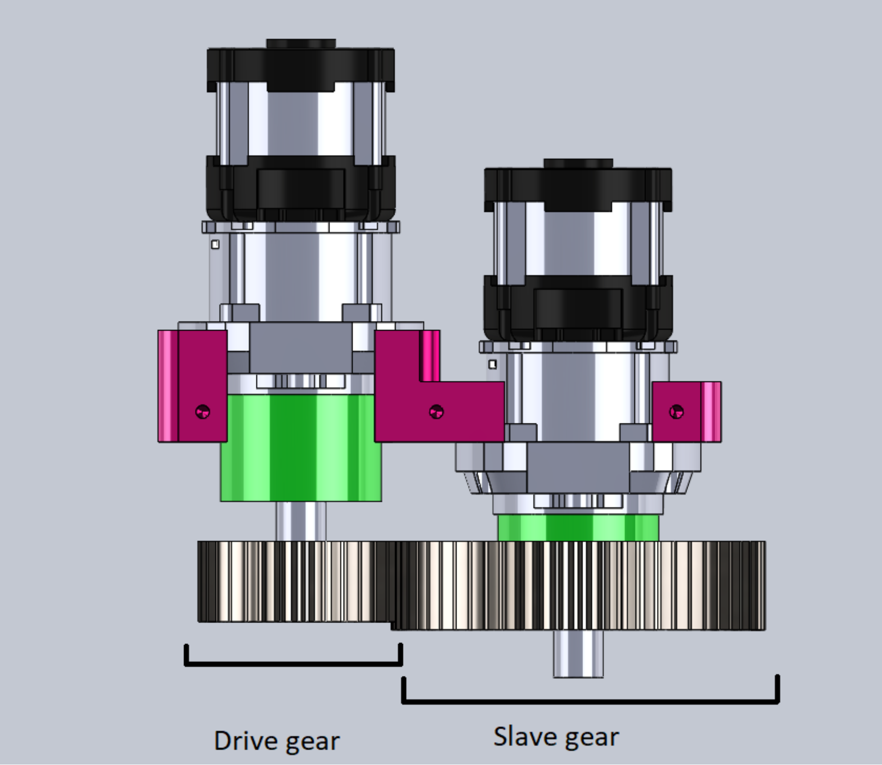


Figure 54: Leg drive gear and Slave gear setup

$$Drive\ gear = DG$$

$$Number\ of\ teeth\ in\ drive\ gear = N_{DG} = 32$$
$$Torque\ of\ the\ drive\ gear = \tau_{DG} = 50\ Nm$$

$$Slave\ gear = SG$$

$$Number\ of\ teeth\ in\ slave\ gear = \ N_{SG} = 60$$
$$Torque\ of\ slave\ gear = \tau_{SG} = ?$$

Using the teeth number, the gear ratio is calculated below.

$$\begin{aligned} Gear\ ratio &= \frac{N_{SG}}{N_{DG}} \\ &= \frac{60}{32} \\ &= 1.875 \end{aligned}$$

Assuming perfect gearbox and using the calculated gear ratio the torque of the slave gear can be calculated.

$$Gear\ ratio = \frac{\tau_{SG}}{\tau_{DG}}$$

$$\begin{aligned} \tau_{SG} \quad &= Gear\ ratio * \tau_{DG} \\ &= 1.875 * 50Nm \\ &= 93.75Nm \end{aligned}$$

The leg plates are connected to the Slave gear. The length from the centre of the slave gear to the tip of the leg is shown below.

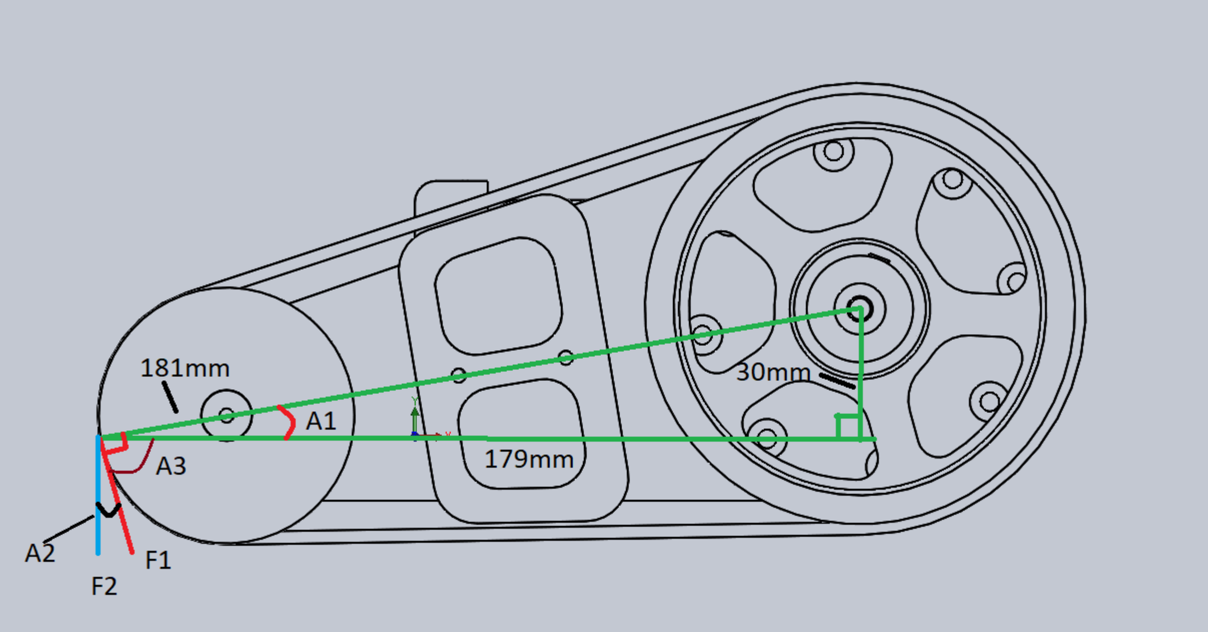


Figure 55: Leg measurements and angles

$$The\ distance\ from\ the\ centre\ of\ the\ slave\ gear\ to\ the\ tip\ of\ the\ leg = d$$
$$d = 181\ mm$$

From the calculated torque and the distance above the maximum force required to stall can be calculated.

$$\begin{aligned} \tau_{SG} &= F * d \\ F \quad &= \frac{\tau_{SG}}{d} \\ &= \frac{93.73Nm}{0.181m} \\ &= 517.8N\ per\ leg \\ &= 517.8N - \text{F1 in Figure 55} \end{aligned}$$

The normal force F2 in figure 55 needs to be calculated.

Angle A1 can be calculated using the sin rule

$$sin\ (A1) = \frac{30mm}{181mm}$$
$$(A1)\ = 9.54°$$

Angle A3 can now be calculated

$$90° - 9.54° = 80.46° = A3$$

From angle A3 angle A2 can now be calculated.

$$90° - 80.46° = 9.54° = A2$$

From angle A2 and F1 now the normal force F2 can be calculated using the cosine rule.

$$cos\ (A2) = \frac{F2}{F1}$$
$$cos\ 9.54 = \frac{F2}{517.8}$$
$$F2 \quad = cos\ 9.54 * 517.8$$
$$= 510.6\ N - per\ leg$$
$$= 510.6 * 4$$
$$= 2042.4\ N - per\ four\ legs$$

The maximum theoretical weight of the payload can now be calculated

$$F = m * a$$
$$m = \frac{F}{a}$$
$$= \frac{2042.4}{9.81}$$
$$= 208.2\ kg$$

The maximum theoretical weight the device can handle before stall is **208.2kg**.

3.3.3 Maximum theoretical speed calculation

The theoretical unloaded maximum speed is calculated in this section. All relevant data was acquired from the Certa datasheet.

$$Radius\ of\ drive\ wheel\ (r) = 50\ mm$$
$$RPM\ (N) = 400 - from\ the\ datasheet$$

The angular velocity can now be calculated using the RPM of the motor

$$\omega = \frac{2\pi}{60} \times N_{rpm}$$
$$= \frac{2\pi}{60} \times 400$$

$$= 41.89 \, rad \, s^{-1}$$

The linear velocity can now be calculated using the angular velocity and the radius of the drive wheel.

$$\begin{aligned} V &= r \times \omega \\ &= \frac{50}{1000} \times 41.89 \\ &= 2.09 \, ms^{-1} \end{aligned}$$

The calculated max theoretical speed is **2.09 m/s**. This is the max unloaded speed. This value will change when the prototype is loaded. There was no data available of the motor characteristics when loaded in the datasheet.

3.3 Prototype and specifications

A prototype was built using aluminium and 3D printed PLA plastic. The four leg modules were mounted to a 450 mm x 250 mm stainless steel base. 8 brushless DC motors were mounted on to the stainless steel plate. The 8 motor drivers were mounted on an MDF wood board and mounted on to the steel plate. Special consideration was taken to insulate all electronics so they will not cause a short circuit and damage the electronics. The second deck of the MDF wood board carried an Arduino Nano and an 18 V lithium ion battery for testing purposes. The figures below (figure 56 and figure 57) shows the built prototype.

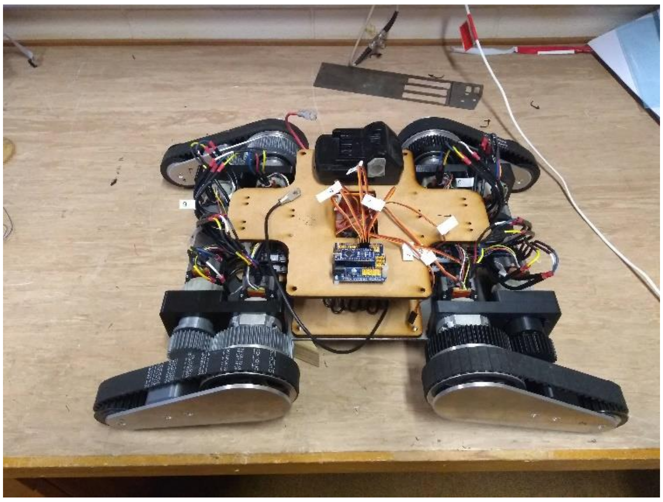


Figure 56: Prototype 1 top view

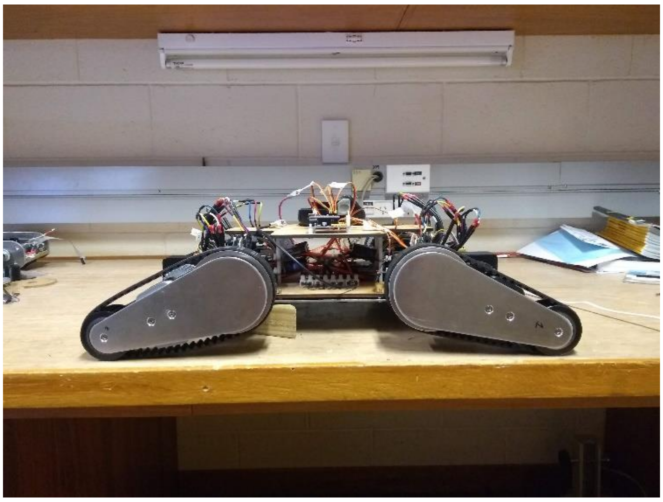


Figure 57: Prototype 1 side view

The calculations in section 3.2 showed the maximum theoretical values from the known parameters. This does not mean the prototype will operate at these values. Using a safety factor when designing is a common practice in engineering. Therefore, a safety factor of 2 will be used for the design to reduce the possibility of failure. Final specifications are shown below in Table 5.

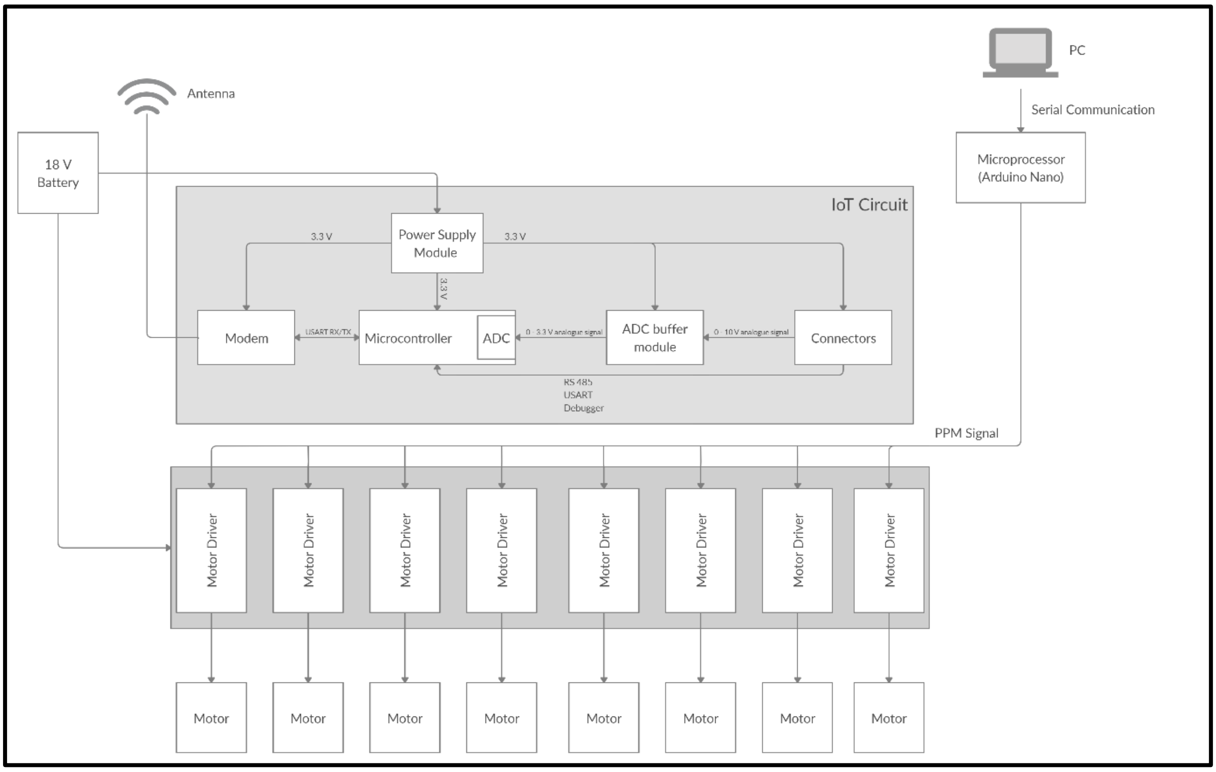
Table 5: Mechanical design specifications

Features	Description
Overall Size	665 mm x 445 mm
Weight	15 kg
Ground clearance in Track	16 mm
Ground clearance in Leg mode	140 mm
Designed Max Payload	100 kg (Safety factor of 2)
Maximum torque	100 Nm (Safety factor of 2)
Maximum unloaded speed	2.09 m/s

3.4 System Electronics and components

Figure 58 shows the functional block diagram of the full electronics of the prototype. The component blocks are as follows and explained in the following sections.

- The IoT circuit (greyed out part in figure 58) consist of five main modules.
- Motor Drivers
- Microprocessor



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- *Figure 58: Functional block diagram*

3.4.1 IoT Circuit

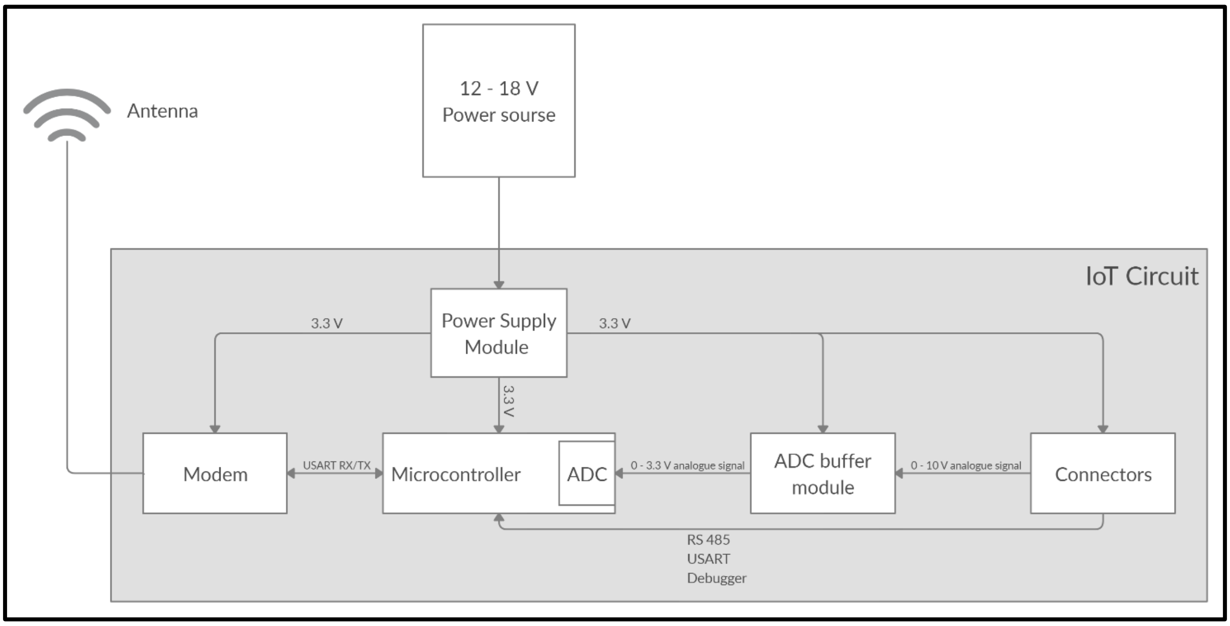


Figure 59: IoT Circuit block diagram

An IoT gateway circuit was designed for this current prototype. This design carries a cellular modem and the ability to connect sensors that outputs a 0 – 10 V analogue output. It can also read data from a RS485 device which is a communication protocol that most devices in agriculture.

This section investigates a design of a circuit that will allow sensors that uses an analogue signal to output data. The proposed circuit will also act as a gateway to send the data to a remote sever via the cellular network. This circuit will be placed in the prototype in the hopes that it will be used to relay data to the user via the internet. The designed circuit will have the following features

- Operate at 12 - 18 V as the full system will operate at that voltage
- Utilises 6 ADC inputs to read an analogue voltage from sensors simultaneously
- The ability to power 6 individual sensors with 18 V at 5 A.
- The ability to cut off the voltage input when the voltage drops below 4 V to avoid sending 'garbage' data packets via the modem
- Connect to the internet via the cellular network
- Find the GPS (Global positioning system) location
- The ability to read data from a sensor that uses RS485 communication protocol to communicate

The designed IoT PCB has the following specifications.

Table 6: IoT PCB specifications

Features	Description
Operating voltage	12-18V
Current draw	0.9 mA
ADC inputs	6
Connectivity	3G Cellular
Communications	via UART
Other	RS485 connection and GPS location

The designed circuit has the following modules:

- Modem module
- Microcontroller module
- ADC input buffer module
- Voltage regulator module
- Connector and RS 485 module

The IoT circuit will be powered by an 18 V battery. This battery will also power other electronics such as the motors and the motor drivers as shown in figure 58.

3.4.1.1 Modem

The chosen modem was the GLYN Mini PCIE LE910C1-AP. This device is designed by GLYN and is based on the Telit cellular modem. The following features made the device appealing for the application. The modem is connected to the microcontroller via USART.

- 3G/4G compatibility
- Dedicated AT command set (Telit unified AT command set)
- Onboard GPS receiver (takes up to 30 seconds to acquire the location)
- Ability to update firmware over the air
- Device can be interfaced to a PCB using a mini PCIE card holder
- Operation voltage of 3.3 V

The chosen cellular mobile provider was 2degrees New Zealand. When purchased the modem is shipped as a PCB which can be connected to a PCI mini port. The designed IoT PCB allowed for a mini PCI port to allow the modem to be interfaced with the IoT PCB.

3.4.1.2 Microcontroller module

The chosen microcontroller for the prototype is the 32 Bit STM32F091VCT6 by ST microelectronics. This device was chosen mainly because of the number of ACD inputs and the ability of interfacing devices with different protocols such as CAN (Controlled area network). The microcontroller is packaged in a LQFP100 package which can be surface mounted. The device also had the following appealing features.

- 16 channel 12 Bit ADC converter
- 256 Kbyte of flash memory
- CAN compliant with a bit rate up to 1Mbit/s
- I2C interface
- 96 Bit unique ID
- Ability to interface UART and USART devices
- The number of I/O available

Additionally, the support for the product and the use of MBED programming platform was also considered when choosing this component. As shown in figure 60 additional external crystals and de-coupling capacitors are placed as noted in the device’s data sheet. The full connections made to the micro controller can be found in appendix A.

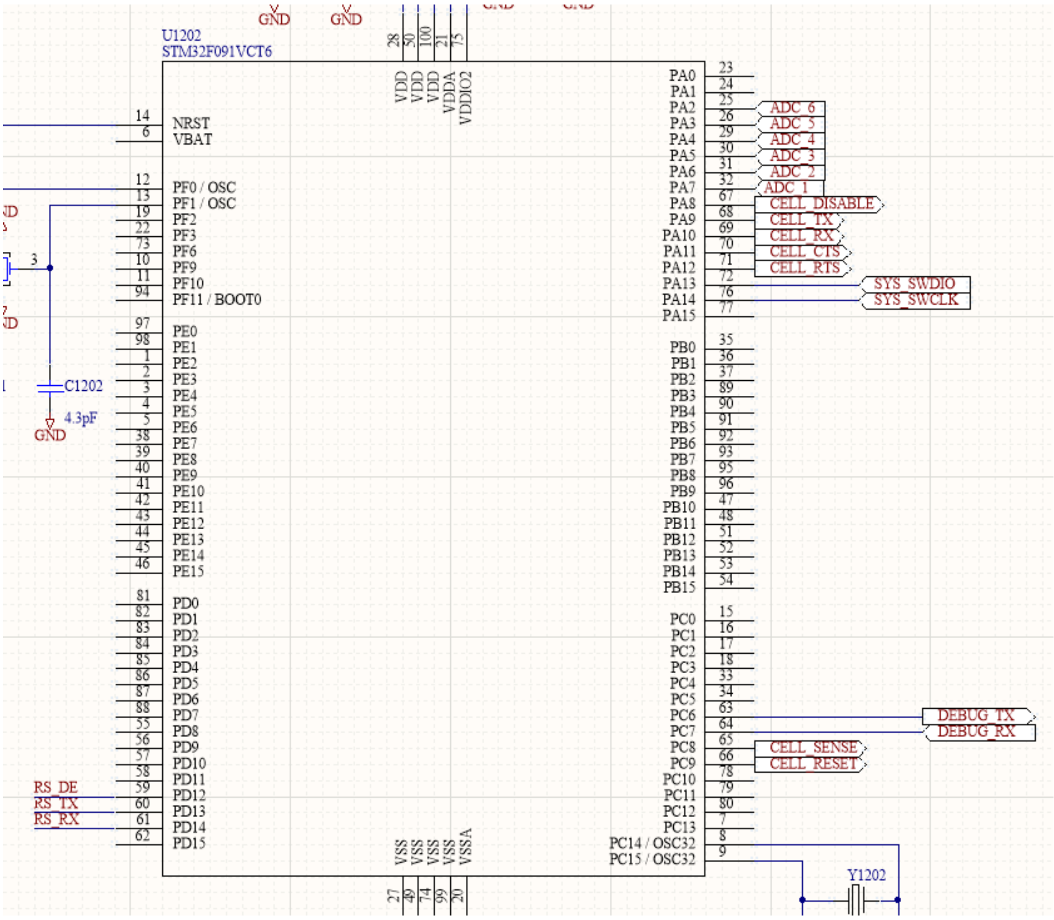


Figure 60: STM32F091VCT6 schematic diagram

3.4.1.3 ADC input buffer module

The board is designed to accept an analogue input of 0-10 V from a sensor. The STM32F091VCT6 can only accept an analogue input of 0 -3.3 V therefore a voltage divider and a non-inverting amplifying op-amp circuit was used to drop the voltage to avoid damage to the micro controller. The op-amp acts as a buffer to the voltage divider. The chosen op-amp device was the MCP6L04T. This device comes in a 14-pin small outline integrated circuit (SOIC) package. One device has 4 op-amp circuits. Two devices were used to allow a total of 6 ADC inputs. The following diagram below shows the non-inverting op-amp circuit and the voltage divider configuration to drop the voltage. The gain of the op-amp circuit is 1 and the use of Zener diodes will make sure the voltage does not exceed 3.3 V. The resistor values were calculated to drop a voltage of 10 V to 2 V.

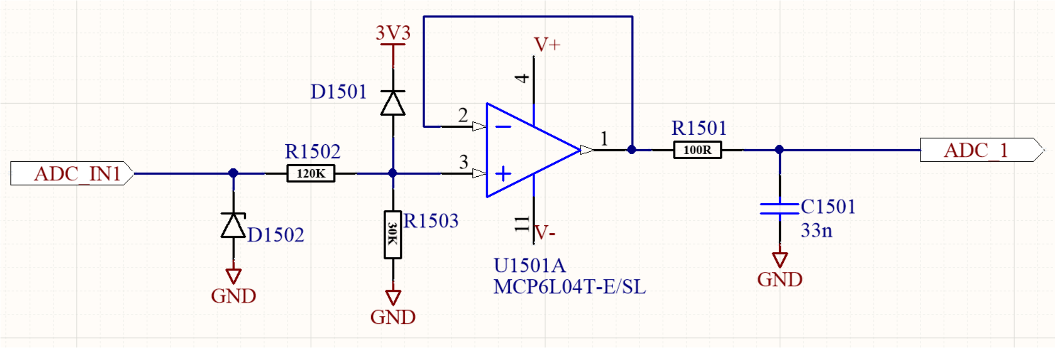


Figure 61: ADC input buffer module

3.4.1.4 Power supply module

Two main sections are included in this module and are explained. The two modules are

- Low voltage cut circuit
- Voltage regulator circuit

Low voltage cut circuit

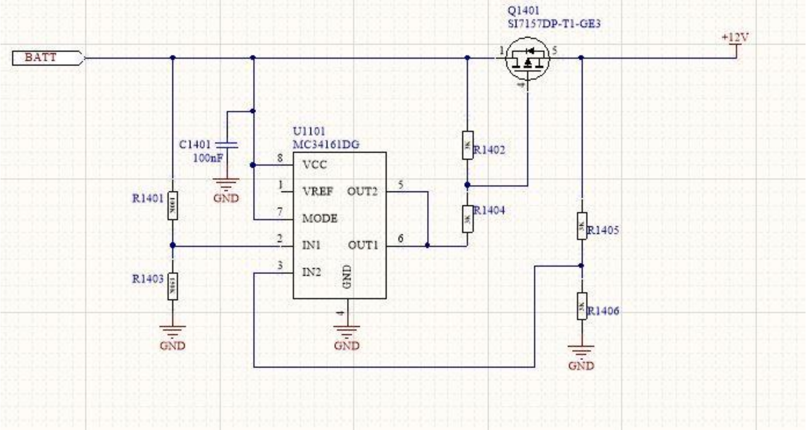


Figure 62: Power module schematic

It was found when reading the literature of IoT devices that there is a problem with some devices transmitting error readings while in operation. One of the reasons was found out to be that when the voltage is not sufficient the device cannot transmit the data properly. To avoid this problem the prototype was designed to have a voltage cut off when the battery reached 4 V or less. The MC34161DG is a universal voltage monitor which is used to switch on and off a high power MOSFET (acting as the switch). The component can handle up to 40 V which was ideal because we are supplying it with 12 - 18 V. As per the datasheet of the component it was setup as a dual positive overvoltage detector. This means the MOSFET will switch off at a specific voltage (4 V) and will switch on when the voltage is above the set voltage. The calculations were done per the datasheet and are shown below.

Voltage regulator circuit

As mentioned, the circuit is designed to operate with a supply voltage of 12 - 18 V. The internal components operate at 3.3 V. Therefore, a voltage regulator was used to supply the 3.3 V required. The chosen regulator was the MPM3630. The following features were considered when choosing the component.

- Complete switch mode power supply
- 4.5 v to 18 V operating input range
- 3 A continuous load current
- Adjustable output to a minimum of 0.6 V

The higher current was a requirement for the GLYN modem. The input voltage was 12 - 18 V and the output voltage was set at 3.3 V. As per the datasheet the resistors were chosen as such to the regulator outputs the desired voltage of 3.3 V. The configuration is shown below (figure 63).

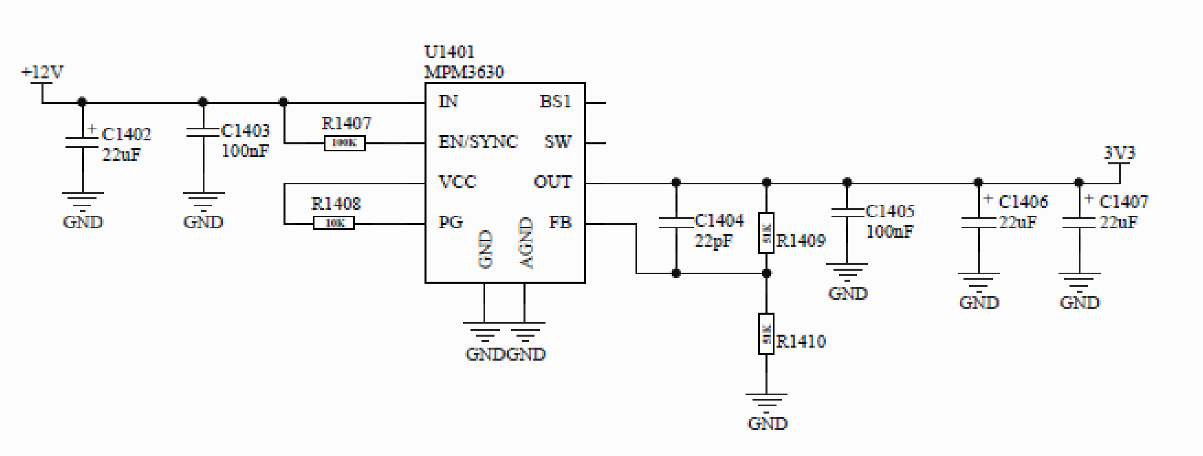


Figure 63: Voltage regulator schematic

3.4.1.5 Connectors and RS485 module

This module contains all the physical input that the circuit needs. ADC inputs, power and the programming inputs are included in this module. As for the first prototype only, male sockets were used. There are various sockets available in the market and a suitable one will be recommended for the final prototype below.

The ISL83078E was chosen as the RS485 transceiver. The higher data transfer rate of 20 Mbps and the ability to operate with 3.3 V were the main reasons of choosing this component. A CAT 5 connector is used as the input connector as this seems to be the trend for RS485 communication method. The schematic of the component was follows as shown in the figure below (figure 64).

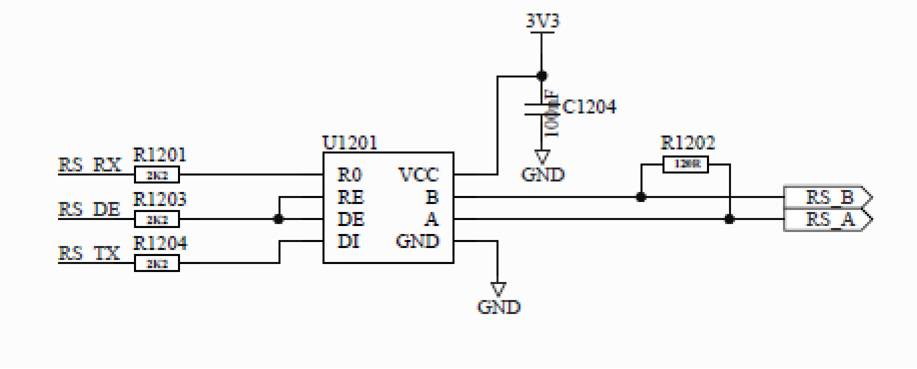


Figure 64: RS-485 module schematic

In this design all recommendations for decoupling capacitors from all component data sheets were taken and implemented in this circuit. Also, protection diodes were used in places such as the voltage monitor circuit to ensure the circuit will not me damaged when if the power was plugged in the wrong way. Also, protection diodes were used in the ADC module to ensure the op-amp was protected from a device that supplied more than 10 V. The full schematic and the components list can be found in appendix B.

3.4.2 Motor Drivers

The Certa used a STM based brushless DC motor driver. It had individual inputs programmed for a series of switches for speed control. It also had a feature which indicated the battery level. The power to the motors were supplied by high power MOSFETs through an 18 V battery. Although the driver used a STM microcontroller it had no port to re-programme it. Therefore, the default motor driver cannot be used for this application.

From all the brushless DC motor drivers in the market currently the open source VESC by Benjamin Vedder Electronics was chosen because of the following specifications.

- Operating voltage of 8 V – 60 V (motor requires 18 V)
- Ability to operate at a continuous current of 50 A via high power MOSFETs.
- Ability to operate with a Hall effect encoder.
- Hardware ready to implement field-oriented control (FOC)
- Hardware ready to communicate via CAN bus (control area network).
- Communication such as UART, PPM signal, I2C, USB
- Ability to adjust protection against high motor current and high voltage.
- Open source software and support by other community members.

The protection features of the driver were an advantage because there was only limited information about the Certa drill's motor therefore, we could set protection parameters while testing.

The prototype uses 8 VESC controllers to control the 4 drive wheels and 4 leg modules.

3.4.3 Microprocessor

The prototype is currently using an Arduino Nano to communicate to the motor drivers. An Arduino Nano with an Arduino servo break out board was used to generate an output of a 50 Hz pulse position modulated (PPM) signal to the drive the motors. The PPM signal was sent to the VESC via a single wire from the Arduino break out board. In addition, the VESC can be used to power the Arduino board. The connections to the Arduino break out board are shown in the figure 65. The VESC motor driver was set to look for the pulse width wavelengths to do the following actions (sown in table 7).

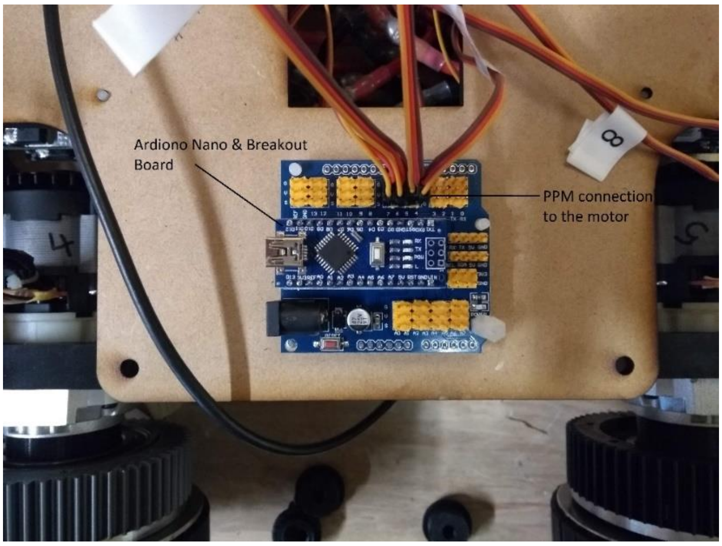
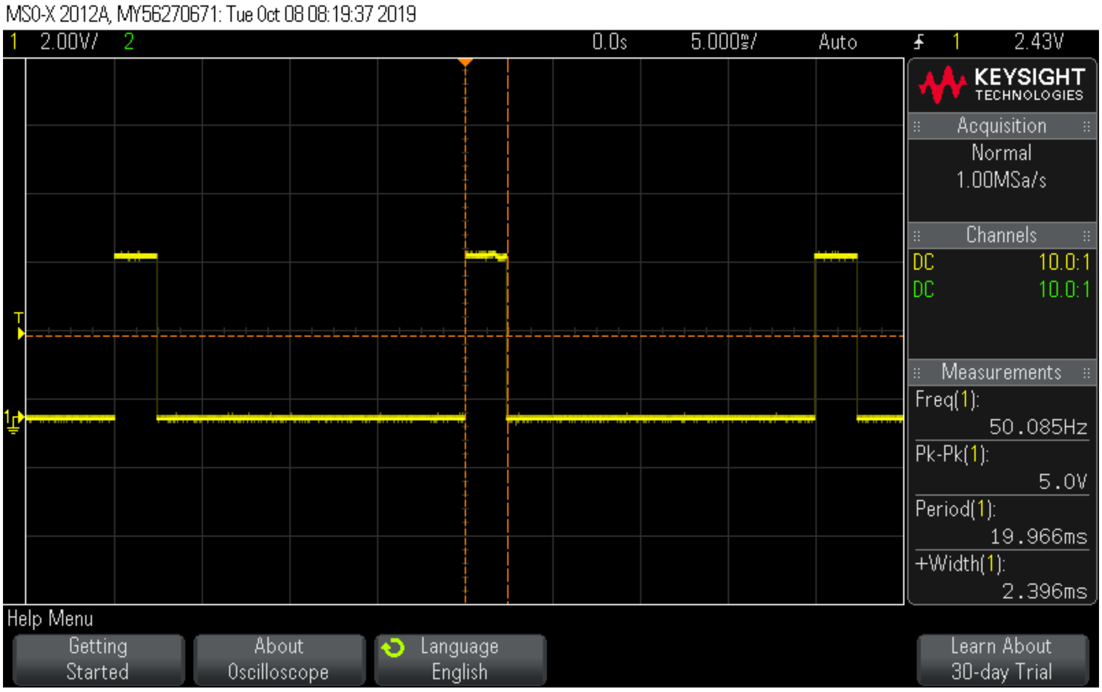


Figure 65: Arduino Nano plugged into a breakout board and the PPM connections

Commands were sent to the Arduino via USB serial. A programme using the Arduino built in servo driver library (Servo.h) was written to output the PPM square wave and vary the wavelength to do the desired action (Code in appendix C).Figure 66, figure 67 and figure 68 shows the square wave output of the three desired states from an oscilloscope. ASCII commands from a PC is sent via USB serial which will move the prototype forwards and backwards and stop it. These are the max values which will operate the motor at a maximum of 95% duty cycle.

Table 7: PPM signals and actions

ACII command	Pulse width (milliseconds ms)	Action
‘w’	2.596	Motor spins forwards
‘s’	1.692	Motor locked in place
‘x’	1.187	Motor spins backwards

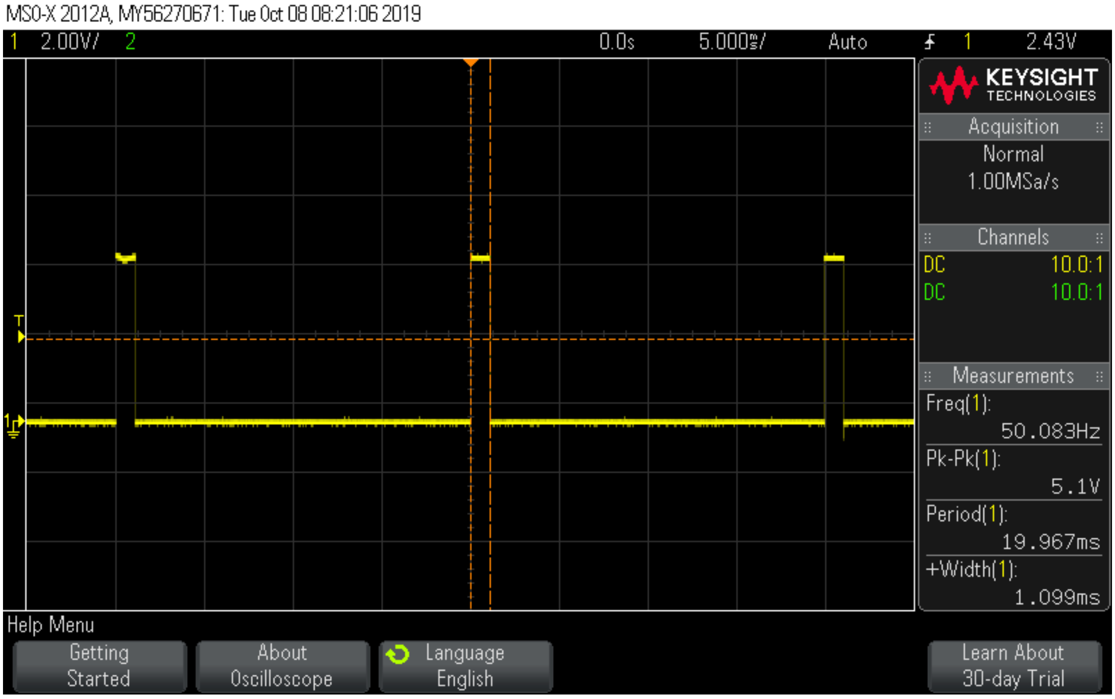

MSO-X 2012A, MY56270671: Tue Oct 08 08:19:37 2019

Acquisition
Normal
1.00MSa/s

Channels
DC 10.0:1
DC 10.0:1

Measurements
Freq(1): 50.085Hz
Pk-Pk(1): 5.0V
Period(1): 19.966ms
+Width(1): 2.396ms

Figure 66: PPM signal in 'w' state

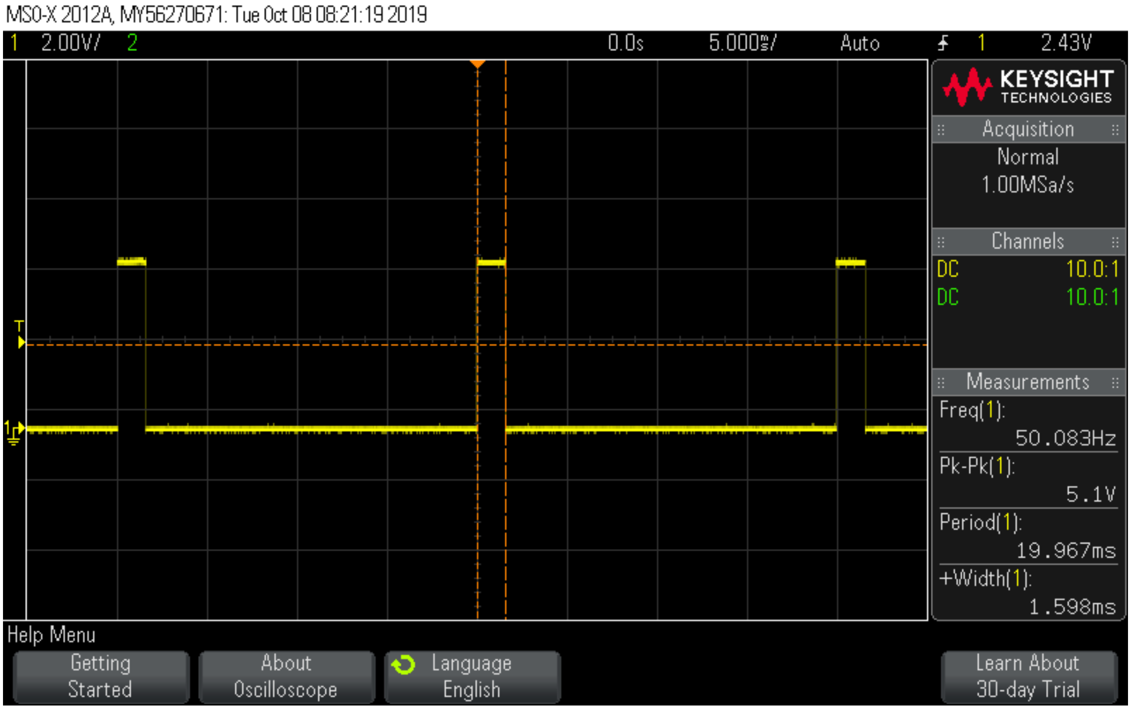

MSO-X 2012A, MY56270671: Tue Oct 08 08:21:06 2019

Acquisition
Normal
1.00MSa/s

Channels
DC 10.0:1
DC 10.0:1

Measurements
Freq(1): 50.083Hz
Pk-Pk(1): 5.1V
Period(1): 19.967ms
+Width(1): 1.099ms

Figure 67: PPM signal in 's' state



MSO-X 2012A, MY56270671: Tue Oct 08 08:21:19 2019

1 2.00V/ 2 0.0s 5.000ms/ Auto 1 2.43V

Acquisition
Normal
1.00MSa/s

Channels
DC 10.0:1
DC 10.0:1

Measurements
Freq(1): 50.083Hz
Pk-Pk(1): 5.1V
Period(1): 19.967ms
+Width(1): 1.598ms

Figure 68: PPM signal 'x' state

3.5 Known Limitations of the current design

The current prototype is designed for a rough flat terrain which may not be suitable for most farms in New Zealand. Because of the low ground clearance, the robot may bottom out in some cases.

The current wheelbase of the robot maybe a limiting factor when operating on rough terrain as when it encounters holes that are distanced apart from each other which maybe more than the wheelbase.

The design uses spur gears to operate the legs of the robot. These gears are exposed to the environment and could be a limitation as mud and rubble from the ground may be picked up and jam the mechanism.

The prototype is not waterproof, which means that it cannot be operated rainy weather.

The brushless DC motors are from a handheld battery-operated drill. Drills are designed for short burst high power operations, not continuous operation. The drill gearbox has a lot of play therefore may not be ideal for complex GAIT techniques.

The IoT aspect of the robot will rely on New Zealand cellular coverage therefore there may be some issues with reception in some areas.

Chapter 4
Preliminary testing

4.1 Testing preparation for tractor mode

From the leg design in chapter 3 a prototype was built. The prototype was built using stainless steel, aluminium plate and PLA plastic. MDF baseplates were designed to hold the motor drivers and other electronics on the platform. Most parts were 3D printed and CNC milled for the prototype. The whole system weighs approximately 15 kg. Figure 69 shows the fully built prototype.

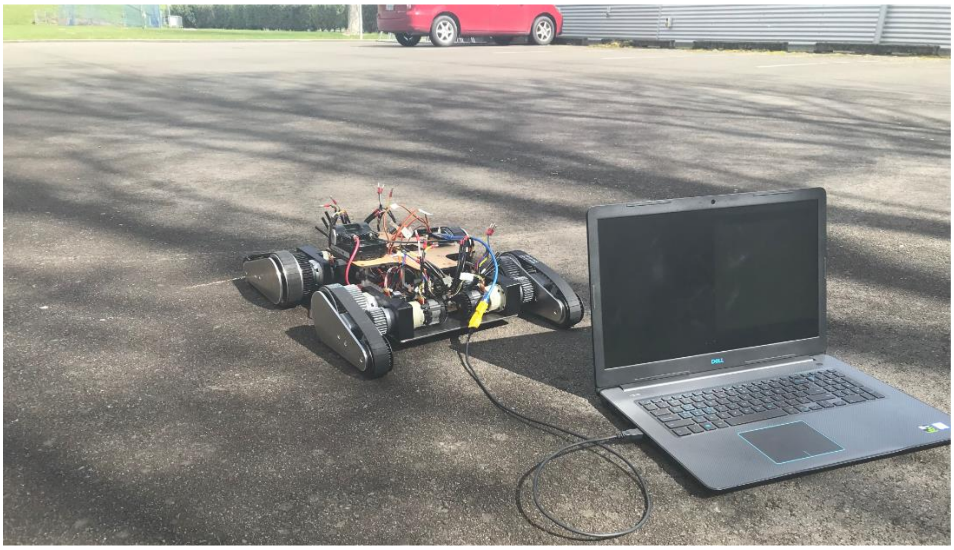


Figure 69: Prototype 1 in a testing area

For testing the prototype was powered using an 18 V 1.5Ahr battery. This battery had a run time for about 10 minutes which was enough for these tests. As mentioned above in chapter 3, the motor drivers can communicate via UART, CAN bus, Serial and PPM (Pulse Position Modulation). The Arduino Nano was programmed to output the required PPM signal.

4.1.2 Preliminary testing (tractor mode)

The aim of these tests is to observe how the prototype will behave in terrains that can be found in a New Zealand farming environment. There is not set terrains that are classified as New Zealand farming environments. As the terrains differs between farm from horticulture, livestock, vineries etc. Dairy farms are usually flat lands and sheep farms could be in hill terrains. The chosen terrains can be found in a New Zealand farm and preliminary test are done on the prototype. More testing in different terrain types is needed to fully validate the final concept.

The prototype was tested on four different terrains listed below which can be found in a farming environment.

- Flat tarmac ground
- Flat grass ground
- Uphill tarmac ground
- Uphill grass ground

The test site for the uphill tarmac ground and the grass ground was parallel to each other with a gradient of 7 degrees. The gradient was measured by an electronic device.

The steps taken to complete the experiment are:

1. Mark the starting point on the terrain
2. Run the prototype for 10 seconds
3. Mark the point where the protype stopped
4. Record the distance travelled
5. Continue the process for 5 times

The protype's behaviour is observed during each run and noted. At this stage, communication is done via USB serial to the prototype therefore, a PC needed to be connected while the prototype was running at all times. The written code ran the prototype in the forwards direction for 10 seconds and stopped.

4.1.2.1 Flat tarmac ground

Figure 70: Flat tarmac ground test area

This test was done on a relatively flat surface in a parking lot. It was a dry day with a temperature of approximately 23° C. A section where the tarmac had minimal imperfections were chosen. The results are shown below.

The expected distance travelled was calculated using the theoretical top speed calculation from section 3.3.3.

$$velocity = \frac{distance}{time}$$

$$\begin{aligned} distance &= velocity \ \times time \\ &= 2.09\ ms^{-1} \ \times 10\ s \\ &= 20.9\ m \end{aligned}$$

Table 8: Flat tarmac ground test results

Run No	Distance Travelled (meters)	Velocity (m/s)
1	3.94	0.394
2	3.87	0.387
3	3.86	0.386
4	3.92	0.392
5	3.86	0.386
Average distance	3.89	0.389

A maximum of 3.94 meters and a minimum of 3.86 meters was recorded in this test. The prototype travelled freely on the ground. The prototype had its maximum designed ground clearance of 16 mm and did not lose traction on this terrain while operating. Furthermore, it travelled in a straight line during this test.

The prototype travelled in average 3.89 m. This is much less than the calculated theoretical distance. The prototype weighs approximately 15 kg. Due to this loading and friction from the mechanical modules and human error while the prototype was built may be a factor for the reduced distance travelled. The velocity from the distance travelled through the experiment is now calculated.

$$Average\ distance\ travelled = 3.89\ m$$

$$\begin{aligned} velocity \ &= \frac{distance}{time} \\ &= \frac{3.89m}{10s} \\ &= 0.39\ m/s \end{aligned}$$

The velocity of **0.39 m/s** will be used as the baseline velocity for comparison between the various terrains.

4.1.2.2 Flat grass ground

Figure 71: Flat grass ground test area

Shown in figure 71 is a photo of the selected terrain used for this experiment. The chosen location has the occasional imperfection is the ground with dips and bumps of grass/weeds. The ground was dry during the runs at an ambient temperature of approximately 23° C. At the starting point of the test the prototype had a ground clearance of 14 mm. The experiment was carried out and the results are shown below.

Table 9: Flat grass ground test results

Run No	Distance Travelled (meters)	Velocity (m/s)
1	2.55	0.255
2	1.70	0.17
3	2.00	0.2
4	2.52	0.252
5	2.40	0.24
Average	2.23	0.223

A maximum of 2.55 meters and a minimum of 1.70 meters was recorded in this test. The prototype struggled to travel freely on this terrain. In run 2 the prototype bottomed out on a grass lump which made the robot stationary hence the low distance travelled. The prototype was fighting for traction at some points on the grass ground hence the reduced distance travelled. Because of the varied traction on the ground the robot did not travel in a straight line as the tarmac surface.

The average velocity between the 5 trials was 0.223 m/s which in comparison to the baseline velocity of 0.39 m/s was 57% lower.

4.1.2.3 Uphill tarmac ground

Figure 72: Uphill tarmac ground test area

The chosen test site shown in figure 72 was an uphill tarmac road. The tarmac was not perfect as it had imperfections throughout the prototypes travel path. The ground was dry during all the runs at an ambient temperature of approximately 23° C. The protype had its maximum designed ground clearance of 16 mm. results are shown below.

Table 10: Uphill tarmac ground test results

Run No	Distance Travelled (meters)	Velocity (m/s)
1	3.60	0.36
2	3.10	0.31
3	3.24	0.324
4	3.45	0.345
5	3.30	0.33
Average	3.34	0.334

A maximum distance of 3.60 meters and a minimum of 3.10 meters was recorded during this test. The prototype travelled freely in this terrain. In run two an obstacle (small rock) caused the reduction in distance travelled. The protype did not lose traction or bottom out in this section. A slight reduction in distance was noted than the flat tarmac ground. The robot travelled in a straight line.

The average velocity in this terrain was 0.334 m/s which in comparison to the baseline velocity was 14% slower than the flat tarmac ground test velocity. The difference could be the result of the prototype gaining potential energy as it climbs the hill which demands more energy.

4.1.2.4 Uphill grass ground

Figure 73: Uphill grass test area

This test was done on an uphill grass slope which was parallel to the gradient of the tarmac test site to make sure the two sites had similar incline (7 degrees). Figure 73 shown the test site. The slope also had imperfections of bumps and dips and patches with thick grass. When placed the protype had a ground clearance of 13 mm. The results are shown below.

Table 11: Uphill grass ground results

Run No	Distance Travelled (meters)	Velocity (m/s)
1	0.6	0.06
2	0.8	0.08
3	0.4	0.04
4	0.5	0.05
5	0.7	0.07
Average	0.6	0.06

A maximum distance of 0.8 meters and a minimum distance of 0.5 meters was recorded during this test. It was observed that the protype was losing traction during this test hence the reduced distance travelled. Run 1, 3 and 4 the prototype bottomed out while travelling. The prototype lost traction most of the runs and was spinning the tracks without moving. Because of the changing traction in this terrain the robot did not travel in a straight line.

The average velocity for this terrain was 0.06 m/s. The platform performed the worst in this terrain. Compared to the baseline velocity of 0.39 m/s during the flat tarmac test the prototype was 85% slower and was 82% slower than the uphill tarmac ground test. The prototype lost traction which held the robot in place without moving forwards at times which caused the slower average velocity and distance travelled.

4.1.3 Discussion on Testing

In the preceding section the prototype shows potential to operate in a New Zealand flat farming environment rather than a farm which contains a terrain with hills. Further testing and development is needed to validate the concept. The prototype performed the best in both tarmac terrains where the vehicle had most ground clearance and traction. The prototype struggled in both grass terrains.

The prototype uses a flat rubber belts as tracks. The traction could be improved by utilising a track design with teeth. The traction can also be improved by using different width belts and different patterned teeth belts. The PPM protocol of communication was enough for the test but for better control a smarter approach will be needed. The programme written to output the PPM signal was only sending the max values. A method such as PID can be used to ramp the PPM signal to allow the robot to accelerate to the top speed. Algorithms to maintain the prototypes course while travelling in a straight line is also needed.

Further testing is needed to be done for the legged mode by implementing the GAIT for the robot. When the GAIT is implemented alongside a vision system it can be used to identify different terrain types different gradients and then travel via the leg mode in these identified areas. The prototype was designed to have a low ground clearance to allow it to carry sensors that require contact with the ground or get closer to the ground. During testing at some points in the terrain the robot grounded because of this low ground clearance. This is the point where the robot will need to use its legged mode. A vision system could be implemented, and these variations of the ground such as grass lumps dips and rocks can be identified. Furthermore, algorithms can be implemented such as path planning to avoid these areas in the terrain.

The Certa drill motors performed well in these tests. There were no motor issues noted while testing. The motors moved the weight of the robot (15 kg) effortlessly. Is was noted that when at the end of each 10 second run an unusual smell like plastic melting or electrical failure smell was identified. The motors where working as normal but this could be because the motors were not designed for continuous operation. Drills are operated in short bursts. After the field tests an individual motor was run at 10 second bursts for up to 30 times. The same smell was identified, however the motor operated normally, and no damage was identified. There was no datasheet of the drill motor therefore more testing is needed to validate the reliability of these motors in this application. This smell could be because of the motor is overheating. This motor is not designed for a continuous operation. They are designed for a handheld drill which is operated in bursts. Therefore, this motor is not recommended for this application.

Although most parts were built using 3D printed PLA plastics they held well in testing with minor wear and tear after the tests. The parts are designed to be manufactured using nylon and CNC machined aluminium therefore it would make the final product more robust and more durable.

During tests it was clear that the prototype struggled because of its low ground clearance. This issue may be overcome by increasing the scale of the robot itself. Having diameter pulleys and tracks will increase the traction. It will also allow the robot to travel over small rocks and other obstacles.

4.2 IoT Testing preparation

The prototype circuit was designed using Altium circuit designer (figure 74). The Printed circuit board (PCB) is a two layer one and many of the components are surface mount devices. Through hole connectors are also used in the design. The PCB design schematics can be found in Appendix A.

The prototype design was manufactured on a double layer printed circuit board by JCL PCB. All components were hand soldered. Figure 75 shows the assembled PCB design. The prototype was short tested before powering. After the short testing the board was powered up using a bench top power supply with 18 V. By using a STM32 utility tool software and a ST-LINK V2 programmer communication with the micro controller was possible. The utility tool could successfully communicate with the micro controller and is now ready for firmware development.

The firmware allowed messages to be sent as an output via the USART. This could be read via PuTTy .

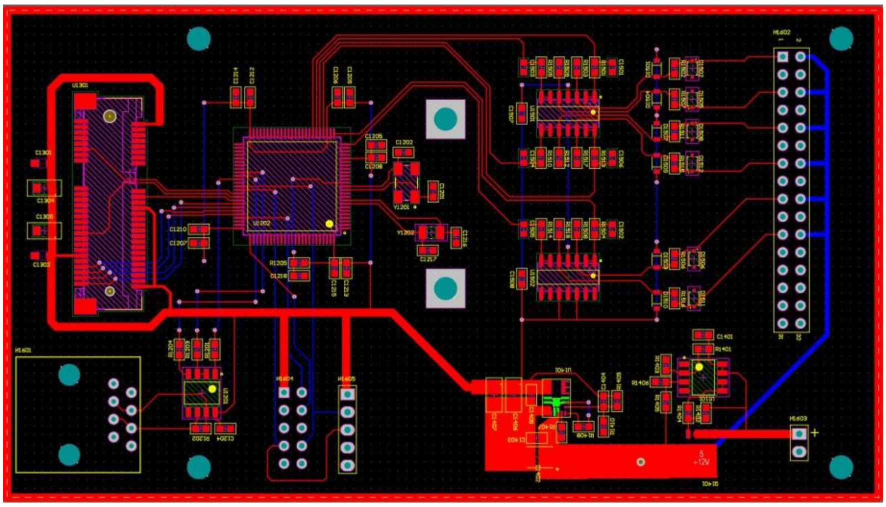


Figure 74: IoT Altium PCB design

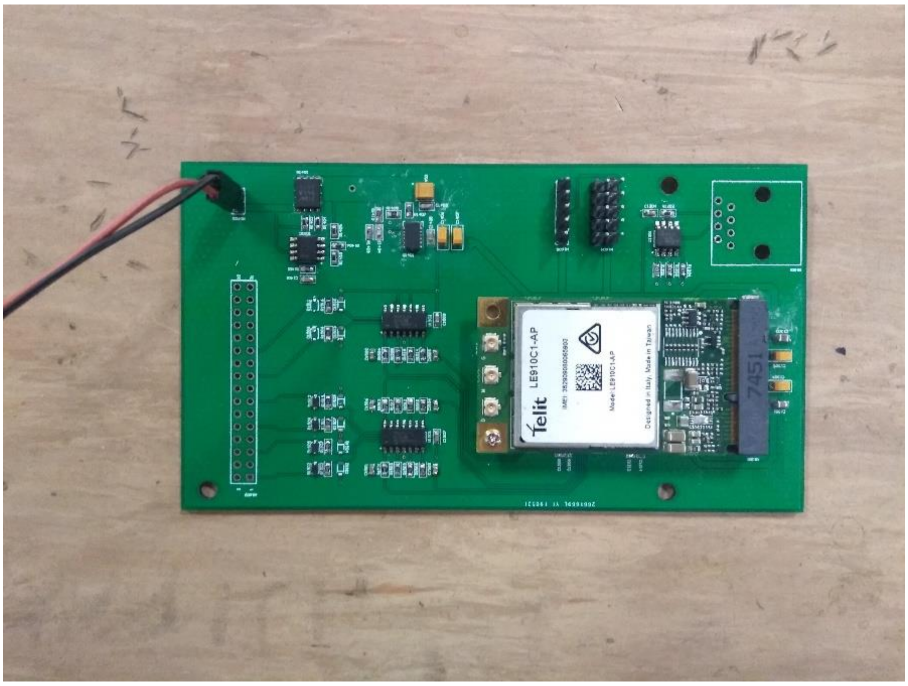


Figure 75: IoT PCB prototype

4.2.1 Preliminary testing of the connectivity

Firmware was developed based on the MBED programming platform. The MBED RTOS (Real time operating system) tools was used to write a code to check if the modem could connect with a remote server. The algorithm had the following threads which are explained below.

- Manager thread: This thread was dedicated to exchange messages with the other threads. The programme relied exchanging data among the threads and communicate with the server.
- Communications thread: This thread was handling the communications with the web server. This thread was dedicated to send and receive information from the web server.
- Monitoring thread: This thread was dedicated to read from the sensors and the RS485 module.

Figure 76 shows the firmware flow diagram.

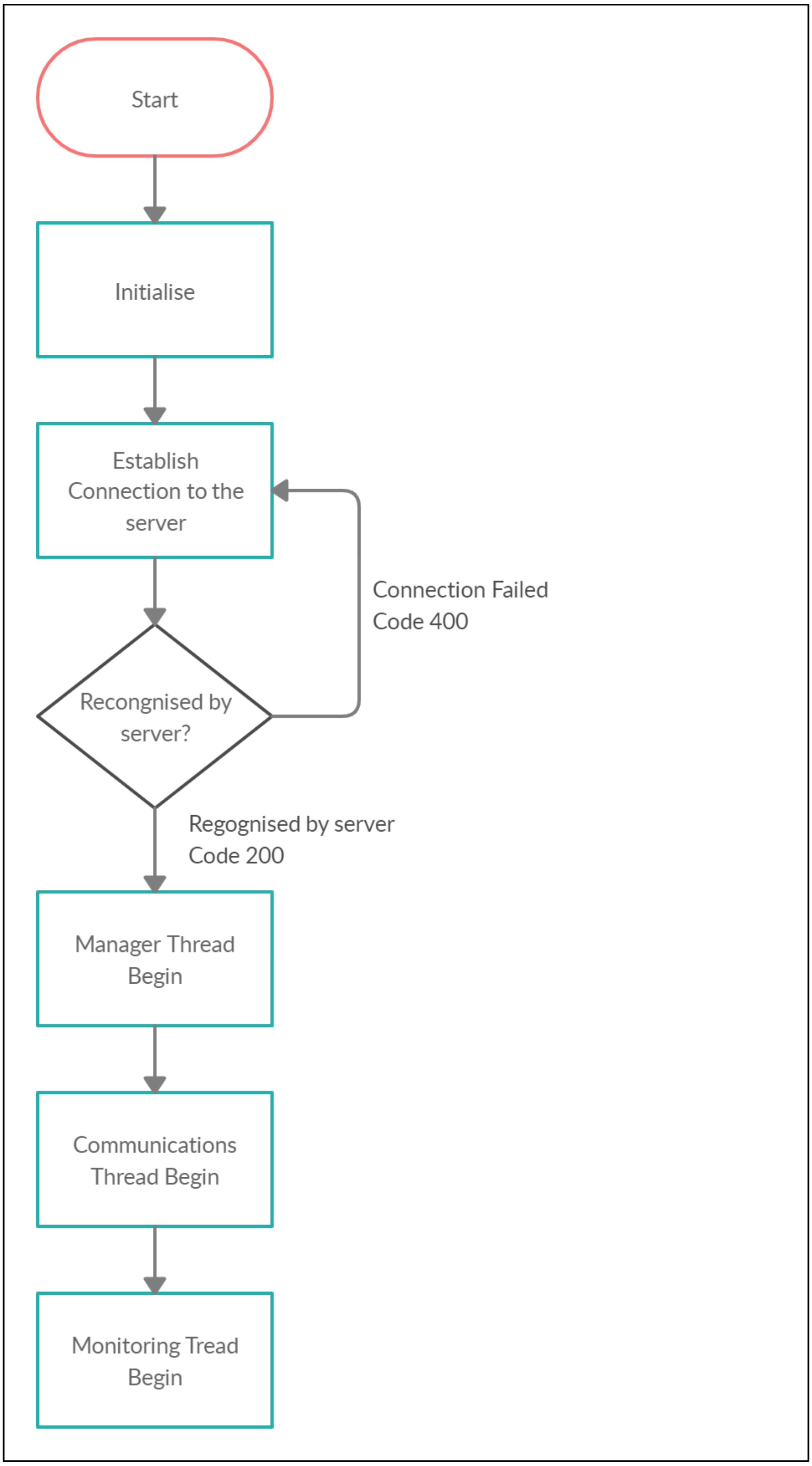


Figure 76: IoT firmware flow diagram

It was established in chapter 1 that the development of the server side of this project is out of the scope of this project. Therefore, for testing purposes we choose an existing established server. When the modem was made to connect to the server the code 400 was visible on PuTTy therefore validating that the modem can communicate via internet. When a dedicated server is developed the code 200 should appear via serial and displayed on the PuTTy window.

4.2.2 Preliminary testing on ADC inputs (Analogue to Digital converters)

To test for the ADC operation a 12 V analogue ultrasonic sensor (Carlo Gavazzi UA1804PKTI) was used. The sensor required a 12 - 20 V to operate and the voltage was supplied via the IoT PCB board. The sensor output a 0 – 10 V analogue signal and had an operating range up to 60 cm. A simple distance vs the ADC reading test was done to validate the operation of the ADC. Figure 77 shows the distance vs ADC reading of the six ADC reading channels.

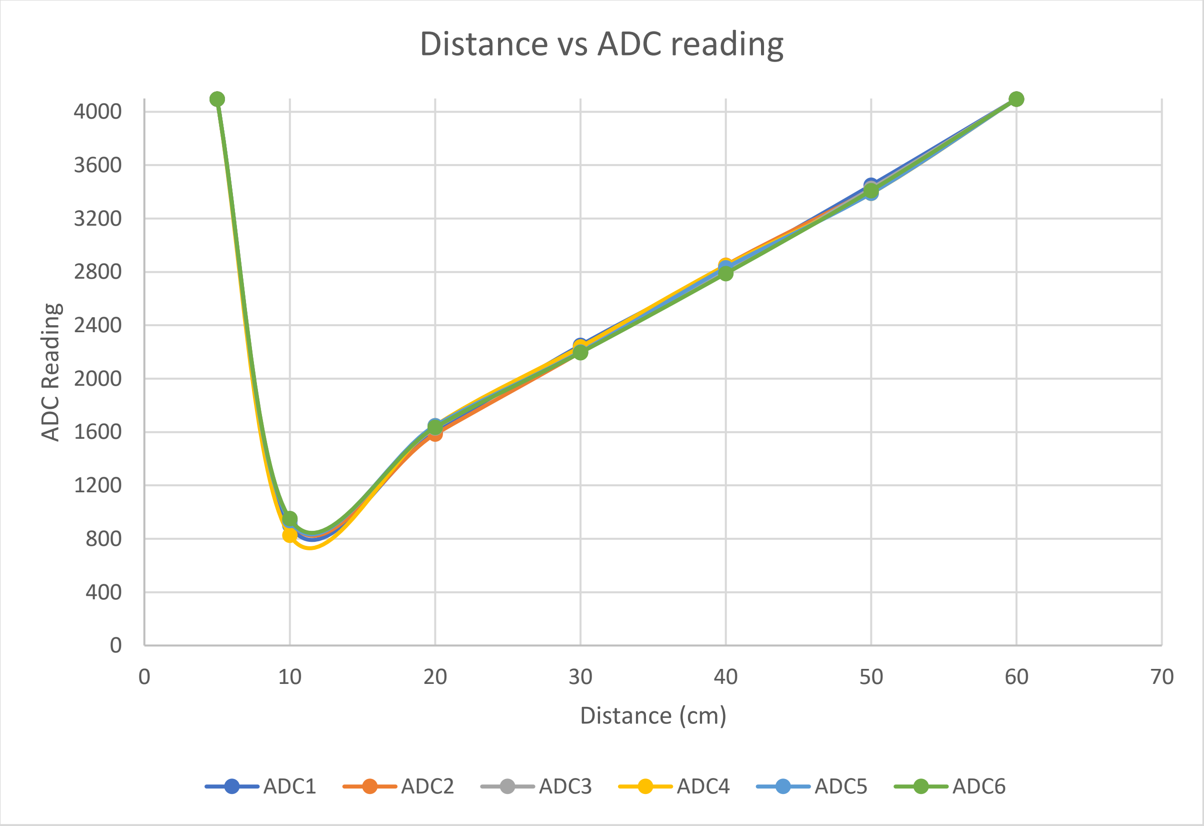


Figure 77: ADC and Ultrasonic sensor testing results

4.2.3 Discussion on Testing

The modem could successfully connect via the internet to a remote server. However, without a dedicated server, we cannot test for data transmission and receiving at this point of the project.

The ACD reading was tested and the results showed that we could successfully read from an analogue ultrasonic sensor which outputs a 0 – 10 V signal. Furthermore, the sensor was powered via the prototype PCB suggesting that the correct voltage can be supplied to sensors. It was noticed that the raw ADC readings was noisy. Filtering methods needs to be explored for the final firmware of the prototype. This test also validated the ADC input buffer circuit in the PCB suggesting that it clamps the voltage between 0 – 3.3 V which is in the safe operating voltage of the microcontroller's ADC.

Chapter 5
Conclusions and Recommendations

5.1 Conclusion

In conclusion a design and prototype of a potential agricultural robot that can operate closer to the ground was discussed in this thesis. The design was inspired by looking into other robots and prototypes that were designed to operate on rough terrains. Hybrid locomotion methods and current products that use such design principals was also investigated in this thesis. Current products on farms were also reviewed. A prototype was designed using the track-leg concept in the hybrid locomotion study area. The prototype had a ground clearance of 16 mm. The prototype was subjected to testing in different terrains that the final product will be placed on (New Zealand farmland) and the results were discussed in this thesis. The tests showed potential but needs more testing and development to validate the final concept. Furthermore, the belt used was a flat belt which cause slippage during testing in some terrains. More testing with different belt types can be researched and tested. It was observed that the robot grounded at some points during the tests because of the low ground clearance.

The following was specified at the start of the project.

- A design that will allow the robot/platform to get within proximity to the ground. At least within 50 mm from the ground
- The prototype will also have to overcome a small obstacle such as small rocks. The robot must have the ability to 'lift' itself up to at least 100 mm. This will allow the robot to overcome small rocks or imperfections in a farming environment.
- A non-complex design that will allow servicing and the overall cost of the prototype low.
- The system should be able to operate from 12 V to 24 V as most sensors and equipment require this range of voltage to operate.
- Since the product is intended to operate autonomously in a New Zealand farm it would be an appealing feature for the product to cover a significant land area. Therefore, a speed of at least 0.5 m/s is desirable.
- The product should be able to carry and array of sensors (sensors not yet decided) and maybe even a robotic arm. Therefore, the robot should be able to carry a payload of at least 100 kg.
- The electronics of the robot will have to accept an input from an analogue reading from sensors. This analogue signal input should be able to accept and reading up to 10 V.

The designed prototype had the following specifications.

- A ground clearance of 16 mm in track mode.
- A ground clearance of 160 mm in leg mode
- A design with non-complex parts
- Can travel with a speed of 2 m/s
- Can carry a payload of 100 kg
- Electronics which can operate from 12 V to 24 V
- The ability to communicate with a remote server using the New Zealand cellular network.

The prototype realised the specifications stated in the beginning of the project.

From the tests it was noted that a smell could be noticed after each 10 second run from the brushless DC motors from the drill. This did not damage the motor, but it may be overheating and reducing the life of the motor. Drills are not designed for continuous operation but for short bursts. The motor was run in 10 second bursts for up to 30 times and no damage was noted. Although the motor and the gearbox provide a great amount of torque and power for the price, this motor may not be suitable for this process. Further testing is needed to validate the reliability for the use of these motors.

Current IoT solutions currently used in farms was also reviewed in this thesis. An IoT gateway was also designed and a prototype was manufactured and presented in this thesis. Bench testing was done, and the prototype was subjected to some preliminary tests. The prototype could connect to a remote server and could read from a sensor that outputs a 0 – 10 V analogue signal.

This work presented in this thesis is a good first step towards a goal of realising a fully automated agricultural hybrid robot that could be placed in a New Zealand farm which can also be operated remotely via the internet to collect soil data such temperature, humidity and even status of crops.

5.2 Recommendations and future works

From testing the prototype performed well in the tarmac terrain. Although it did perform well in the grass terrains it could be improved by changing the flat tracks to a track with teeth for better grip.

While testing the prototype bottomed out on a mound of grass. This could be overcome by increasing the scale of the robot. Using bigger diameter wheels will allow the robot to go over obstacles much more easily.

Since this was the first prototype most of the parts were manufactured using 3D printed PLA plastic. Although none of the parts failed during testing but wear and tear was visible. For the next prototype it is recommended to rebuild parts it with harder material such as aluminium or nylon which can be manufactured using a CNC mill. Although it will be expensive it will make the design more robust and more durable.

An Arduino was used to output a PPM signal to operate the drivers to run the motors. Smart control strategies will be beneficial for the final product.

Sensors could be mounted below and to the sides of the chassis. A vision system and/or a Lidar system for path planning and obstacle avoidance could be beneficial for the final prototype.

The Certa drill motors gave a burning smell during operation. This could be because the motors are overheating. The gearboxes also had a significant play in them. Therefore, this motor gearbox combo may not be suitable for the final product. Further testing on these motors are needed to validate the reliability of these motors.

The IoT circuit could communicate via the internet. The next step is to develop the server side of the IoT system. Once a server is established data can be transferred between the robot platform and the server. Within the server the data can be processed and displayed to the end user for research and development.

It is known that some areas in New Zealand have poor reception. The 3G aspect of this IoT circuit will not operate well in poor reception areas. Therefore, methods to keep a strong connection with the server needs to be researched. Furthermore, other IoT methods such as LoRa or satellite communication can be explored.

The main microprocessor used in this prototype was the Arduino Nano. Although this was sufficient for the testing done in this project it is recommended that a better micro processor is used. The Intel NUC is a single board computer. ROS (Robot Operating System) is a Linux based operating system for robots which can be installed on to the computer. The VESC motor drivers can be communicated via ROS which will allow the robot to be smarter in control algorithms for both the track mode and the leg mode. ROS will also allow the user to integrate a vision system and/or Lidar system.

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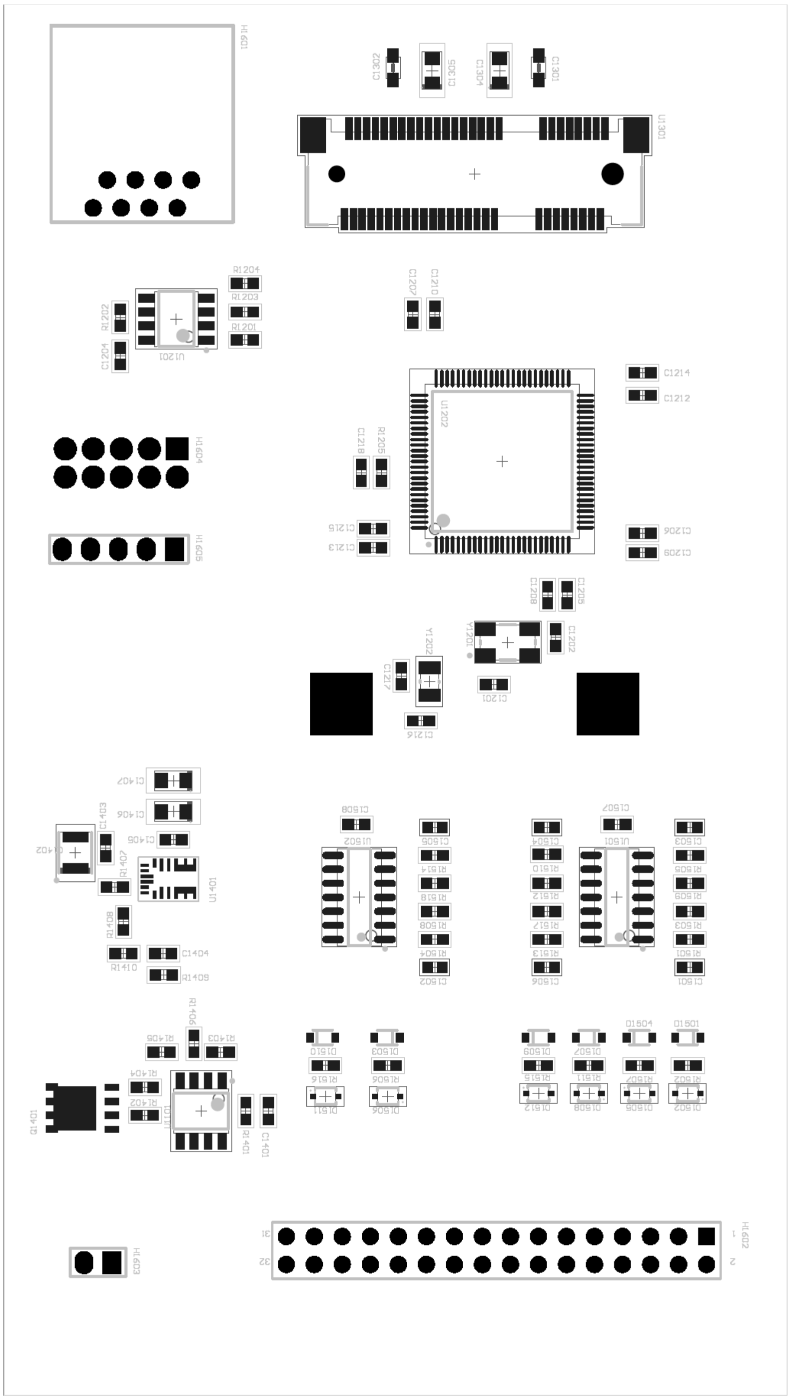
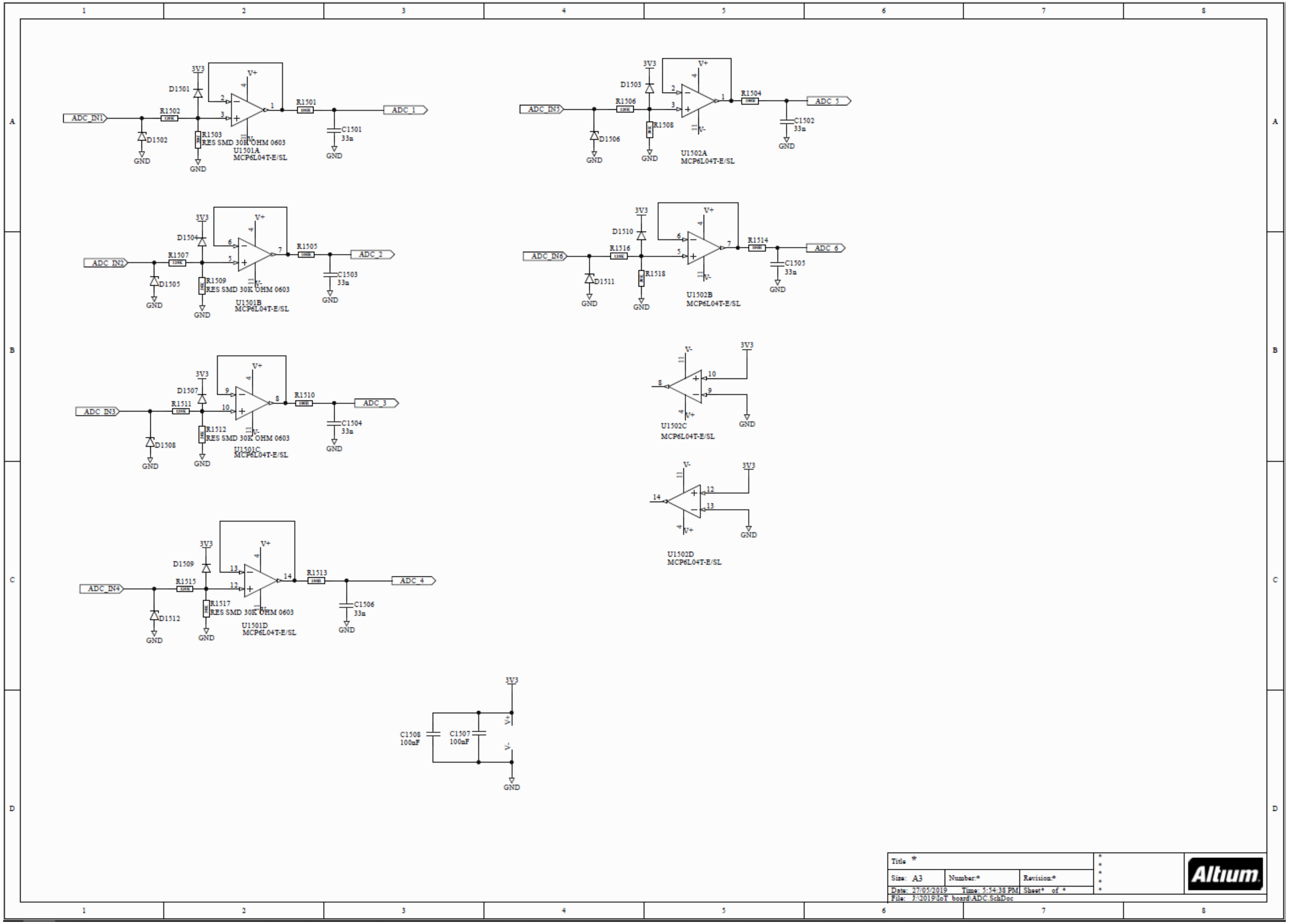
Appendices

Appendix A: IoT board Schematic files

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ADC_IN2
ADC_2
ADC_IN3
ADC_3
ADC_IN4
ADC_4
ADC_IN5
ADC_5
ADC_IN6
ADC_6
3V3
V+
V-
GND
D1501
D1502
D1503
D1504
D1505
D1506
D1507
D1508
D1509
D1510
D1511
D1512
R1501
R1502
R1503
R1504
R1505
R1506
R1507
R1508
R1509
R1510
R1511
R1512
R1513
R1514
R1515
R1516
R1517
R1518
RES SMD 30K OHM 0603
C1501 33n
C1502 33n
C1503 33n
C1504 33n
C1505 33n
C1506 33n
C1507 100nF
C1508 100nF
U1501A MCP6L04T-E/SL
U1501B MCP6L04T-E/SL
U1501C MCP6L04T-E/SL
U1501D MCP6L04T-E/SL
U1502A MCP6L04T-E/SL
U1502B MCP6L04T-E/SL
U1502C MCP6L04T-E/SL
U1502D MCP6L04T-E/SL
1
2
3
4
5
6
7
8
9
10
11
12
13
14
A
B
C
D
Title *
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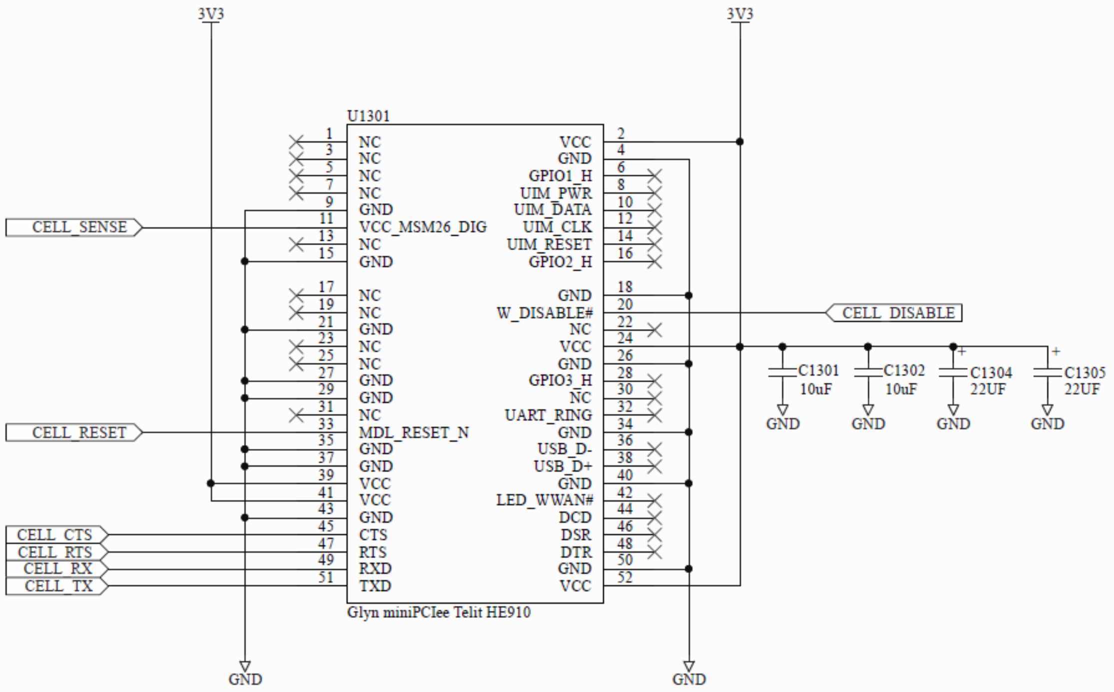
Revision:*
Date: 27/05/2019
Time: 5:54:38 PM
Sheet* of *
File: J:\2019\IoT_board\ADC.SchDoc
Altium



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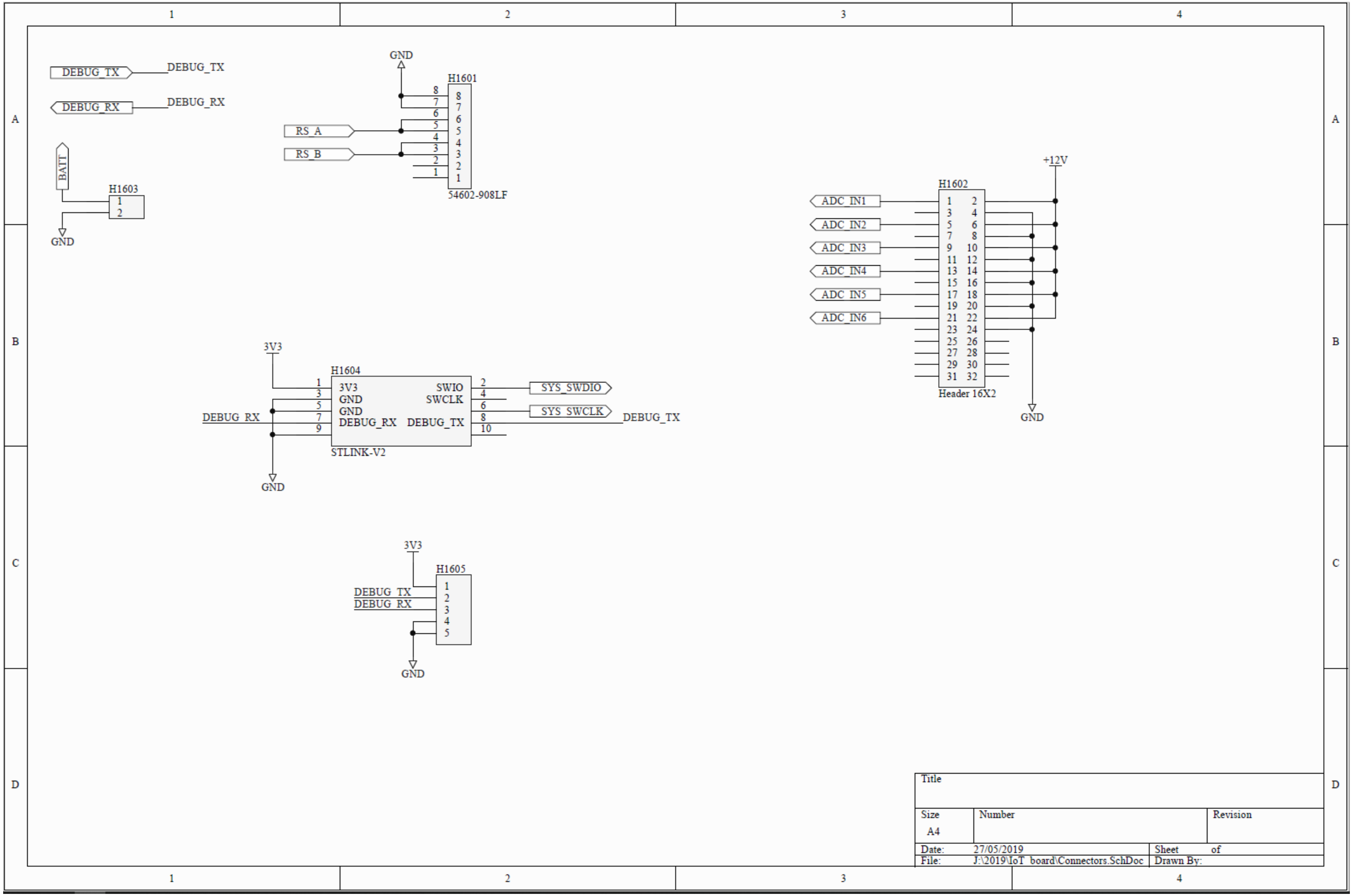

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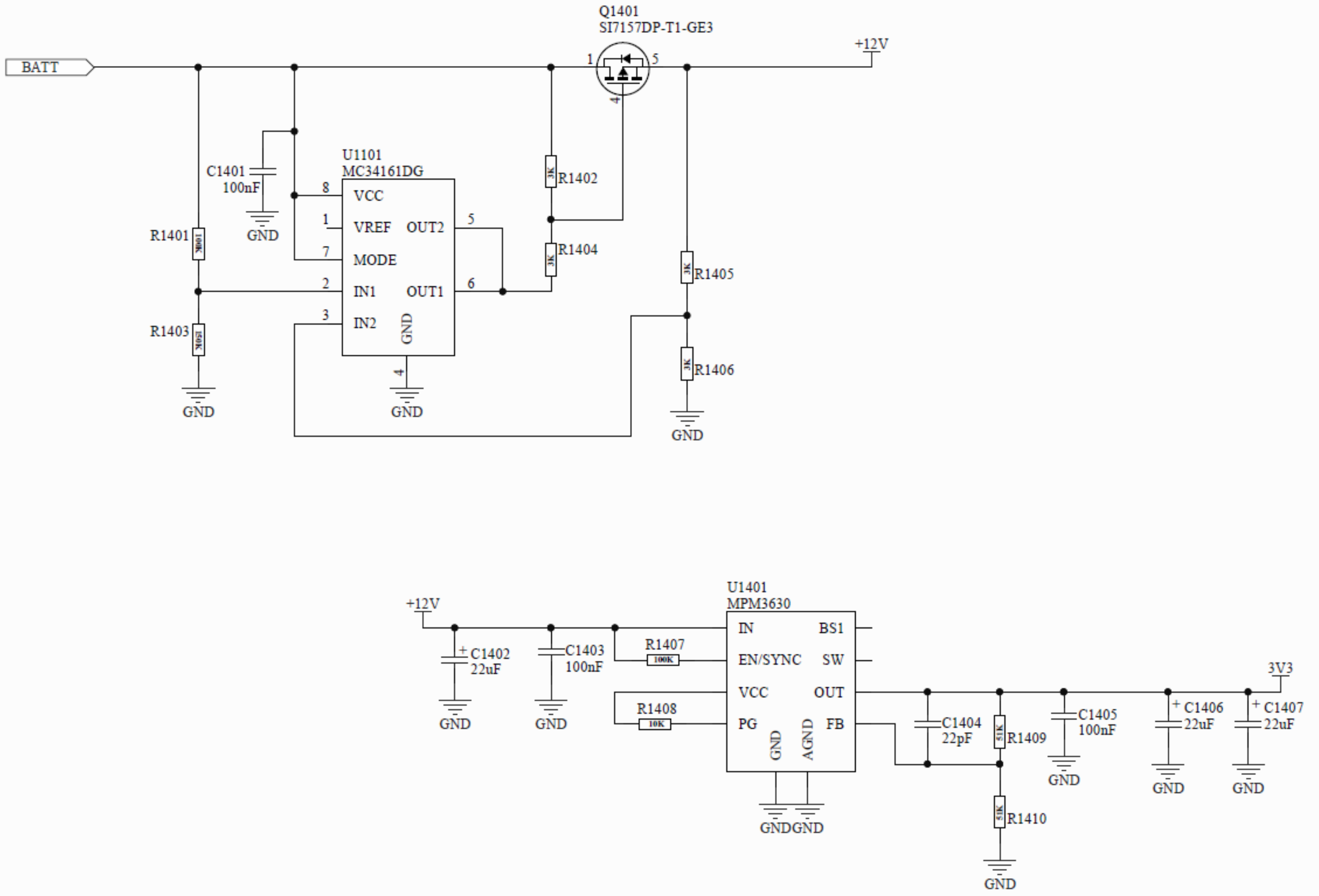

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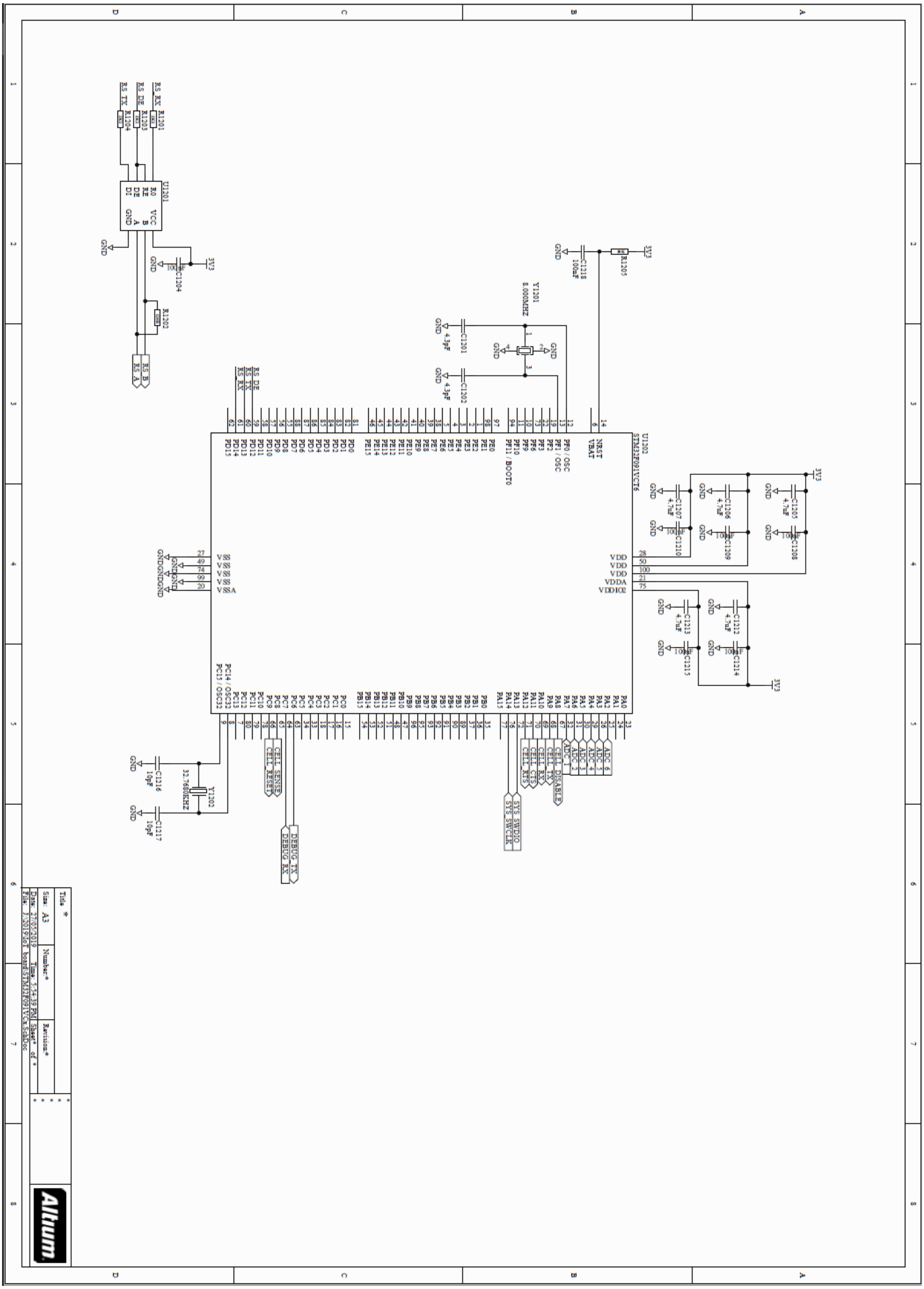

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RE
DE
DI
VCC
B
A
GND
R1201
R1202
R1203
R1204
RS_RX
RS_DE
RS_TX
RS_B
RS_A
C1204
100nF
3V3
GND
U1202
STM32F091VCT6
NRST
VBAT
PF0 / OSC
PF1 / OSC
PF11 / BOOT0
VDD
VDDA
VDDIO2
VSS
VSSA
PC14 / OSC32
PC15 / OSC32
Y1201
8.000MHZ
C1201
C1202
4.3pF
R1205
C1218
100nF
C1205
C1206
C1207
C1208
C1209
C1210
C1212
C1213
C1214
C1215
4.7uF
100nF
Y1202
32.768KHZ
C1216
C1217
10pF
CELL_SENSE
CELL_RESET
DEBUG_TX
DEBUG_RX
SYS_SWDIO
SYS_SWCLK
CELL_DISABLE
CELL_TX
CELL_RX
CELL_CTS
CELL_RTS
ADC_1
ADC_2
ADC_3
ADC_4
ADC_5
ADC_6
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Altium

Appendix B: Component IoT board component list

Index	Quantity	Part Number	Manufacturer Part Number	Description	Customer Reference	Available	Backorder	Unit Price	Extended Price NZD
1	10	712-1165-1-ND	500R07S4R3BV4T	CAP CER 4.3PF 50V C0G/NP0 0402		10	0	0.346	3.46
2	100	1276-1000-1-ND	CL10B104KB8NNNC	CAP CER 0.1UF 50V X7R 0603		100	0	0.0208	2.08
3	10	1276-1907-1-ND	CL10A475MQ8NNNC	CAP CER 4.7UF 6.3V X5R 0603		10	0	0.106	1.06
4	10	478-1163-1-ND	06035A100JAT2A	CAP CER 10PF 50V C0G/NP0 0603		10	0	0.118	1.18
5	10	490-12736-1-ND	GRM188R61C106KAALJ	CAP CER 10UF 16V X5R 0603		10	0	0.457	4.57
6	10	478-11490-1-ND	TPSA226K006R0300	CAP TANT 22UF 10% 6.3V 1206		10	0	0.543	5.43
7	10	399-3717-1-ND	T491B226M016AT	CAP TANT 22UF 20% 16V 1411		10	0	0.798	7.98
8	10	478-1167-1-ND	06035A220JAT2A	CAP CER 22PF 50V C0G/NP0 0603		10	0	0.098	0.98
9	10	399-13150-1-ND	C0603X333K5RAC7867	CAP CER 0.033UF 50V X7R 0603		10	0	0.51	5.10
10	10	BAQ333GICT-ND	BAQ333-TR	DIODE GP 40V 200MA MICROMELF		10	0	0.467	4.67
11	10	F6445CT-ND	SD24-01FTG	TVS DIODE 24V 42V SOD323		10	0	0.574	5.74
12	5	SI7157DP-T1-GE3CT-ND	SI7157DP-T1-GE3	MOSFET P-CH 20V 60A PPAK SO-8		5	0	2.99	14.95
13	10	311-2.20KHRCT-ND	RC0603FR-072K2L	RES SMD 2.2K OHM 1% 1/10W 0603		10	0	0.04	0.40
14	10	P120HCT-ND	ERJ-3EKF1200V	RES SMD 120 OHM 1% 1/10W 0603		10	0	0.11	1.10
15	10	RNCP0603FTD10K0CT-ND	RNCP0603FTD10K0	RES 10K OHM 1% 1/8W 0603		10	0	0.113	1.13
16	10	RMCF0603FT100KCT-ND	RMCF0603FT100K	RES 100K OHM 1% 1/10W 0603		10	0	0.029	0.29
17	10	P3.00KHCT-ND	ERJ-3EKF3001V	RES SMD 3K OHM 1% 1/10W 0603		10	0	0.11	1.10
18	10	P150KHCT-ND	ERJ-3EKF1503V	RES SMD 150K OHM 1% 1/10W 0603		10	0	0.11	1.10
19	10	RMCF0603FT51K0CT-ND	RMCF0603FT51K0	RES 51K OHM 1% 1/10W 0603		10	0	0.029	0.29
20	10	RMCF0603FT11K3CT-ND	RMCF0603FT11K3	RES 11.3K OHM 1% 1/10W 0603		10	0	0.029	0.29
21	10	RMCF0603FT100RCT-ND	RMCF0603FT100R	RES 100 OHM 1% 1/10W 0603		10	0	0.029	0.29
22	10	RMCF0603FT120KCT-ND	RMCF0603FT120K	RES 120K OHM 1% 1/10W 0603		10	0	0.029	0.29
23	10	RMCF0603FT30K0CT-ND	RMCF0603FT30K0	RES 30K OHM 1% 1/10W 0603		10	0	0.029	0.29
24	2	MC34161DGOS-ND	MC34161DG	IC MONITOR VOLTAGE UNIV 8SOIC		2	0	1.84	3.68
25	2	ISL83078EIBZA-TCT-ND	ISL83078EIBZA-T	IC TXRX RS422/485 20MBPS 8SOIC		2	0	3.02	6.04
26	2	497-15168-ND	STM32F091VCT6	IC MCU 32BIT 256KB FLASH 100LQFP		2	0	8.64	17.28
27	5	1589-1253-1-ND	MPM3630GQV-P	DC DC CONVERTER 0.6-18V		5	0	6.18	30.90
28	3	MCP6L04T-E/SLCT-ND	MCP6L04T-E/SL	IC OPAMP GP 4 CIRCUIT 14SOIC		3	0	0.69	2.07
29	2	535-9720-1-ND	ABM3B-8.000MHZ-B2-T	CRYSTAL 8.0000MHZ 18PF SMD		2	0	1.06	2.12
30	2	631-1002-1-ND	FK135EIHM0.032768-T3	CRYSTAL 32.7680KHZ 12.5PF SMD		2	0	1.52	3.04
									128.90

Appendix C: PPM code for testing

```
#include <Servo.h>

//Motor Positions
//2  8
//4  6
//5  1
//7  3



const uint8_t VESC_OUTPUT1 = 4;
const uint8_t VESC_OUTPUT2 = 5;
const uint8_t VESC_OUTPUT3 = 6;
const uint8_t VESC_OUTPUT4 = 7;

//const uint8_t VESC_OUTPUT5 = 5;
//const uint8_t VESC_OUTPUT6 = 6;
//const uint8_t VESC_OUTPUT7 = 7;
//const uint8_t VESC_OUTPUT8 = 8;

Servo MOTOR1;
Servo MOTOR2;
Servo MOTOR3;
Servo MOTOR4;

//Servo MOTOR5;
//Servo MOTOR6;
//Servo MOTOR7;
//Servo MOTOR8;



void setup() {
  Serial.begin(115200);
```

```
  Serial.println("START");

  MOTOR1.attach(VESC_OUTPUT1);
  MOTOR2.attach(VESC_OUTPUT2);
  MOTOR3.attach(VESC_OUTPUT3);
  MOTOR4.attach(VESC_OUTPUT4);

  //MOTOR5.attach(VESC_OUTPUT5);
  //MOTOR6.attach(VESC_OUTPUT6);
  //MOTOR7.attach(VESC_OUTPUT7);
  //MOTOR8.attach(VESC_OUTPUT8);
}

void loop(){

  if (Serial.available())
  {
    char inChar = Serial.read();

   int REVERSE = 1250; //Pulse start
   int STOP = 1500; //Pulse centre
   int FORWARD = 1800; //Pulse end

    //int REVERSE = 1100; //Pulse start
    //int STOP = 1600; //Pulse centre
    //int FORWARD = 2500; //Pulse end

    if (inChar == 'w')
    {
     MOTOR1.writeMicroseconds(FORWARD);
     MOTOR2.writeMicroseconds(FORWARD);
     MOTOR3.writeMicroseconds(FORWARD);
     MOTOR4.writeMicroseconds(FORWARD);
```

```
 delay(10000);

 MOTOR1.writeMicroseconds(STOP);
 MOTOR2.writeMicroseconds(STOP);
 MOTOR3.writeMicroseconds(STOP);
 MOTOR4.writeMicroseconds(STOP);

 Serial.println(inChar);
 Serial.println("Moving forwards: Pulse width: 1800 microSeconds");
}

if (inChar == 's')
{
 MOTOR1.writeMicroseconds(REVERSE);
 MOTOR2.writeMicroseconds(REVERSE);
 MOTOR3.writeMicroseconds(REVERSE);
 MOTOR4.writeMicroseconds(REVERSE);

 delay(2000);

 MOTOR1.writeMicroseconds(STOP);
 MOTOR2.writeMicroseconds(STOP);
 MOTOR3.writeMicroseconds(STOP);
 MOTOR4.writeMicroseconds(STOP);

 Serial.println(inChar);
 Serial.println("Moving backwards: Pulse width: 1000 microSeconds");
}

if (inChar == 'd')
{
 MOTOR1.writeMicroseconds(FORWARD);
 MOTOR2.writeMicroseconds(FORWARD);
 MOTOR3.writeMicroseconds(REVERSE);
```

```
     MOTOR4.writeMicroseconds(REVERSE);

     Serial.println(inChar);
     Serial.println("Turning left");
    }

    if (inChar == 'a')
    {
     MOTOR1.writeMicroseconds(REVERSE);
     MOTOR2.writeMicroseconds(REVERSE);
     MOTOR3.writeMicroseconds(FORWARD);
     MOTOR4.writeMicroseconds(FORWARD);

     Serial.println(inChar);
     Serial.println("Turning right");
    }

    if (inChar == 'x')
    {
     MOTOR1.writeMicroseconds(STOP);
     MOTOR2.writeMicroseconds(STOP);
     MOTOR3.writeMicroseconds(STOP);
     MOTOR4.writeMicroseconds(STOP);

     Serial.println(inChar);
     Serial.println("Stopping: Pulse width: 1500 microSeconds");
    }
  }
}
```