DESIGN OF A LIGHTWEIGHT, MODULAR ROBOTIC VEHICLE FOR THE SUSTAINABLE INTENSIFICATION OF BROADACRE AGRICULTURE

Owen John Bawden

Bachelor of Industrial Design (Hons)

Supervisors

Dr David Ball, Prof. Tristan Perez, Prof. Peter Corke.

Submitted in fulfilment of the requirements for the degree of

BN72 - Master of Engineering (Research)

School of Electrical Engineering and Computer Science

Science and Engineering Faculty

Queensland University of Technology

June 2015

Keywords

Agriculture, Agricultural Robotics, Broadacre Farming, Integrated Weed Management, Lightweight Vehicle Design, Robotic Vehicles, Future Farming Systems, Precision Agriculture, Industrial Design, Engineering, User Centred Design.

Abstract

This thesis presents the design process and the prototyping of a lightweight, modular robotic vehicle for the sustainable intensification of broadacre agriculture. The latter is to be achieved by the joint operation of multiple autonomous vehicles that can improve energy consumption, reduce labour, and increase efficiency in the application of inputs for the management of crops.

The introduction of robotics in agriculture can be seen as a revolutionary step away from the current direction in farming of increasingly large machines designed to optimise an individual farmer's productivity. Larger machines cause severe subsoil compaction issues and greater machinery complexity resulting in longer disruptions from single vehicle failure. In addition, Australian farmers are facing increasing levels of herbicide resistance in weeds, a problem costing 4 billion dollars a year. Losses are occurring in production efficiency because large farm machinery can no longer mitigate weeds using current management modalities. The field of agricultural robotics is responding to these challenges by developing robots that can operate with greater effectiveness, for longer hours and at less cost than traditional farm machinery and labour.

The Small Robotic Farm Vehicle (SRFV) is a lightweight and energy efficient robotic vehicle with a configurable, modular design, which enables interchangeable implement units to span between the modular side units. The SRFV is capable of undertaking a range of agricultural tasks, including seeding, fertilising and weed management through mechanical intervention and precision spraying. The robot is designed to be more than an order of magnitude lower in weight than existing broadacre agricultural equipment.

The vehicle is based on a four wheel configuration, capable of bi-directional driving through the use of differential steering wheels and caster wheels. Travelling at a maximum speed of 10km/hr, the vehicle is driven by two 5kW electric in-hub motors powered by Lithium Iron Phosphate ($LiFePO_4$) batteries. The prototype vehicle has been developed using the latest rapid manufacture technologies and incorporates aesthetic features unique to agricultural robotics.

Incorporating aspects of engineering and industrial design practices, this project uses a user-centred design model, weaving human factors into technical problem solving. This approach to innovation draws from the designers and engineer's toolkit to integrate the needs of people, the possibilities of technology, and the requirements for business success. This thesis presents a design methodology suitable for autonomous farm vehicles and applies it to the design and prototyping of the SRFV.

The images below depict the completed SRFV prototype.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Definition
QUT	Queensland University of Technology
DAFF	Department of Agriculture Forestry and Fisheries
SIFR	Strategic Investment in Farm Robotics
ACRV	Australian Centre for Robotic Vision
SRFV	Small Robotic Farming Vehicle
CTF	Control Traffic Farming
VRT	Variable Rate Technology
HMI	Human Machine Interface
GUI	Graphical User Interface
FEA	Finite Element Analysis
PA	Precision Agriculture
GPS	Global Positioning Systems
GNSS	Global Navigation Satellite Systems
GNC	Guidance, Navigation and Control

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

QUT Verified Signature

Signature:

Date: 15th June 2015

Acknowledgements

I wish to thank my supervisors Dr David Ball, Prof. Tristan Perez and Prof. Peter Corke for their encouragement, advice, feedback and support throughout this project.

My warmest gratitude to my wonderful partner Jowita for your love and support.

Thank you to the Agricultural Robotics team to QUT including Ass. Professor Ben Upcroft, Dr Jason Kulk, Andrew English and Patrick Ross for your enthusiasm, inspiration and friendship.

My sincerest thank you to Ray Russell for your mentorship, energy and assistance in hitting the deadlines and achieving the high standards we set ourselves in this project.

I am indebted to all the team at the ARC Centre of Excellence for Robotic Vision for your hard work and generosity.

Special acknowledgement to Andrew Bate at Swarm Farm, John Cameron at ICAN Rural and all the farmers in the Darling Downs area who have contributed to the project through your farming knowledge, insight and experience.

I am also grateful to all the component suppliers for your professionalism and expertise, without whom the project would not have happened; QUT Manufacturing Workshop, QUT J Block Workshop, Acute Laser, FEI Best – China, Rapid Concept Design, Langford's, GP Stainless, Hartman ATV, White Horse Industries, Golden Motor, Tyres for Bikes, Bolts and Industrial Supplies and McMaster-Carr.

Financial Support

This research has been supported by funding from the Strategic Investment in Farm Robotics (SIFR) grant, through the Queensland Government Department of Agriculture, Fisheries and Forestry (DAFF).

Chapter 1: Introduction

1.1 BACKGROUND

To sustain higher population levels estimated to reach 9.1 billion people by 2050, the United Nations predicts that global food production will need to increase by 70% [1]. This far greater supply of food will need to be produced to feed the demand of a larger, more urban and wealthy population [2].

Over the past century, agricultural productivity growth has been achieved through farm consolidation leading to greater economies of scale, increased mechanisation, crop improvements through accelerated breeding and genetic modification, as well as through the application of inputs including herbicide, fertilizer and water. As countries have shifted to broadacre farming to increase food production [1], crops and landscapes that were once tended by humans are now tended almost entirely by machines through large scale mechanical and chemical interventions.

Increasingly larger vehicles combined with precision guidance systems have been designed and used to improve production on broadacre farms [3]. The benefits have been greater productivity and reduced labour cost per hectare and an economical platform for the latest technological developments. However, this trend has resulted in new problems for farmers. As vehicle size has increased so have the detrimental effect of soil compaction through the ground pressure of these vehicles [4], while increased engineering complexity of the vehicle has resulted in disruptions due to single machine failures.

Within Australia a high proportion of broadacre farmers now use zero-till agricultural practices to limit soil disturbance resulting in reduced erosion, permanent ground cover leading to greater moisture retention, reduced input costs and reduced soil compaction [5]. However, the nature of the practice requires greater use of herbicides to mitigate weeds and this has led to increased herbicide resistance in weeds costing Australian agriculture around $4 billion dollars a year [6].

The field of agricultural robotics is responding to the challenges in the agricultural sector by developing robots that can operate with greater effectiveness, for longer hours and at less cost than traditional farm machinery and labour. So far, robots have been slow in their translation to farming because of the unstructured environment of biological production processes and the inherent variability of biological systems [7]. In addition to this, the cost of mechanical technology, limited capacity and potential legal risks [8] are but a few of the challenges to be overcome.

Agricultural robots will work safely alongside humans across a broad range of environments to help improve agricultural efficiencies and boost crop yields [9], with benefits including reduced crop wastage, pesticide usage and energy consumption. By successfully overcoming the challenges in these areas and creating an integrated, coherent system, agricultural robotics will change entirely how food is farmed.

Presently at QUT, as part of the ARC Linkage grant project in collaboration with Swarm Farm Robotics (Swarmfarm.com) entitled *Robotics for Zero Tillage Agriculture*, a John Deere 'Gator' utility vehicle has been outfitted with a range of components for testing. This has been useful for early experimentation work however the impetus as the project moves forward to the next stage of long term field trials is to have a dedicated robotic vehicle capable of undertaking a range of tasks and on which developing technology can be tested and validated.

This research project falls under the umbrella of the ARC Centre of Excellence for Robotic Vision (roboticvision.org) and is being supported by the Queensland Government through a Department of Agriculture, Fisheries and Forestry (DAFF) grant. The Strategic Investment in Farm Robotics (SIFR) is a three-year program to fast track robotic technology aiming to improve agricultural productivity and sustainability. One of the key themes of this program concerns with the development of autonomous vehicles for agriculture (see SIFR Vision). The vehicles will enable the undertaking a range of agricultural task, with a focus on weed mitigation through mechanical intervention and precise spraying.

This thesis presents the design and engineering of the first prototype vehicle developed as part of SIFR. The Small Robotic Farm Vehicle (SRFV) will form part of a larger suite of innovations that includes implement, sensor, navigation and obstacle avoidance systems. The SRFV is a lightweight and energy efficient robotic vehicle with a configurable, modular design, enabling interchangeable implement units to span between the modular side units. This modular design allows the SRFV to undertake a range of agricultural tasks and experiments, including seeding, fertilising and weed management. The robot is designed to be more than an order of magnitude lower in weight than existing broadacre agricultural equipment. Utilised as a system, coordinated fleets of SRFV's present solutions to the issues of soil compaction, single machine failure and weed resistance and offer the return to individualised plant care without the high labour cost.

1.2 PROJECT OVERVIEW

1.2.1 Objectives

1. Research, specify and design an autonomous vehicle suitable for a range of agricultural tasks (weeding, spraying, crop scouting, seeding).
2. Engineer, prototype and fabricate one vehicle.

1.2.2 Scope

- Research the field of agriculture and food production, looking at current and future issues. The focus will be predominantly on Australian broadacre farming.
- Review the state of the art in agricultural robotic vehicles. What has been tried, what technologies and techniques have been employed, what has become commercially available.
- Engage in insight research at key farm locations, using observational studies and contextual interviews.
- Detail the requirements for an autonomous vehicle suitable for broadacre farming.
- Develop conceptual designs of an autonomous vehicle suitable for broadacre farming. Integrate the key areas of locomotion, steering, chassis design, motors and power supply, electronics, human-machine interface (HMI) and recharging/re-fuelling.
- Create prototypes for testing and evaluating the vehicle configurations for stability, manoeuvrability, transportability and tipping. Undertake kinematic analysis of the vehicle configurations.
- Select an appropriate vehicle concept for detailed design and engineering.
- Undertake detailed design and engineering development of the selected concept for the purposes of building a prototype vehicle.
- Fabricate a prototype vehicle.

1.3 PROJECT BENEFITS

Introducing robotics into agriculture is seen as a revolutionary step away from the current direction of improved productivity through greater precision on ever larger machines. Moving away from larger agricultural machines towards fleets of smaller autonomous vehicles is a paradigm shift in agriculture seen as having the following benefits:

- Lighter impact on the environment, reducing occurrence of soil compaction.
- Multi-purpose vehicle for weed mitigation, crop scouting, seeding, fertilizing and harvesting.
- More manoeuvrable vehicle, reducing the amount of unused land.
- Scalable, allowing farmers to utilise robots on farms of all sizes.
- No single point of failure (multi-robot redundancy).
- Improve yields on existing land whilst allowing for the economical cultivation of marginal land.
- Lower vehicle and implement stresses, reducing the complexity of the engineering and the overall cost.
- Variable rate application of inputs for weed mitigation.
- Reduced expenditure on chemicals - greater environmental protection.
- Multi-mode weed management (chemical, mechanical, electrical-thermal) - reduced pressure for herbicide resistance in weeds.
- Smaller, more precise implements, capable of targeted operations.
- Long endurance throughout the diurnal cycle (Day/Night).
- Reduced labour demands.
- Reduced energy consumption per hectare - reduced fuel costs.
- Better understanding of soil – crop requirements.

1.4 PROJECT STAKEHOLDERS

Project stakeholders are individuals and organizations that are actively involved in the project, or whose interests may be affected as a result of project execution or completion. They also exert influence over the project's objectives and outcomes [10].

Figure 1 illustrates the key stakeholders linked to this project.

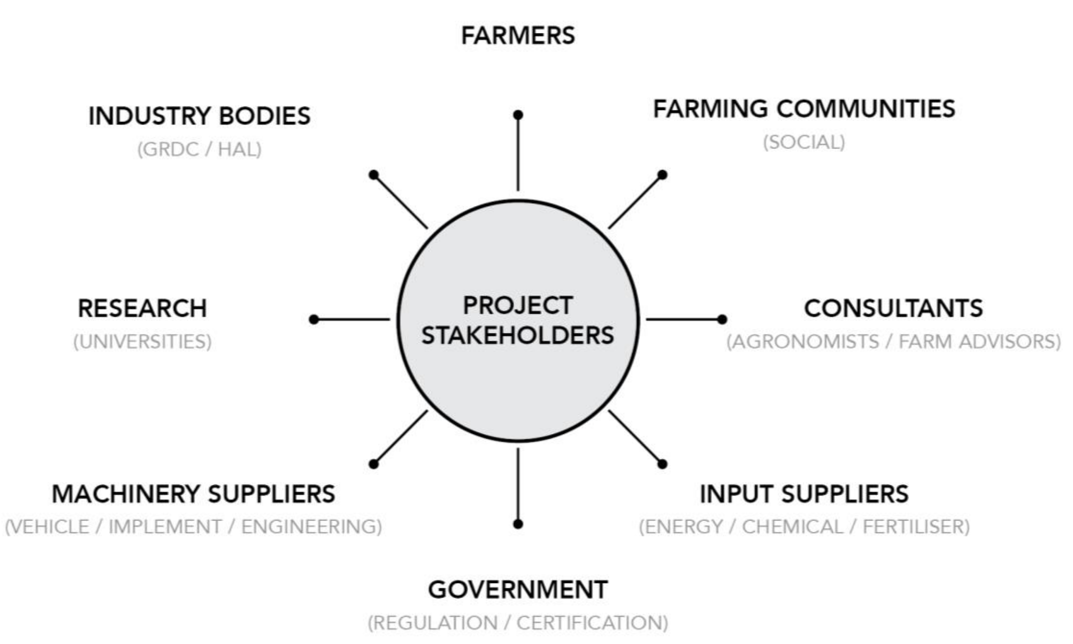


Figure 1. Key project stakeholders.

1.5 PROJECT METHODOLOGY

Incorporating aspects of engineering and industrial design practices, this project uses a user-centred design (UCD) model [11], weaving human factors into technical problem solving. This approach to innovation draws from the designers and engineer’s toolkit to integrate the needs of people, the possibilities of technology, and the requirements for business success. The role of industrial design is to address the entire experience of the product, including the use, attitudes, perception, and emotion, ideological and social aspects, which contribute to product success.

User-centred design is a process in which the needs, wants and limitations of end users of a product or service are given extensive attention at each phase of the design process.

User-centred design is a multi-phase problem solving process that requires designers to analyse and foresee how users are likely to interact with a product, and then evaluate the validity of their assumptions with regard to user behaviour in real world tests with actual users. The result of this process is a high level of usability, with the emerging designs intersecting the areas of feasibility, viability and desirability. The process can be applied to all design practices that have the aim to provide a good user experience

The ISO standard for human-centred design for interactive systems (ISO 9241-210, 2010) describes 6 key principles that will ensure a design is user-centred:

- The design is based upon an explicit understanding of users, tasks and environments.
- Users are involved throughout design and development.
- The design is driven and refined by user-centred evaluation.
- The process is iterative.
- The design addresses the whole user experience.
- The design team includes multidisciplinary skills and perspectives.

The focus of the work undertaken for this thesis has been developed across four keys phases. In the section below each phase has an explanation outlining the actual tasks completed. The four phases are:

- Research
- Conceptual Design
- Requirements and Specifications
- Detailed Design and Engineering

Research phase

The research phase is generative and used to inspire imagination and inform intuition about new opportunities and ideas. Initial research looked at the major agricultural areas and crop varieties grown in Australia. Information was gathered on current farming practices and technologies. A detailed review was conducted on agricultural robotics, looking at the areas of modelling, learning and decision making, sensing and perception, systems and architecture, vehicle design and engineering along with human-machine interaction and usability. Key project stakeholders were defined.

Qualitative research methods developed understanding of the requirements of specific farms and crops within the agricultural industry. Insight research was undertaken on farms in Queensland and involved observational studies in conjunction with contextual interviews. An understanding of opportunities was developed through farmer experience mapping and product lifecycle mapping. Key project parameters were established to explore during the conceptual design phase.

Conceptual Design phase

The conceptual design phase involves diverging concepts around the key project parameters. Aggregating, editing and condensing what was learnt in the research phase established new perspectives and identified opportunities for innovation. Brainstorming was used to think expansively and without constraints. The generation of impractical solutions often sparks ideas that are relevant and reasonable!

Core themes were refined and system concepts explored. Proof of Principle (POP) prototyping was used to quickly test and gather information on particular components and assemblies. Trials of scale models were conducted to review stability, traction, manoeuvrability, suspension and implement placement options. Concept sketching and simple CAD renderings were used to communicate ideas. A portfolio of innovation opportunities was created.

Requirements and Specification phase

This phase involved converging ideas and developing specific system requirements and vehicle specifications. A delivery strategy was developed for the detailed design and engineering phase.

Detailed Design and Engineering phase

This phase involves clearly integrating into the design; functionality, desirability, identity and purpose. Concurrent engineering was used to identify and solved problems as early as possible in the design process. This reduced costs as problems were more easily and cheaply solved early in the design process.

The development of the vehicle assemblies and sub-assemblies were planned, developed, prototyped and refined. Iterative prototyping and testing is used, as well as finite element analysis to review components. Human factors such as anthropometrics and ergonomics were considered.

Figure 2 below outlines the four phases of the UCD process.

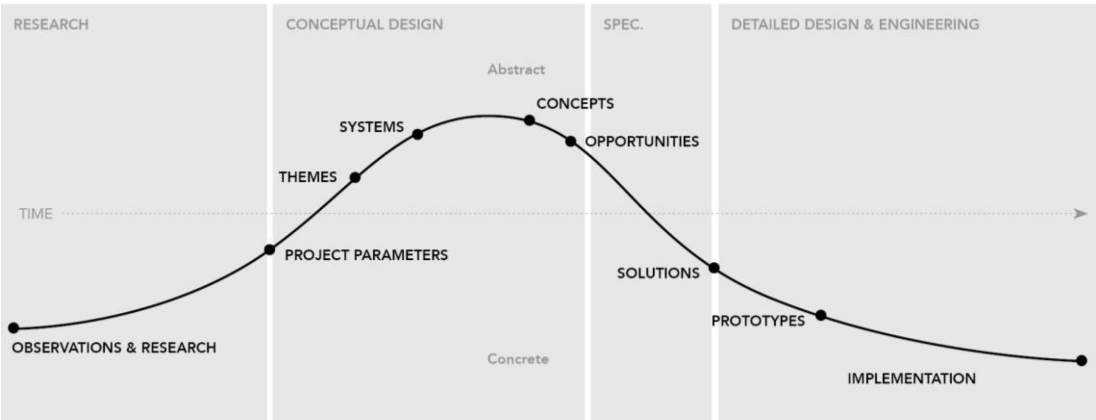


Figure 2. The UCD process includes four phases of research, conceptual design, requirements and specifications and detailed design and engineering. Concepts progress through the vertical axis from “Concrete” to “Abstract” as the project develops. Concrete refers to observation about users, tangible solutions and prototypes while Abstract refers to uncovering insights, identifying themes and opportunities.

Continuation

The next phase of the project will involve the Verification and Validation of the work undertaken throughout these first four stages.

Workshop trials followed by field trials of the robotic vehicle will be conducted at farms in Queensland and potential other states. Integration of implements for agricultural tasks along with stakeholder input will lead to iterative design changes as will testing of the overall system.

Chapter 2: Research

2.1 LITERATURE REVIEW

2.1.1 Overview

By 2050 the UN predicts that global food production will need to increase by over 70% to sustain higher population levels, estimated to reach 9.1 billion people [1]. Increases in demand for food from both new and traditional sources will put growing pressure on agricultural resources. Strong competition for land and water will come from housing, industry and the preservation of natural habitats for maintaining biodiversity.

As the population grows and the wealth of people rise, the demand for more varied collections of food will increase. Most notable will be the move to high protein diets [13]. This will have a greater impact on the environment. The challenge is how to produce more and impact on the environment less. To feed the increasing number of people on earth we need to think about an agriculture that develops in a way that doesn't significantly increase greenhouse gas production as it increases its own production [14].

The results of current trends in farming practices will not enable farmers to meet the demand for future food production without severely detrimental environmental effects. For production increases to occur farmers must either increase production efficiencies per hectare or per unit of key inputs such as fertilizer and water [7].

Australia faces many challenges to ensure its agricultural production is sustainable and competitive. Competitive global markets make it difficult for Australia to supply the lowest–cost agricultural commodities. Additionally diminishing availability and increasing cost of water, and an ageing workforce where the median age of farmers is 54 [15] and a decline in the younger generations taking over family farms are but a few of the issues.

The agricultural industry is in transition, and that transition differs from country to country, state to state and region to region. The general trend is towards greater precision agriculture supplement by advanced technologies including robotics

[16]. Many farmers, particularly in Australia are already running high tech, digitally–controlled farm vehicles and implements. Yield mapping, soil sensors and aerial profiling are feeding back into farm control software to enhance their operations. This is in conjunction with GPS guided auto-steer systems that maintain vehicle traffic.

Whenever technology meets nature, considerable technical and non-technical challenges have to be solved. As robots begin working outdoors in complex and challenging environments they will face field conditions, such as light, wind, temperature and dust. Most robotic agricultural vehicles developed until now have been focused on requirements for research. The challenge for the future will be developing lightweight robust vehicles that meet the needs of the users.

In a recent market report, Wintergreen Research estimates that the size of the agricultural robotics market in 2013 was $817 million and is anticipated to reach $16.3 billion by 2020 [17], a hefty growth for a nascent market. Regardless of the size of the growth the availability of simple yet robust vehicles will be an important next step for agricultural robotics because of the complexity involved in the agricultural tasks themselves. The implementation of additional mechatronic systems like weeding or seeding will only increase the complexity of the system due to technical and logistical challenges and influence the probability for developmental success in the prototype stage.

The following section in the literature review will explore the key challenges faced by Australian farmers over the next 20-40 years and continue by reporting on a selection of robotic vehicles and technologies being researched and commercialised around the world, with a focus on agricultural technology.

2.1.2 Australian Agricultural Challenges

Agriculture has been a major contributor to the Australian economy since the start of European Settlement. In the first half of the 20th century, agriculture accounted for around a quarter of the nation's output and up to 80% of Australia's exports. In recent decades, the growth of other industries, including a thriving services sector, has seen a relative decline in Australia's reliance on agriculture. While this is consistent with trends in other developed countries, Australia's agricultural output as a proportion of the economy is among the highest in the OECD [15].

Within Australia the proportion of grain growers using zero-till agricultural practices has grown to 90% in many areas [5]. Zero-tillage is widely regarded as best practice in Australian broadacre farming. For farmers the fundamental benefits of zero-till agriculture have been limited soil disturbance resulting in reduced erosion, permanent ground cover leading to greater moisture retention, reduced fuel costs and reduced soil compaction [5]. However the nature of the practice requires greater use of herbicides to mitigate weeds and this has led to increased herbicide resistance in weeds in many areas of the country [18].

Weeds cost Australian agriculture around $4 billion dollars a year [6]. Since the 1990's, with the introduction of glyphosate herbicides such as Roundup and their tremendous effectiveness, there has been a decrease in the investment in new technologies for weed mitigation. No major new site-of-action herbicide has been introduced into the marketplace in the last 20 years [19]. With the option to control weed successfully with herbicide alone rapidly running out, there needs to be a change to the way weed control is undertaken.

Farmers are using more herbicide with less effect [20]. As a result the cost of weed control has increased dramatically. It is estimated in Australia that herbicide resistance is currently costing $200 million annually and rising [18]. Costs are much higher in the United States and other countries. Losses are occurring in production efficiency because farmers are now forced to spray resistant weeds multiple times or use tillage to remove weeds which effect the conservation of topsoil nutrients and moisture protected through zero-tillage agricultural practices [21].

Increased agricultural production depends upon vehicle traffic. Modern production practices require tractors and combines to plant, manage and harvest agricultural crops. However, as vehicles have become progressively heavier over time (as illustrated in Figure 3), they have increased their damage to the soil. Soil compaction has many detrimental effects on soil properties important to soil workability [4]. This includes poor drainage, which can lead to increased surface runoff and top-soil erosion, occurring by impeding water infiltration. Farmers must often balance the desire to tend crops, particularly after periods of rain when weed growth is most intense [18], with the ramifications of soil compaction from heavy vehicles.

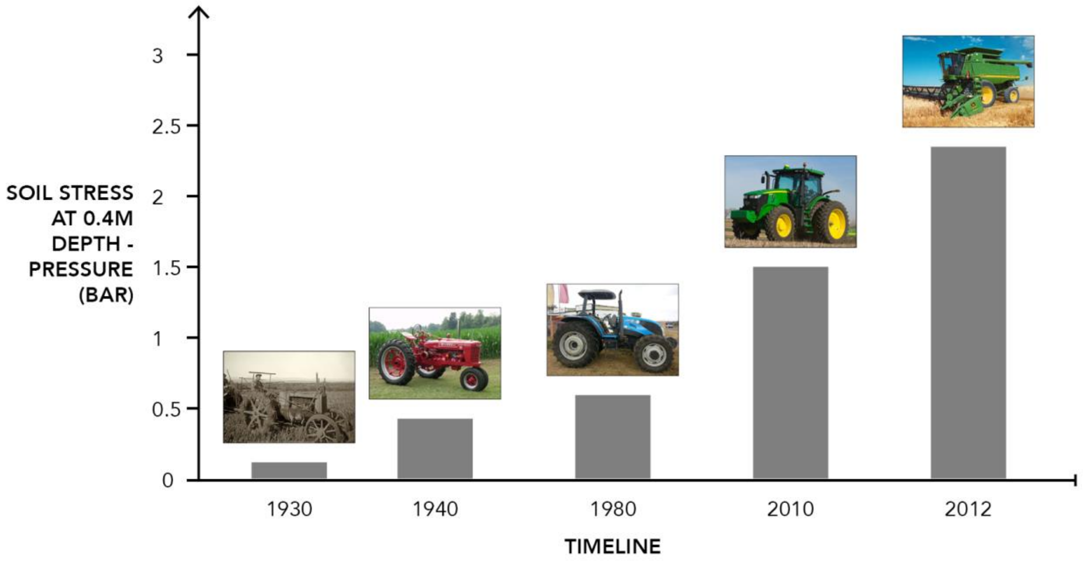


Figure 3. Historical increase of subsoil stress with increasing weight of farm machinery in Europe; conservative in comparison to the effects on Australian dryland farming soils [22] [23].

Soil compaction due to heavy farming equipment has a direct impact on the gross yield of crops. Farmers can deter soil compaction by reducing axle loads, reducing tractive element-to-soil contact stress by using high floatation tyres or steel or rubber belted tracks on vehicles, increasing soil drying prior to traffic, incorporating reduced tillage or no tillage farming methods or by using controlled traffic, wide span vehicles .

Other challenges in Australian agriculture include an aging workforce. Not only is the agricultural workforce older than the workforce in general, but the average age of farmers has increased significantly over the past three decades. The average age has risen from 44 in 1981 to the current average age of 54. Factors contributing to this trend include fewer young people entering farming, and low exit rates at traditional retirement age.

The next section will review research undertaken into Agricultural robotics and vehicle design and expanded on some of the technologies involved in these systems.

2.1.3 Research into Agricultural Robotic Vehicles

Vehicle design has been extensively researched and developed since 1886 with the design of the first automobile by Karl Benz. The work of Bekker [24, 25] and Wong [26, 27] into vehicle mobility, off-road locomotion and terramechanics has been well referenced in the design of specialist vehicles and has influence the development of many robotics platforms including the Mars rover. Through this work and the work of many other researchers including Apostolopoulos [28] who focused his research on the analytical configuration of wheeled robotic vehicles, a great body of knowledge exists in the area of vehicle design, much of it applicable to robotic farm vehicles.

The work of Madsen & Jakobsen [29], Astrand et al. [30] Jensen et al. [31] and Bakker et al. [32], among others, have described the design of autonomous agricultural vehicles, predominantly for experimental robotic weeding. Their design approach to the considerations of traction, steering, dimensions, power-supply and control architecture has varied.

In 2001, Madsen & Jakobsen [29], developed an experimental four wheel drive (4WD) four wheel steering (4WS) platform, incorporating in-hub motors for the purpose of testing software and navigation systems and different steeling strategies. This battery powered vehicle could operate for 2-4 hours, and has been designed for driving in-crop by including 500mm of ground clearance and a narrow wheel and transmission setup.

Astrand et al. [30] designed a small (0.7m x 1.2m) mobile robot limited to the task of weed control in sugar beet fields (a crop grown widely in Europe for sugar production). Developed as purely an experimental platform, the mobile robot incorporated weed identification and row tracking systems. Two wheel drive (2WD), two wheel steering (2WS) (Ackermann) was used. The vehicle was powered by batteries for indoor use and a petrol generator for field trials. The systems utilised a mechanical weeding tool which consisted of a spinning wheel that is rotated perpendicular to the crop row. The tool only processes the area between the crops in the crop row.

Jensen et al. [31], created a mobile implement carrier incorporating track modules mounted on the side of an exchangeable implement. This system allow for the adjustment of height and width of the vehicle. Their argument for using tracks as opposed to wheels was to reduce complexity (compared 4WD, 4WS vehicles) while still allowing for flexible steering (turning the vehicle about its geometric centre), though it was acknowledge that track systems were harder on the soil. Power was supplied to the vehicle from the implement unit.

Bakker et al. [32], designed an autonomous platform using a systematic design method that consists of development stages at different levels of abstraction. The stages in order were: problem definition, alternative definition and forming. The objective of their vehicle was targeting mechanical weed removal from organic sugar beet fields. A 4WD, 4WS hydraulic system is employed powered by a 31kW diesel engine. The 1.5m wide by 2.5m long platform weights 1250kg and is capable of driving up to 6.5km/hr in 4WD mode and 13km/hr when switched to 2WD for moving the robot between fields.

The majority of robotic agricultural platforms designed until now have been 4 wheeled vehicles with either 2 or 4 wheel steering. These include the Hortibot [33] and Weedy Robot [34] (depicted in Figure 4), BoniRob [35], Zeus [36], Skinny Boy [37] and the Mobile Robot [30]. The Omnirota [38], designed by the University of Southern Denmark (USD) is the only 3 wheeled agricultural robot studied.

Figure 4. Hortibot [33] and Weedy Robot [34]. Image copyright resides with the cited authors.

Of all the robotic vehicle designs reviewed only the Armadillo [31] and Spirit Tractor [39] (depicted in Figure 5), utilised track systems.

In the case of the Armadillo, tracks were chosen for manoeuvrability over soil disturbance and were seen as a simple and reliable solution. Each track module includes a motor controller, electric motor and transmission and is controlled by a robot computer integrated into the implement section of the vehicle. Shielding the powertrain on the track system from dirt and mud was a noted issue during development.

The Sprit Tractor developed by Autonomous Tractor Corp. uses diesel-electric generators to power the electric wheel motors that drive the track-over-wheel system. Developed as a modular tractor, the vehicle can be configured with up to three 200hp modular power generators or combinations of implements and generators. A variation of the vehicle is being developed for mowing applications.

Figure 5. Armadillo [31] and Spirit Tractor [39]. Image copyright resides with the cited authors.

When designing robots for agriculture, determining the power requirements for the vehicle is an important consideration of the design process. A vehicle carrying an implement for soil cultivation tasks such as mechanical hoeing will require more power than a robot selectively spraying herbicide. In the case of the Armadillo [31], power for the track modules are supplied by the implement as well. This allows the use of various power sources such as battery packs or an electrical generator depending upon the requirements of the implement. On several of the vehicles reviewed including the Mobile Robot [30], and the BoniRob [35], the vehicle was powered by batteries for indoor testing and by an internal combustion driven generator for field tests.

While agricultural robots have been in development for many years the path to commercialisation for many vehicles has been slow. In 2013 a modified version of the Armadillo [31] named the Vibro Crop Robotti [40] was commercialised by Kongskilde Industries and Conpleks Innovation. Shown below in the left image of Figure 6, the track driven Robotti is a tool carrying platform, allowing different forms of working implements to be attached between the side units. Currently implements for mechanical weed control, precision seeding, and mechanical crop row cleaning are available.

Figure 6. Robotti [40] and BoniRob [35]. Image copyright resides with the cited authors.

Developed primarily for plant phenotyping (crop scouting) experiments, the Amazone BoniRob [35] (Right image in Figure 6) has recently been licenced by Bosch (one of the project industry partners) and is being developed for commercialisation as a research platform to universities and other organisations. The vehicle design incorporates individual wheel drives, adjustable ground clearance (40-80cm) and track widths (75-200cm). The vehicle is either powered by either batteries or a petrol generator for field trials.

Additionally, the Clearpath Robotics Grizzly [41] (Figure 7) robotic utility vehicle is also being promoted as an agricultural robotics platform for use like a small tractor. The Grizzly uses lead acid batteries to power motors producing 58kW peak power; it has a max speed of 19km/hr, max. payload of 600kg and using an all-electric system has a runtime of 12hrs.

Figure 7. Clearpath Robotics Grizzly [41] and the Harvest Automation HV-100 [42]. Image copyright resides with the cited authors.

Operating in a more controlled setting is the Harvest Automation HV-100 [42] (Figure 7), which is used predominantly for spacing, collecting and consolidating potted trees and shrubs in plant nurseries. It utilises a swappable rechargeable battery that can operate for 4-6 hrs.

Another vehicle that is currently undergoing field trials and is close to commercialisation is the Rowbot [43]. Represented in Figure 8, this is a self-driving multi-use vehicle that travels between corn rows - often under the leaf canopy - to apply nitrogen fertilizer and to seed cover crops. It can also collect sensor data to inform both current and future work. GPS and sensors are used for navigation.

In the area of modifying existing tractors to be fully autonomous, Kinze Manufacturing are developing the world's first autonomous row crop solution [44]. The tractor and grain cart developed for corn and soybean cropping functions to autonomously garner row crop grains from combine machines and transport these out of the field to the collection area (shown below in Figure 8). The Kinze system marries off-the-shelf components, including GPS, radar, laser sensors and video cameras, with custom software for obstacle detection. It was developed in partnership with Jaybridge Robotics.

Figure 8. Rowbot [43] and Kinze autonomous grain cart [44]. Image copyright resides with the cited authors.

The design of agricultural robotic vehicles has looked to incorporate technology from many other industrial sectors, including car and motorcycle manufacturing, where significant research has gone into developing chassis incorporating stronger and lighter materials [7]. This will enable the manufacture of lightweight agricultural vehicles, helping to achieve a key goal of reduced soil compaction. In the area of lightweight, solar powered vehicles, the ecoRobotix concept field robot [45] (shown in Figure 9) is a vehicle for inter/intra row weeding which utilises a delta-arm implement manipulator. The delta-arm consists of three arms connected to the universal joints at the base. They use parallelograms in the arms, which maintain the orientation of the end effector. This design was developed to manipulate light and small objects at a very high speed. In the case of the ecoRobotix concept vehicle a rotating blade is used to dig small weeds out of the ground.

Under development recently by the Australian Centre for Field Robotics (ACFR), the Ladybird [46] is an omni-directional platform developed for the horticultural industry (see Figure 9 below). It is solar electric powered and utilises a variety of sensors and a manipulator arm for undertaking a range of tasks including weed mitigation and plant phenotyping.

Figure 9. ecoRobotix [45] and ACFR Ladybird [46]. Image copyright resides with the cited authors.

2.2 MARKET ANALYSIS

Many opportunities for robotics exist within agriculture, horticulture and viniculture markets. Focusing on the farming cycle for broadacre agriculture, the image below outlines the four key stages of the farming cycle and associated activities that could be influenced by robotics in the coming decades.

Weed mitigation has been selected as one of the first tasks for agricultural robotics because of the high cost and environmental impact associated with it. In Australia it's estimated that the agricultural cost of weeds is in the vicinity of $4 billion per annum [6].

In the area of broadacre herbicide spraying, competitive products include existing technologies such as dedicated high clearance self-propelled spray rigs and tow behind tractor spray rigs. Vehicles of this nature can cost upwards of $350,000. For much smaller scale applications, four wheel drive and quad bike mounted spray rigs are used. A spray system of this nature (without the vehicle) can cost up to $5000 or more.

Crop spraying from the air using fixed wing aircraft and helicopters is less commonly used. Small helicopters (Yamaha RMAX) have been used successfully in Japan for some time and are currently being trialled in Australia.

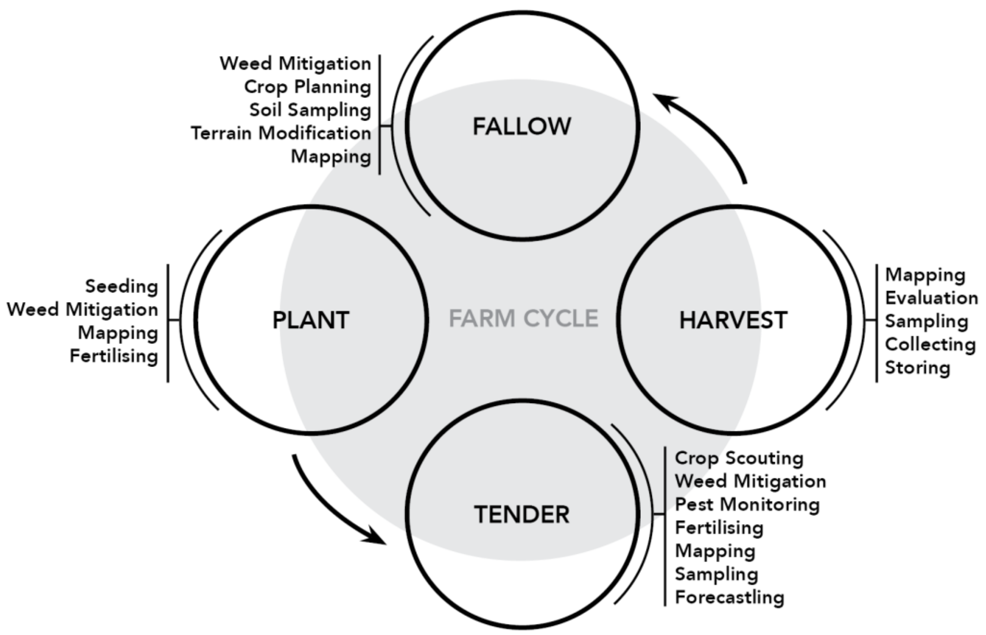


Figure 10. Opportunities for robotics in the farm cycle.

Spray vehicles are also being fitted with precision detection and spraying technology such as the WeedSeeker and WeedIT systems that detect light reflected from green plants, analyse it and trigger a spray nozzle to spray the area. Used primarily in fallow periods for weed mitigation, this technology can reduce herbicide usage by up to 90%.

There are many products for the mechanical destruction of weeds, with the most common being tilling undertaken with a tractor rig pulling tines or disks through the soil. These are used infrequently in zero-till broadacre farming to avoid soil disturbance.

As shown previously, there are very few autonomous robotic vehicles for weed mitigation actually on the market. However the opportunities in this sector are enormous. The next section will look at the economic benefits of introducing robotics in broadacre agriculture looking specifically at the task of weed mitigation.

Economic Benefit of Robotics for Weed Mitigation

An earlier Milestone (Milestone 3, Objective 3) for the SIFR program was the development of a report detailing the economic case for the use of broadacre agricultural robots in Queensland [47].

The report considered the input savings associated with reduced energy, labour and chemical application in weed control. A model was constructed for the cost per hectare associated with energy, labour, and applied herbicide. Four technologies were compared: electric robots, diesel-electric robots, self-propelled sprayers, and tractor with spraying boom. The result of the analysis is show in Table 1 below. These include fuel, labour and applied herbicide. 5 robots were considered a comparable replacement for a dedicated spray rig.

Table 1. Cost comparison of weed control technologies.

Technology	Cost (A$/ha)
Robot Electric (5 Robots)	1.16
Robot Diesel-electric (5 Robots)	1.34
Self-propelled Sprayer with WeedSeeker	2.05
Self-propelled Sprayer with Blanket spraying	4.03
Tractor-boom with WeedSeeker	2.58
Tractor-boom with Blanket spraying	4.56

In the above cost comparison the use of smaller electric vehicles benefit from reduced rolling resistance and increased efficiency compared to larger agricultural vehicles. There was an estimated reduction of 60% in the use of herbicide relative to blanket spraying by using spot spraying technology such as WeedSeeker, and the labour cost of the tractor/sprayer driver was considered compared to the labour cost of the robot keeper who would manage several robots.

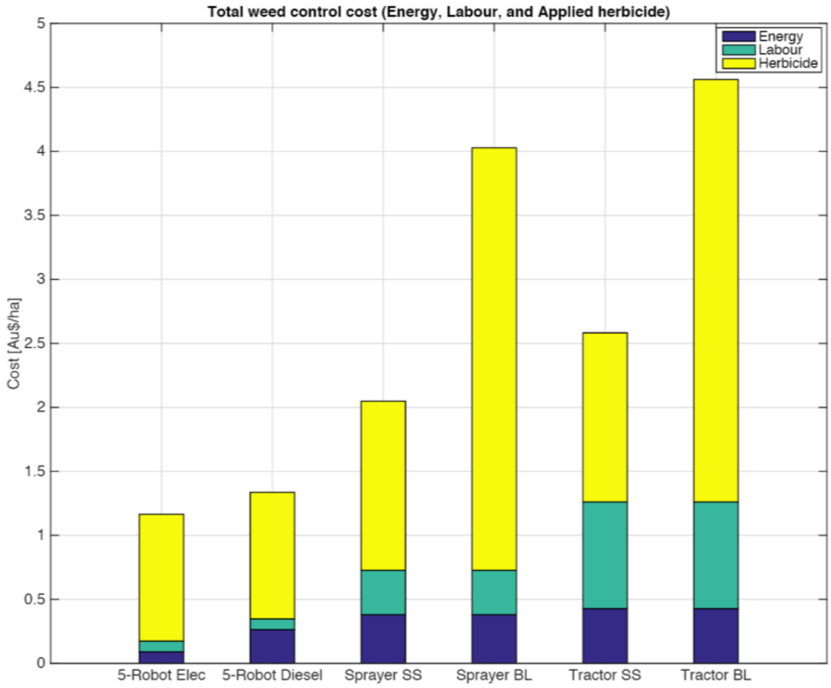


Figure 11. Total cost for weed control per hectare for the use of the difference machinery and spraying technologies. SS stands for spot spraying and BL stands for Blanket spraying [47].

The results shown above are promising. For example, with a 50% adoption rate it is anticipated a 36% (8.66 A$ m/y) reduction in the cost of weed management for Queensland, which can increase to 54% (12.98 A$ m/y) reduction with a 75% farmer uptake of robotic technology [47].

Farm Machinery Investment and Costs

With the introduction of disruptive technologies, it is important to understand there can be substantial capital investment involved in upgrade to new specialised machinery and equipment.

A farms level of investment in machinery is driven by factors such as changes to farming practices, farm scale expansion, labour skills and availability, family and lifestyle needs, the importance placed on machinery relative to other aspects of the business and the competing investment and personal demands for capital [48].

Machinery is a key component for a farmers business. It can be accessed through direct ownership, outsourced through contractors, hired, syndicated or shared with neighbours. And the contributions to machinery to a farm business can be measured through timeliness of operation; labour efficiencies; and lifestyle and operator comforts.

According to a GRDC business management report, farm machinery costs including the use of contractors, are on average, one third of farm income and are higher than fertiliser and chemical costs combined. Generally farm machinery is financed over 3-5 years and becomes a fixed overhead cost across all years, averaging 11% of the farm income [48].

Business models supporting the implementation of robotics in agriculture will possibly focus on two areas of ownership, direct to farmers or through contractors (outsourced model). Depending on the model, total lifecycle costs including; capital costs, operating costs, labour costs and contracting costs will need to be considered.

2.3 INITIAL FEEDBACK FROM FARMERS

As part of the user-centred research for this project, farmers and agronomists were asked to participate in contextual interviews and observational studies at farm locations in the Darling Downs regions (west of Toowoomba) and around Emerald in central Queensland.

The purpose of the research was to better understand the farmer perspective of agricultural robots in order to inform design decisions that address both the technology specific features and usability issues. Ethics approval documentation was prepared and approved for undertaking the farm visit and for later survey correspondence, (a copy of the Ethics Approval for Participant Research can be seen in the appendix).

A detailed Farm & User Research brief was written covering the aims, research objectives and methods for undertaking the research, along with specific research questions for farmers and other project stakeholders.

The objectives of the research were:

Farming

- To identify the critical drivers for the agriculture industry now.
- To identify the key drivers impacting the farming industry in the next 10 years.
- To identify the farming demographic.
- To understand the farmer's needs and issues in regard to weed management, soil compaction, energy usage, labour usage etc.
- To investigate the costs currently associated with dealing with issues such as herbicide resistant weeds.

Integration of Robotics in Agriculture

- To establish the level of technology currently used on farms.
- To understand farmers perception of the development of small robotic farm vehicles and incorporating fleets into a farm?
- To understand how Robotics, Automation, Mechanisation and Sensing (RAMS) solutions can be implemented and likely barriers to their uptake.

- To investigate what information farmers might find useful if collected on a robot. What level of detail do they want? How do they want to interact with the information?
- To understand the flexible required in the robot platform.
- To determine the level of autonomy and interaction farmers want with the robots.
- To understand the safety needs and expectations of the farmer in relation to vehicles and machinery.

Farming environments and infrastructure

- To establish information about the farming environment, e.g. how are fields organised, what do they look like, what features are typical etc.
- To understand infrastructure on a farm. Including digital information, telecommunications, roads, power, water supply etc.
- To investigate the level of infrastructure farmers are willing to put into a new technology.

Vehicle / Machinery Investment

- To understand the key drivers when purchasing equipment.
- To investigate the lifecycle of machinery on the farm.
- To understand how technologies are incorporated into the long term strategic objectives of businesses.
- To establish what the most successful delivery method of new technology is to farmers.

Presented at the start of the farm visit was the concept of fleets of SRFVs working in cooperation to undertake agricultural tasks such as weed mitigation through precise spraying and mechanical weed removal. This helped to shape the contextual enquiry.

Also discussed were other novel non-chemical weed destruction methods such as microwave and thermal weeding.

Methods

Fields visits were undertaken at four farms in Queensland; in the Darling Downs region west of Toowoomba and around Emerald in central Queensland. These visits included contextual interviews with nine farmers. The farmers interviewed came from a range of properties of various sizes from 236ha to 15,000ha, with the majority farming multiple lots of land. The farmers were the owners of the land we visited, or were farming neighbours with an interest in participating in the interviews and field visits.

The farms visited were family run with the farmers working fulltime on the properties. Several visiting farmers with smaller farms worked individually with occasional help around the farm during time critical periods such as harvesting. Farmers with larger properties had fulltime employees to carry out farming, machine maintenance and administrative duties around the farm. Crops grown included sorghum, wheat, barley, chickpea, corn, lucerne and cotton.

The purpose of the field visits was to develop an understanding of farming practice, and to hear the farmer's thoughts about incorporating agricultural robots in their farming practice. During the visits we introduced the robotic fleet farming concept for multiple cooperative SRFVs, and showed videos (Figure 12) of autonomous driving (e.g. sensing and navigation around obstacles).

Figure 12. Video image of fleet cooperation around a farm (courtesy of ACFR) and the AgBot I undertaking autonomous driving and obstacle avoidance trials.

Contextual interviews were carried out, including a tour of the fields, crops, buildings, machinery and associated technology. This contextual enquiry enabled us to learn about farming practice and to see, through discussion and demonstration by the farmers (e.g. undulations in the land, the growth stages of weeds), the potential and challenges of adopting agricultural robots.

The contextual enquires were audio recorded and photos were taken primarily of the farming infrastructure. The observations were distilled and grouped into areas of common themes and the finding compiled. Later on the key insights were mapped and design implications were identified. Farmers were also left with probe materials with the aim of capturing further insights about farming practices and ideas for agricultural robots that came to mind over time after the visits. The probe materials were given to participants as a kit and included a diary, disposable camera, stationary and printed images. A questions page was prepared to help prompt the farmers for ideas about how agricultural robots might be incorporated into their farming practices. We encouraged farmers to use diagrams, photos, images and text to describe their ideas.

Questions included:

- How could a robot/s help with farming tasks (the problem and autonomous solution)?
- What would be ways to control the robot/s (farmer control)?
- What are the things that the robot/s would need to know (intelligence and sensors)?

An example of probe material that was created by farmers and returned can be seen in the Field Visit Responses from Farmers in the Appendix.

Figure 13 shows some images taken during the farm visits.

Figure 13. Broadacre fields with stubble from a previous crop and large scale farming machinery used for broadacre farming.

Design Implications from Contextual Enquiries

The following are a list of the design implications drawn from the findings of contextual inquires with farmers for future work towards the development and application of agricultural robotics.

- Farmers view SRFVs as being most suited to precision work that requires accuracy (e.g. recognising and killing individual weeds).
- Farmers are competent at and interested in thinking through mechanical build problems, and participatory design methods for prototype development would be beneficial to both the farming community and this research.
- The mechanical build of the system should remain open for ongoing maintenance and adaptability.
- Varying levels of access to the interface system are necessary (e.g. a simple user level, and a more complex admin level).
- Rural communication infrastructure cannot be assumed to be adequate for reliable remote access, and should be addressed as part of the design of autonomous agricultural robots.
- The data collected from agricultural robots should be relevant to the scale of the operation.
- Farmers welcome an open source community model for the software development of agricultural robots and this should be set up early and in a way that encourages participation from farmers.
- The ratio of operators to SRFVs needs to be manageable in terms of the workload for monitoring and maintenance of the vehicles.
- Remote views of SRFVs should give adequate and easily interpreted visual information about the state of the machine and nature of failures.

2.4 ESTABLISHING KEY RESEARCH THEMES

This chapter has presented a survey of the research applicable to agricultural robotic platforms, looking at the challenges facing farmers, reviewing the research already undertaken into agricultural robotics, highlighting the market opportunities that exist and giving insight into the farmer's perspective on the application of robotics in agriculture.

From this survey several key themes appear that highlight the research gap surrounding agricultural robotic platforms that this project will address.

Platform Application

Research has indicated that the development of robotic platforms has been focusing on high value crops in the horticulture sector and has skipped the opportunities in broadacre farming and low value crops such as wheat, sorghum and chickpea. Examples of this can be seen in the Robotti [40] and the Ladybird [46].

Many opportunities exist in the broadacre sector for the application of robotic vehicles operating in fleets to undertake a variety of precision agricultural tasks, such as weed mitigation and fertiliser application.

Cost of Platform Development

Platform development in the field of agricultural robotics has been predominantly focused on research applications, as can be seen in the BoniRob [35] and Hortibot [33]. The few platforms that have proceeded to commercialisation such as the Grizzly [41], have come at a high cost.

To enable the uptake of robots in agriculture, focus has to be placed on keeping the costs of the platforms down. An important theme of this research project will be to look at low cost manufacturing and assembly techniques, as well as the integration of off-the-shelf componentry including electric motors and batteries.

Platform Configuration and Dimensions

Platform development for broadacre applications offers research opportunities in alternative vehicle configurations and dimensions suitable for this type of farming.

As can be seen in the Amazone BoniRob [35] and Zeus [36], Hortibot [33] and Weedy Robot [34], many examples exist of four wheel drive, four wheel steered platforms that come at a high cost and complexity due to the number of drive and steering motors inherent in the design. A major theme of this project will be to look at alternative vehicle configurations suitable for broadacre farming that offer optimum traction and steering using the minimum of components.

Additionally, opportunities exist to look at alternative dimensions for the vehicle that take into account the unique operating environments of broadacre farming. This includes enabling the platform to operate in-crop, by driving between crop rows and clearing crops heights. With this in mind research will be undertaken into modular assembly techniques that utilise lightweight materials and manufacturing technologies.

Usability for Farmers

Finally, a major theme of this project will be to design a platform focused on the end-user – the farmer, rather than as a research platform solely for experimental usage. Incorporating elements of the designers and engineer's toolkit, the needs of people, the possibilities of technology, and the requirements for business success will be integrated into the project. This will result in a high level of usability, with the emerging designs intersecting the areas of feasibility, viability and desirability.

Chapter 3: General Requirements and Specifications

3.1 OBJECTIVE

This research project is concerned with the design and development of a small, lightweight and energy efficient robotic vehicle with a configurable modular design. The Small Robotic Farm Vehicle (SRFV) will be capable of undertaking a multitude of precision agricultural tasks, demonstrate efficiency and reliability, and deliver more productive farming outcomes in broadacre crops.

3.2 GENERAL ROBOT REQUIREMENTS

- The robot must be suitable for a range of precision agricultural tasks related to weed management, fertiliser application and seeding.
- The robot must be capable of autonomous driving over a variety of agricultural terrain including in-crop driving, along farm roads and in fallow fields.
- The robot must be lightweight to reduce or remove the impact of soil compaction.
- The robot must be transportable on a standard road-going flatbed trailer.
- The robot must be able to carry payloads of liquid including herbicide, fertiliser and water as well as seeds.
- The robot must be able to carry various implements for agricultural tasks and experimentation. These will include weeding, fertilising, crop scouting and seeding.
- The robot must be able to identify (detect and classify) weeds in order to select and apply the most appropriate weed treatment, which includes the integration of novel non-chemical destruction methods.
- The robot should be low cost.

- The robots must be mechanically reliable and easy to maintain.
- The robot must operate safely in farming environments.
- The robot must be energy efficient; delivering increased levels of efficiency compared to existing technologies as well as incorporating renewable energy power options.
- The overall system must be scalable, allowing farmers to utilise SRFV's on farms of all sizes. Single operators will be able to manage a fleet of robots across large areas.

3.3 VEHICLE PARAMETERS

Considerations

The design of the vehicle started with the consideration of general requirements regarding dimensions, weight, configuration and coverage. Questions were posed that helped to define and focus the research. These were kept in context of a prototype design development so estimates were more important that in-depth analysis.

Questions included:

- How will the dimensions of the vehicle be defined?
- How do we estimate the mass of the vehicle including payload?
- What will the vehicle's coverage be? How does this change with payload, weight etc.?
- How will the operating speed and operating time be determined?
- How do we decide the ideal vehicle configuration? What factors need to be considered?

Each one of these considerations interrelates and directly affects the outcome of the vehicle design. The following section deals specifically with these questions and details the analysis undertaken to determine the key vehicle parameters.

3.4 VEHICLE DIMENSIONS

The overall dimensions for the SRFV are defined based on a range of operating requirements and design criteria. The width, height and length of the vehicle are a balance between vehicle transportability, stability, payload capacity, effective operating area, operating times, crop varieties and farming practices.

Although not designed to drive on public roads a key requirement of the vehicle is its ability to be transported on public roads to farms using a standard flatbed truck or trailer. With this requirement in mind, a review of the Australian Vehicle Standards Rules 1999 specified that the width of a vehicle must not be over 2.5m, while the length of the vehicle must not be over 12.5m [49] as illustrated in Figure 14. This meant that to move the vehicle on a typical flatbed trailer the length (or width, depending upon the orientation of the SRFV to the truck/trailer) needs to be less than 2.5m.

Australian Vehicle Standards Rules 1999

Rule 66 of the vehicle standards regarding vehicle width stated that: "A *vehicle must not be over 2.5 metres wide."*

Rule 67 regarding the length of single motor vehicles stated: "*A motor vehicle, except an articulated or controlled access bus, must not be over 12.5 metres long."*

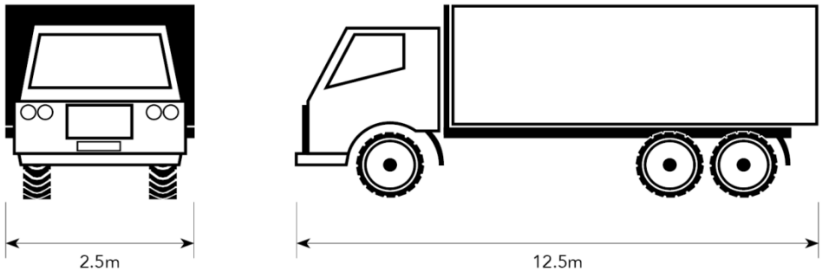


Figure 14. General dimensions of a flatbed truck with load allowed in Australia [50].

With these vehicle standards and dimension in mind, a review of farming infrastructure was undertaken covering two main areas:

1. Commonly used crop row spacing in broadacre farming in Australia. And,
2. Commonly used track width for Control Traffic Farming (CTF) in Australia.

Optimising the vehicle for these requirements will allow it to take advantage of the farming infrastructure already in place on many farms.

Crop Row Spacing

For farmers the most appropriate row spacing is a compromise between crop yields, ease of stubble handling, optimised vehicle travel speed, management of weed competition and soil throw and achieving effective use of pre-emergent herbicides [51].

With cereal crops such as wheat and oats, the impact of row spacing on crop yields varies depending on the growing season rainfall, the time of sowing and the potential yield of the crop. Narrow rows of 180-250mm are common in many wheat growing regions around Australia. Studies undertaken to investigate the interaction between row spacing and crop yield have shown that for high yield wheat crops, wider row spacing (0.5m) resulted in a yield reduction compared to narrower rows [52].

For broadleaf crops such as pulses and oilseeds, wider crop row spacing is generally preferred. Wider rows (0.5 to 0.6m) have higher yield potential than narrow rows in warm, dry environments [51]. This is because the crop uses less water during winter so there is more available at the end of the growing season.

The following Figure 15 shows common row spacing's in metric and imperial measurements:

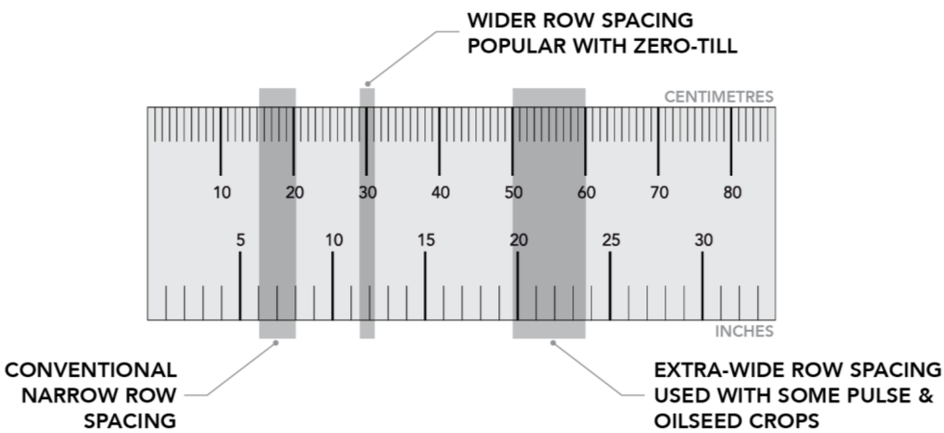


Figure 15. Source GRDC crop placement and row spacing fact sheet [51].

Crop row spacing is important also for establishing the width of the wheel unit. A key requirement of the vehicle is in-crop driving, enabling the vehicle to undertake scouting operations for pests and weeds and conduct other tasks and experimentation.

To avoid damaging the crop while driving, wheel units would need to be narrower than the spacing between the crops. Looking at local farming practices in S.E Queensland, where the prototype vehicle would be conducting the majority of its work, it was determined that a wider row spacing would be appropriate. Below are several images of crops investigated as part of the user research, illustrating the wider row spacing being used by farmers in the Toowoomba/Darling downs region.

A wide variety of crop row spacing is used depending on soil moisture, weed competition, crop variety and equipment setup. No particular spacing is ideal of every crop, which makes defining the overall vehicle width and wheel width based on crop spacing alone challenging.

Figure 16. Wider crop row spacing for drought affected Sorghum (Left) and spacing for recently harvested wheat crop (right).

After some discussion with farmers and agronomists regarding this issue, it was decided that a standard row width of 0.5m would be appropriate for a large portion of broadacre applications. With allowance for overhanging leaves and drift in steering, a working width of 300mm was considered safe for the wheel unit. This dimension of 0.3m was included in the specification as a key vehicle parameter.

Key vehicle parameter – 0.3m wheel width (for in-crop driving).

Control Traffic Farming

Control Traffic Farming (CTF) is a crop production system in which the crop zones and the traffic lanes are distinctly and permanently separated. In practice it means that all implements have a particular span, or multiple of it and all wheel tracks are confined to specific traffic lanes. The benefits of CTF can be broadly viewed as either economic (improved profit from grain growing) or environmental (better condition of the soil, water and atmosphere) [22].

Farms that have been converted over to CTF may find it easier to transfer to robotic operations because many farmers have already made changes to the layout of their farms to improve efficiency, by modifying surface water control structures, fence removal and removal of rock heaps and other obstacles. Many of these changes were made when straight line auto-steer was adopted.

When converting farming equipment over to CTF, farmers have looked at the machinery width or implement width (header, seeder, and sprayer) and the wheel track width.

Generally, farmers have worked backwards from their header. The header (or harvester / combine harvester) is commonly the hardest machine to modify as well as being the heaviest machinery used in farming operations, with a full capacity of 10t of grain. It can also have the widest wheel base and tyres. Track widths for these vehicles are usually around 3m or 10ft.

Table 2 lists the conventional implement widths for harvesters, seeders and sprayer. When converting to CTF, farmers will match the widths of their machinery to establish a uniform ratio. 3:1 is common for broadacre machinery, but other ratios such as 5:1 are used for narrow seeders [22]. A 3:1 machinery ratio is illustrated in Figure 17.

Table 2. Common machinery widths for broadacre farming [22].

Machinery	Conventional Implement Widths				
Harvester	9m	10.5m	12m	13.5m	
Planter/Seeder	9m	12m	18m	21m	24m
Sprayer	18m	21m	24m	27m	36m

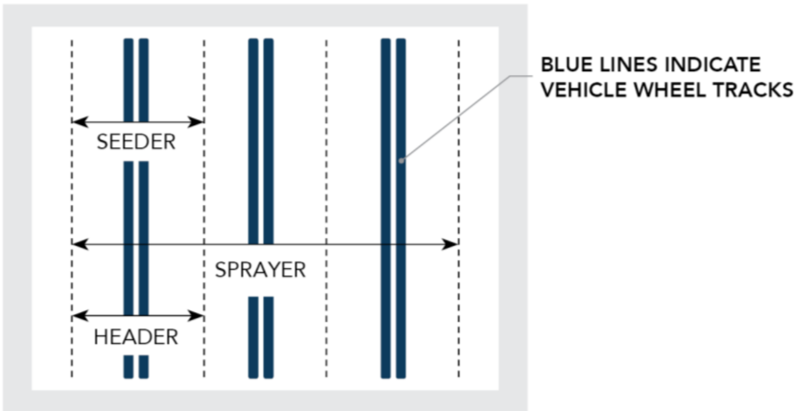


Figure 17. 3:1 seeder/header to sprayer ratio. Blue lines indicate wheel tracks.

When converting to CTF farmers need to match the wheel tracks across their machinery to reduce the occurrence of soil compaction. Wheel track spacing on agricultural vehicles is commonly 2.2-2.4m or 3m, with some large sprayers running on 4m. Three metres is around the ideal spacing as this will incorporate the header. Wheel tracks of 2.2m are usually used in systems that only match the seeder and the sprayer. Farmers would commonly modify the wheel track widths across their machinery by adding spacers to the wheel axles. In response to this, there is an increasing range of machinery that comes for the manufacturer with wheel tracks of 3m [22].

Based on this research a vehicle width (wheel centre to centre) of 3m was chosen for the first prototype. As illustrated in Figure 18, this would allow the SRFV to take advantage of CTF layout already in place on many farms. Being wider than the width permissible for carriage on a public road mean that the vehicle would need to be loaded perpendicular to the truck or trailer used for carrying the SRVF. The implement section will be design to be modified in width and height to allow for adjustment for individual farming setups, so if farmers prefer to run a 2.5m vehicle width, the implement section can be modified to accommodate this.

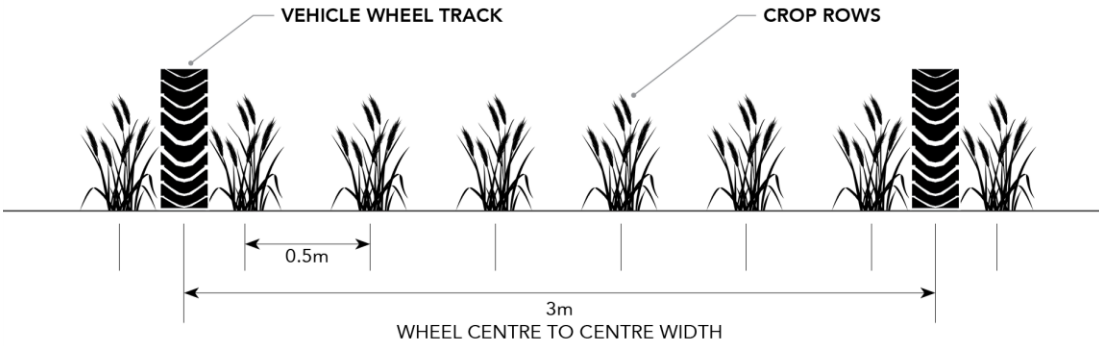


Figure 18. 3m width on crop spacing on 0.5m.

Key vehicle parameter – 3m width (wheel centre to centre)

Other factors influencing the general dimensions of the SRFV were common broadacre crop heights. For in-crop driving the height of the crop would play a role in determining how high the implement unit should sit above the ground.

Crop Heights

Broadacre crop heights vary according to region, crop variety, moisture availability, soil nutrients and weed competition. A general overview of broadacre crop heights can be seen in the following Figure 19.

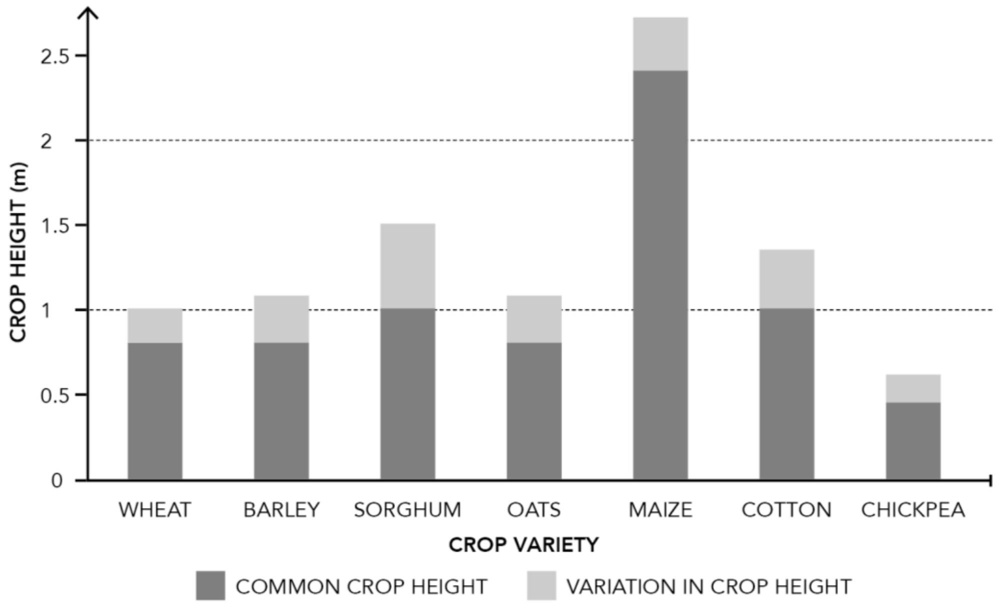


Figure 19. Growing heights of major broadacre crop varieties [53]

Based on the above average crop heights, it was determined that a clearance height for the vehicle of around 0.75-1m would be suitable for a large percentage of the agricultural tasks. Adjustment in the width and height of the implement section is a planned feature of the design. For the first prototype a lower height of 0.75m will be used to increase vehicle stability.

Key vehicle parameter – 0.75m clearance height

3.5 VEHICLE MASS

Estimated Vehicle Mass Requirements

Traditionally mass estimation has been a difficult parameter to specify in vehicle design, especially in the prototyping stage, where daily design changes keep the final mass determination in flux. Even with today's advanced CAD programs, defining items such as fasteners, wiring harnesses, cosmetic skins, electronic components, etc. is just not practical given the rapid pace of change during the prototyping stage.

For most prototyping then, taking a statistical approach to mass estimation may prove more realistic in the early stages of the design. By identifying existing vehicles of similar payload and capability, one can start with the vehicle's defined mass and work backwards. This is done by breaking the vehicle down into its individual components, then assigning mass to each of these components to recreate the vehicle's original mass. This breakdown can be as simple, or as complex as required, depending on the accuracy of the desired estimation.

Empirical evidence from farmers informed the mass target of the prototype vehicle. Reports from farmers suggested that ATV’s used for farming resulted in minimal soil disturbance when driven over fields in varying conditions. ATV’s range in sizes and mass from 200 – 600kg; so based on this we estimated 400kg as the target for the vehicle.

A deconstruction analysis was undertaken of an ATV, in this case a John Deere Gator, which we had available at the university for farm experimentation work. This was heavier than our targeted mass however it included a lot of superfluous equipment not required in an autonomous vehicle. In Table 3 below an estimation of the mass from the Gator TE model are presented. The total mass of the vehicle was known as 664kg and the individual components were assessed by supplier data, material volume and estimation.

The mass breakdown is used as a guide for estimating the mass of assemblies in the new vehicle build. This estimation can be seen in Table 4. The mass estimation spreadsheet is a working document and is constantly updated during the design phases of the project and used to evaluate the target mass of the vehicle. Weight analysis in CAD provided important feedback to check if the assembly masses were on target or if changes needed to be made to material selection or designs details.

Table 3: Gator TE mass estimation.

Component	Quantity	Mass - kg	Mass - kg Total	% of Vehicle Mass
Complete Vehicle	**1**		**664**	**100**
T145 Battery	8	32.7	261.8	39.4%
Motor - 6hp - 4.6kW	1	9	9	1.4%
Motor Controller	1	4.5	4.5	0.7%
Tyres/Rims	4	6.8	27.3	4.1%
Frame	1	170.5	170.5	25.7%
Bed	1	113.6	113.6	17.1%
Front Suspension	1	11.4	11.4	1.7%
Rear Axle/Differential	1	40.9	40.9	6.2%
Rear Brakes	2	4.5	9.1	1.4%
Seats	2	3.4	6.8	1.0%
Steering Racks/Rods	1	9.1	9.1	1.4%
Mass (Empty)			**664**	**100.0%**
Max. Payload	1	490.9	490.9	73.9%

Table 4. Mass estimation for the development of the agricultural robot.

Component	Quantity	Mass - kg	Mass- kg Total	% of Vehicle Mass
Power System - Gen/Batteries	1	70.5	70.5	16.80%
Battery Box Assembly	2	7.7	15.5	3.69%
Drive Unit Assembly	2	15.0	30.0	7.15%
Electronics/Wiring	1	40.9	40.9	9.75%
Drive Tyre/Rim	2	9.1	18.2	4.34%
Swingarm	2	27.3	54.5	12.99%
Drive Unit "Cage"	2	4.5	9.1	2.17%
Shock Absorber	2	2.3	4.5	1.07%
Caster Assembly (with Tyre/Rim)	2	20.0	40.0	9.53%
Side Unit	2	45.5	90.9	21.67%
Implement Unit	1	45.5	45.5	10.83%
Covers	1	0.0	0.0	0.00%
Mass (Empty)			**420**	**100.00%**
Max. Payload (H^2O)	1	200	200.0	47.67%
Max. Mass			620	

Key vehicle parameter – Estimated vehicle mass 400kg (without payload)

3.6 VEHICLE COVERAGE

Spray Coverage

Calculations were made to estimate the spray coverage achievable with various vehicle widths for spray operations using a WeedIT system. WeedIT, along with its competitor WeedSeeker are plant detection systems used to detect, measure and apply chemicals to plant matter. They are used to significantly reduce chemical application in broadacre, horticulture & viticulture. Explained in Figure 20, the system works by sensing light reflectance using an LED which signals a spray nozzle to deliver a precise amount of chemical—spraying only the weed and not the bare ground. It is most effective in areas where weeds occur intermittently. Users of WeedIT systems report spraying around 10% of a field's area. The actual spray rate in L/ha can depend on the type of weed being targeted and the herbicide being used. 50L/ha to 100L/ha of product solution are common.

Table 5 was used to evaluate options of payload capacity, implement width, time to refill and time to completion. It was noted that tank size effects refill time but with the inclusion of an autonomous refilling station in the system, would not affect the time to completion.

Information from our weight estimation suggested that a 200L tank would be a suitable size for achieving the target vehicle mass. This tank size was compared against similar tank sizes to gauge the coverage, time to refill and time to completion achievable with the vehicle and determine if the solution was feasible for spray operations.

Figure 20. WeedSeeker system [54].

Table 5. Coverage review table.

Spray Coverage	Opt. 1	Opt. 2	Opt. 3	Opt. 4	Opt. 5
Capacity of Liquids tank (L)	100	200	400	1000	10000
Spray Rate L/ha	50	50	100	50	50
WeedIT Spray Rate %/ha	10	10	10	10	10
Output Spray at Nozzle L/ha	5	5	10	5	5
Spray Coverage (ha)	20	40	40	200	2000
Average Vehicle Speed (km/hr)	10	10	10	15	25
Width of Implement (w)	6	9	6	9	36
Coverage (ha/hr)	6	9	6	13.5	90
Refill Time (hr)	3.33	4.44	6.67	14.81	22.22
Farm Size to spray (ha)	800	800	800	800	800
Number of Vehicles	1	5	3	2	1
Vehicle Operation Time (hr/day)	10	16	10	10	8
Time to Complete (days)	13.33	1.11	4.44	2.96	1.11

Operating Scenarios

An operating scenario considered for the SRFV would be the following:

- Utilising a 400L liquids tank.
- Spray rate of 100L/ha.
- Spraying herbicide at 10%/ha average coverage would result in 10L/ha.
- Average vehicle speed – 10km/hr.
- Width of spray boom is 6m.
- Spraying at 6ha/hr.

In this scenario the liquid tank on the SRFV's would need to be refilled approx. every 6hr40min. Using 3 SRFV for periods or 10hrs at a time it would be possible to spray a 800ha farm in under 4.5 days. An alternative scenario could be the following:

- Utilising a 200L liquids tank.
- Spray rate of 50L/ha.

- Spraying herbicide at 10%/ha average coverage would result in 5L/ha.
- Average vehicle speed – 10km/hr.
- Width of spray boom is 9m.
- Spraying at 9ha/hr.

In this scenario the liquid tank on the SRFV's would need to be refilled approx. every 4hr30min. Using 5 SRFV for periods or 16hrs at a time it would be possible to spray a 800ha farm in a little over a 1 day. Based on this review it was determined that a 200L tank would be suitable if autonomous refilling was available. Without it farmers would be spending too much time manually refilling.

Key vehicle parameter – Payload capacity 200L

3.7 OPERATING SPEED

Specifying the vehicle operating speed is determined through analysis of multiple factors:

- Operational safety.
- Obstacle detection and processing time.
- Herbicide application requirements.
- Coverage requirements.

Safety

The walking speed of a human and is considered a safe speed for operation of autonomous vehicles. This enables an operator to get out of the way of the vehicle if an impact is possible. The average walking speed for humans is around 5km (1.38m/s).

Obstacle detection

Current sensor packages used for obstacle detection have an optimal range of around 10m. The speed of the vehicle effects the time to impact from detection. The faster a vehicle is traveling the less time there is to detect and avoid the obstacle.

- For a vehicle travelling at 30km/hr the time to impact with the obstacle is 1.2 seconds.

- For a vehicle travelling at 10km/hr the time to impact with the obstacle is 3.6 seconds.
- For a vehicle travelling at 5km/hr the time to impact with the obstacle is 7.2 seconds.

Herbicide application requirements

Many factors contribute to safe herbicide/pesticide application to achieve maximum effectiveness and reduce possible damage and contamination to off-target crops and areas. Amongst these are wind speed, ambient air temperature, nozzle height from crop and vehicle speed. Current

The recommended speed for many herbicide applications is 15km/hr (4.16m/s) but the push to optimise an operators coverage per hour has seen many farmers increase their spraying speeds to 25km/hr (6.94m/s).

Coverage requirements

As can be seen on the spray coverage in Table 5, an average vehicle speed of 10km/hr was suitable to achieve coverage of an 800ha farm using 5 vehicles in around 1 day. This is comparable to a spray rig using a 36m boom, travelling at 25km/hr operating for 8hrs.

Key vehicle parameter – Operating speed 5 – 10km/hr (1.38m/s – 2.77 m/s)

3.8 OPERATING TIME

Operating time of the vehicle is effected by a wide range of contributing factors including the power supply and the power requirements of the vehicle operation. Operating time directly affects the speed at which the vehicle can complete coverage of a designated area. In broadacre farming timeliness of operations are critical. For instance with spraying , being able to apply herbicide shortly after rain has fallen can greatly reduce a weeds ability to take hold in a field. Additionally, crops often need to be harvested around the clock to ensure a particular quality is captured at the right time. Timeliness of operation can result in a big difference in crop yield.

Presently, farm vehicles are able to run almost continuously with short breaks for refuelling. With this in mind it was important to specify a 24hr operating time for the vehicle. The same operating time would be achievable on an agricultural robot with an on-board generator, a large enough battery pack or the ability to rapidly exchange or recharge batteries.

Key vehicle parameter – Operating time 24hrs

3.9 OPERATING GRADIENTS

Broadacre farming is generally undertaken on relatively flat terrain. Operating gradients of 0-3% are very common. Properties with 5-10% gradients are less common because the land is more energy intensive to cultivate. A review of GPS data from farm trials in Emerald showed a gradient of 1-3% was encountered across several fields of this property. This was similar to three properties visited in the Darling Downs Area.

Topographical information relating to farms is collected by farmers through RTK GPS systems. The GPS systems are generally set up for auto-steering vehicles but are also capable of measuring vertical accuracy to 5cm. These are variation of the same systems used by surveyors. Once the data is collected, it can be used to produce contour, drainage, elevation, slope and aspect maps.

Although not conclusive, it is estimated that anything over a 10% gradient would be considered steep for broadacre farming. Based on this an operating gradient of 15% was estimated as the worst case the agricultural robot would see in field conditions.

Key vehicle parameter – Operating gradient 15%

3.10 VEHICLE CONFIGURATION

The configuration is the foundation of the vehicle and critically important to its successful development. During this analysis locomotion concepts are synthesised and evaluated and a decision regarding which concepts to carry to full design development are made.

Analysis of vehicle configurations began with a consideration of the following area:

- Manoeuvrability.
- Stability.
- Locomotion type - Tracks vs Wheels.
- Number of drive and steering motors.

3.10.1 Manoeuvrability

The areas in Australia in which broadacre crops are grown vary widely. On larger farming operations, fields cultivated for wheat and other broadacre crops can stretch for many kilometres in unbroken tracts of land. Vehicles operating in this environment spend a large portion of their operating time traversing in relatively straight lines along crop rows to give even coverage to the entire area. Manoeuvrability around headlands and between fields is undertaken only a small percentage of the operating time.

The precision of steering required has a direct relationship to the cost, complexity and robustness of the vehicle. 4 Steering schemes were considered as part of the configuration analysis: differential, Ackermann, articulated and 4 wheel independent steering.

Differential Steering (Skid Steering)

Differential steering works by controlling the velocity and direction of rotation of one or more wheels on each side of a vehicle chassis. Steering is enabled by the lateral displacement of the chassis rather than steering the wheels. The difference in velocities between the two sides defines the turning radius and affects the power draw. For example, if both wheels are rotated in the same direction, at the same velocity, the vehicle moves forward. If the wheels rotate in opposite directions at an equal velocity, the vehicle will turn around the central point of the axis between the two wheels. Adjusting the velocity and direction of wheel rotation will lead to the vehicle turning anywhere on the line between the two contact points of the tyres. Differential steering is favoured in many mobile robotic applications because of its low cost and simplicity.

Ackermann Steering (Coordinated steering)

Ackermann steering or coordinated steering uses a mechanical coupling such as angled steering linkages and a tie-rod, to synchronise the turning of two or more wheels subject to the desired kinematic geometry. The linkages are generally angled to meet the central point on the rear axle. Ackermann steering can also be achieved through the use of independent steering motor. It's used extensively for commercial vehicles.

Articulated Steering

Articulated steering operates by changing the angle between the front and rear axle of the vehicle. This requires the vehicle to be split into front and rear sections which are then connected by a vertical hinge. The disadvantage of using articulated steering for agricultural robots is that there is little space for implements between the front and rear axle.

Independent Steering (4 Wheel Steering)

With independent steering each wheel is explicitly steered. Independent steering schemes can emulate any rigid-chassis steering type, including skid steering. Independent steering provides excellent manoeuvrability and allows for steering options like "crabbing" which are not available with any other steering scheme. This works when all wheels are angled in the same direction enabling the vehicle to move sideways. This is desirable in many mobile robots and is seen in agricultural robots where its implementation leads to low energy consumption manoeuvring. However there are issues around actuator complexity and accuracy of coordination control.

3.10.2 Stability

In all circumstances, stability is a major factor in vehicle design and configuration. One and two wheeled configurations inherently suffer from stability issues at low speeds that can be alleviated with gyroscopic mechanism. Their payload capacity is also restricted to a very small area. Three wheeled configurations may benefit from a reduced number of components in the vehicle build but suffer from stability issues at some operating angles and speeds and can affect the ground coverage by adding an additional, central drive track to the soil. Four-wheeled configurations offer increased stability because of the four points of contact. This enables a larger payload carrying capacity. Tracked configurations can offer the same stability benefits as 4 wheeled configurations.

3.10.3 Tracked vs Wheeled Vehicles

The relative performance characteristics of tyres and tracks were compared in agricultural soil conditions. Tracked vehicles offer many advantages over wheeled vehicles in off-road environments. Track laying vehicles increase traction and off-road traversability through their larger soil contact area. High pull ratios (pull/vehicle weight) can also be obtained due to track grouser penetration and low ground contact pressures. Furthermore, the larger surface contact area of tracks reduces soil compaction by distributing the weight of the vehicle more evenly over a larger area.

As a result of the greater contact area, rolling resistance and overall efficiency is reduced with tracked vehicles. Tracked vehicles also increase the weight and mechanical complexity of the vehicle and generally have a higher total operating cost than wheeled vehicles of an equal power. Vehicles designed with tracks for locomotion generally manoeuvre using skid-steer which enables tight turning circles but increases soil disturbance over wheeled vehicles. Having reviewed these factors it was determined that a wheeled vehicle configuration would be more appropriate for broadacre applications.

3.10.4 Four Wheel Drive, Rear Wheel Drive or Front Wheel Drive.

The choice of which wheels should be driving depends on the steering strategy, traction requirements and obstacle manoeuvring. Four Wheel Drive (4WD) gives the best off-road performance because all wheels can contribute to overcoming an obstacle. When drive up a slope, Rear wheel Drive (RWD) is better than Front Wheel Drive (FWD) because a part of the weight on the front wheels is on the rear wheels however in many FWD vehicles were the mass of the engine is over the tyres, loss of traction is almost never an issue.

3.10.5 Suspension

Suspension contributes to the vehicles handling and braking characteristics and works to isolate the vehicle from road noise, vibration and bumps in the terrain. A variety of suspension systems have been implemented on robotic vehicles such as: independent suspension, articulated split body suspension, rocker-bogie and active suspension. Where suspension plays a major role in ride comfort in passenger cars, the same can be said for sensor comfort in robotic vehicles. Suspension can help to smooth out the ride making data collection from camera and lasers less jittery. At relatively low speeds suspension will not play a major role in the handling of the vehicle.

Incorporating some form of passive suspension with springs or shock absorbers into the design of the agricultural robot is desirable to help with ride stabilisation over uneven terrain and to aid in the transfer of weight under emergency breaking situations.

The following configuration analysis reviews a selection of steering schemes and wheel and track configurations.

3.11 CONFIGURATION ANALYSIS

As illustrated in Figure 21, 20 vehicle configurations including both tracked and wheeled variants were explored. Each configuration was created in Lego as a test model and rated in a matrix against a series of performance criteria that included: stability, manoeuvrability, steering complexity and carrying capacity. The purpose of the review was to define a smaller list of possible configurations to put forward for discussion and analysis. From this list a final vehicle configuration suitable for autonomous broadacre use would be selected.

Figure 22, Figure 23, Figure 24 and Figure 25 outline the comments, pros and con are that were discussed for each vehicle configuration.

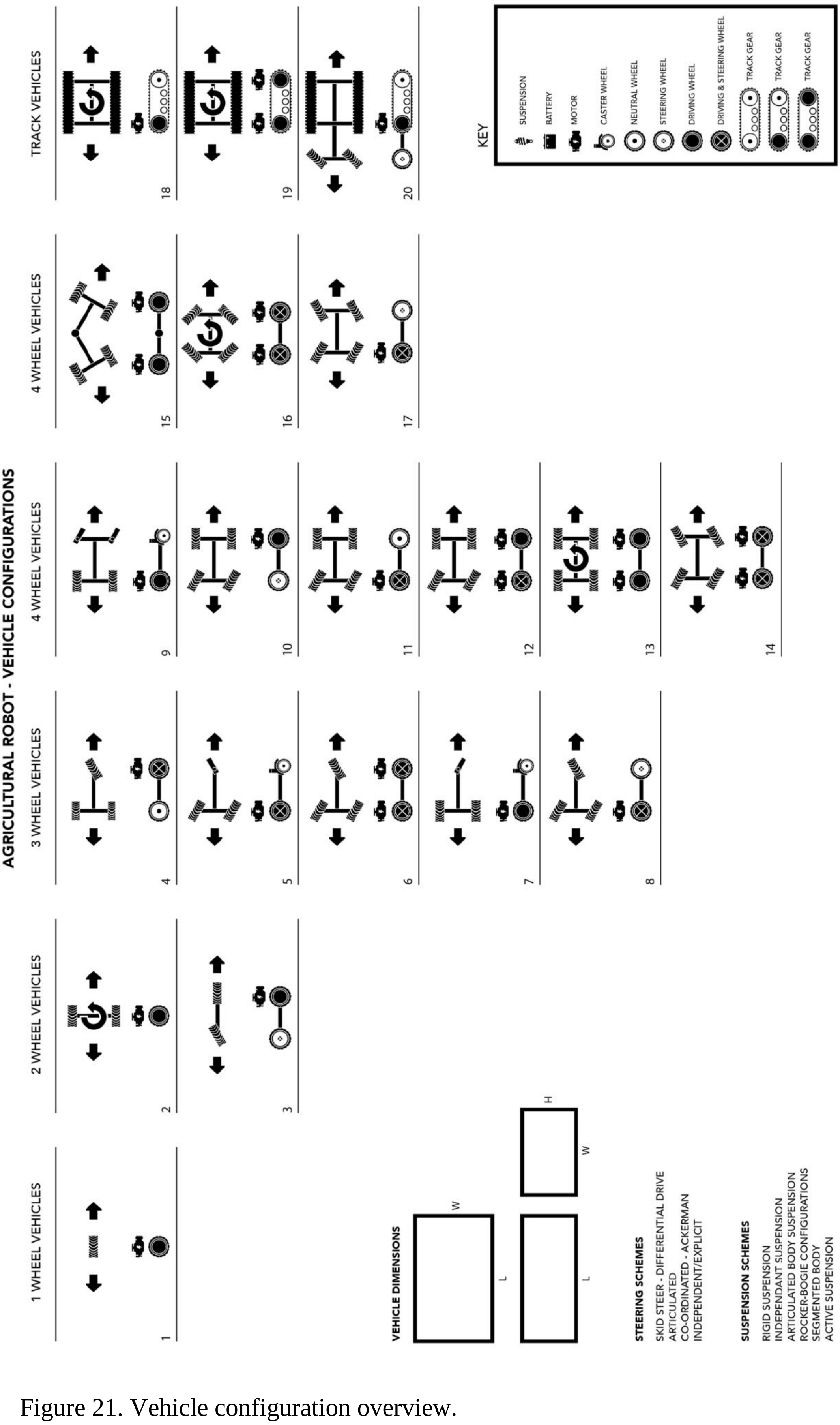


Figure 21. Vehicle configuration overview.

AGRICULTURAL ROBOT - VEHICLE CONFIGURATIONS

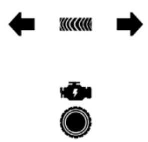
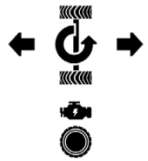
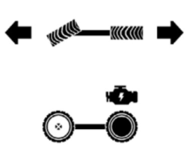
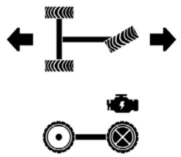
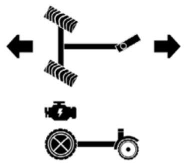
Identifier	Image	Configuration	Steering	Drive System	Comments	Pros	Cons	Rating
1		Single wheel.	Transference of weight required to steer.	Single wheel drive. Suitable for driving in both directions.	Gyroscopes required for balanced operation. Example: *http://www.inventist.com*	Few components. Minimal footprint. Potentially useful for crop scouting.	Unable to carry large implements. Requires gyroscopic corrections to keep balance.	
2		Two wheels (opposite).	Differential wheel steering.	Differential drive. Suitable for driving in both directions.	Gyroscopes required for balanced operation. Example: *http://www.segway.com/*	Reduced number of components. Ideal configuration for spanning crop rows. Potentially useful for spraying and crop scouting. High manoeuvrability.	Gyroscopes required for balanced operation. Difficulty in carrying implements & loads.	
3		Two wheels (in-line).	Independent front steering (Motorbike style).	Rear wheel drive. Suitable for driving in both directions.	Gyroscopes required for low speed operation. A stabilising wheel could be used for balance at low speed.	Narrow contact area. Single motor drive.	Unbalanced at low speeds. Difficulty in carrying implements & loads.	
4		Three wheels.	Fixed front wheel and independant rear steering.	Rear wheel drive. Suitable for driving in both directions.	Commonly used three wheel configuration for car, tricycles etc.	Tight turning radius. Single drive motor. Can be driven forward and backwards. Simple robust design.	Triangular payload area. Third line of soil contact. Stability issues on uneven ground and with uneven weight distribution.	
5		Three wheels.	Ackermann front wheel steering, caster rear wheel.	Front wheel drive. Central drive motor or independent wheel motors. Suitable for driving in both directions.	Commonly used three wheel configuration for strollers, trolleys, mowers etc.	Tight turning radius. Can be driven forward and backwards. Simple robust design.	Triangular payload area. Third line of soil contact. No traction on rear wheel. Stability issues on uneven ground and with uneven weight distribution.	

Figure 22. Vehicle configuration comparison 1.

AGRICULTURAL ROBOT - VEHICLE CONFIGURATIONS

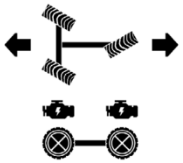
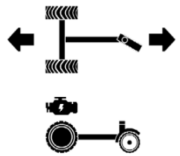
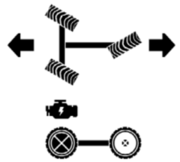
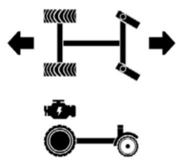
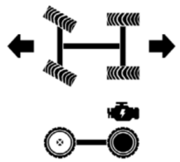
Identifier	Image	Configuration	Steering	Description	Comments	Pros	Cons	Rating
6		Three wheels.	Independent front and rear wheel steering.	All wheel drive. Front wheels can be driven by central drive motor or independent wheel motors. Suitable for driving in both directions.	This configuration allows the vehicle to move in all directions.	Tight turning radius. Traction on all wheels. Able to crab and move in all directions.	Triangular payload area. Third line of soil contact. Three drive and steering motors. Stability issues on uneven ground and with uneven weight distribution.	
7		Three wheels.	Differential front wheel steering, caster rear wheel.	Front wheel differential drive. Suitable for driving in both directions.		Tight turning radius. Simple design requiring 2 motors for power and steering.	Triangular payload area. Third line of soil contact. Stability issues on uneven ground and with uneven weight distribution. No traction on rear wheel.	
8		Three wheels.	Ackermann front wheel steering and independent rear wheel steering.	Front wheel drive. Front wheels can be driven by central drive motor or independent wheel motors.	Ackermann steering can be achieved with either a traditional linkage or via coordinated independant motors. Traditional linkage may reduce crop clearance height.	Tight turning radius. Simple design.	Triangular payload area. Third line of soil contact. Stability issues on uneven ground and with uneven weight distribution. No traction on rear wheel.	
9		Four wheels.	Differential front wheel steering, caster rear wheels.	Front wheel differential drive.	Configuration used in agriculture for Windrowers. Example: *http://www.roprodesign.com/projects/lagr/*	Tight turning radius. Simple design requiring 2 motors for power and steering.	No traction on rear caster wheels.	
10		Four wheels.	Ackermann front wheel steering.	Rear wheel drive. Rear wheels can be driven by central drive motor or independent wheel motors.	Commonly used for vehicles of all types. Ackermann steering can be achieved with either a traditional linkage or via coordinated independant motors. Traditional linkage may reduce crop clearance height.	Simple design.	No traction on front wheels, May require a steering linkage to span the width of the vehicle.	

Figure 23. Vehicle configuration comparison 2.

AGRICULTURAL ROBOT - VEHICLE CONFIGURATIONS

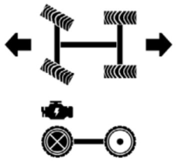
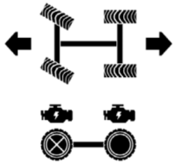
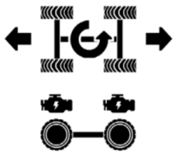
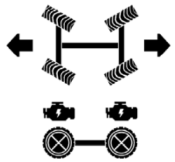
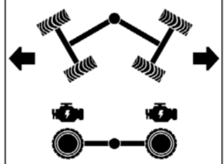
Identifier	Image	Configuration	Steering	Description	Comments	Pros	Cons	Rating
11		Four wheels.	Ackermann front wheel steering.	Front wheel drive.	Commonly used for vehicles of all types. Ackermann steering can be achieved with either a traditional linkage or via coordinated independant motors. Traditional linkage may reduce crop clearance height.	Simple design.	No traction on rear wheel.	
12		Four wheels.	Ackermann front wheel steering.	Four / All wheel drive. Front and rear wheels can be driven by central drive motors or independent wheel motors.	Common off-road vehicle configuration. Supplies traction to all four wheels.	Excellent traction off-road.	Additional weight from motors.	
13		Four wheels.	Skid steer - differential steering.	Skid steer - differential drive.	Used extensively for small earth moving equipment. Example: *http://www.clearpathrobot-ics.com/grizzly/*	High manoeuvrability. Excellent traction off-road, Robust design with no steering components	Damage to soil from skid steering. Increased power requirements for skid steering	
14		Four wheels.	Ackermann front and rear wheel steering.	Four / All wheel drive. Front and rear wheels can be driven by central drive motors or independent wheel motors.	Ackermann steering can be achieved with either a traditional linkage or via coordinated independant motors. Traditional linkage may reduce crop clearance height.	Capable of tight turns. Can crab and move close to 90 degrees,	Greater advantages with 4 wheel independant steering,	
15		Four wheels.	Articulated body steering.	All wheel drive. Front and rear wheels can be driven by central drive motors or independent wheel motors.	Articulated body vehicles are common in agriculture, civil engineering and mining applications. Articulated body track vehicles are also common. Turning radius dependent on body geometry.	Central articulation point. Separate payload area	Steering angle increases as length increases. Requires a larger area to turn as wheels don't follow same path.	

Figure 24. Vehicle configuration comparison 3.

AGRICULTURAL ROBOT - VEHICLE CONFIGURATIONS

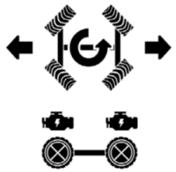
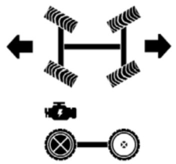
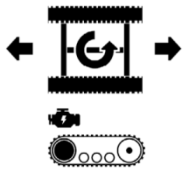
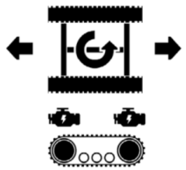
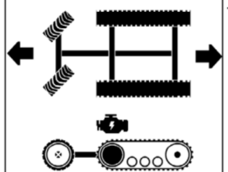
Identifier	Image	Configuration	Steering	Description	Comments	Pros	Cons	Rating
16		Four wheels.	Independent four wheel steering.	Independent all wheel drive.	Configuration used in many agricultural robotic platforms. Allows movement in any direction and .	High manoeuvrability, Able to move in any direction. Traction on each wheel.	Requires 8 motors for steering and drive. Constraints on chassis dimensional requirements for point turns.	
17		Four wheels.	Ackermann front and rear wheel steering.	Front wheel drive.	Vehicle length and width determine steering angle.	High manoeuvrability.	Greater advantages with 4 wheel independant steer-ing,	
18		Tracks.	Skid steer - differential steering.	Skid steer - differential drive.		High manoeuvrability. Excellent off-road capability. Reduced soil contact pressure.	Damage to soil from skid steering. Increased power and weight requirements over wheeled vehicles.	
19		Tracks.	Skid steer - differential steering.	Skid steer - differential drive.		High manoeuvrability. Excellent off-road capability. Reduced soil contact pressure.	Damage to soil from skid steering. Increased power and weight requirements over wheeled vehicles.	
20		Two Wheels and Tracks.	Ackermann front wheel steering.	Track Drive.	Allows for tight steering with little resistance.	Good off-road and on-road capability. Reduced soil contact pressure.	Damage to soil from skid steering. Increased power and weight requirements over wheeled vehicles.	

Figure 25. Vehicle configuration comparison 4.

Figure 26 illustrates the 6 vehicle configurations that were selected as being the most suited for achieving the objective of the project and meet the vehicle requirements.

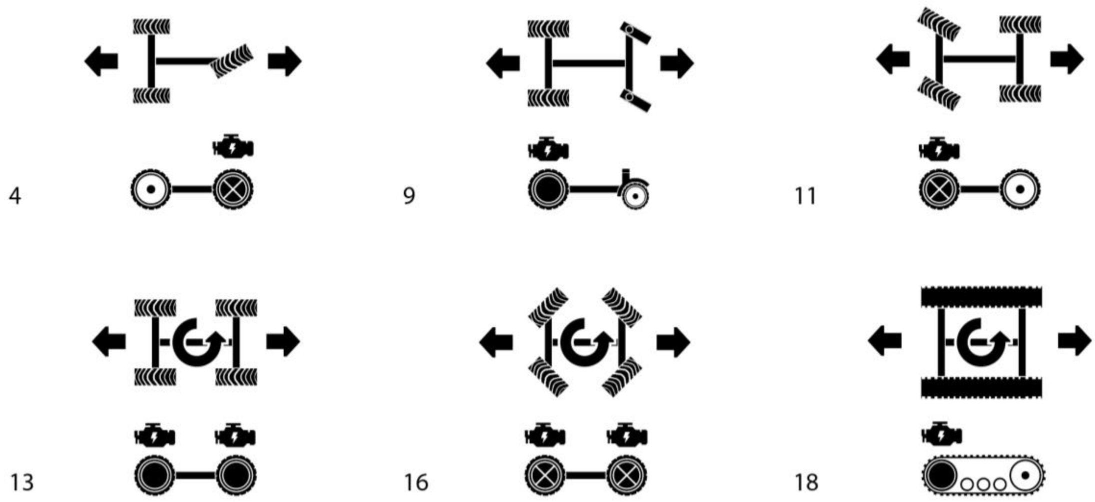


Figure 26. Shortlisted vehicle configurations

3.12 RESULTANT CONFIGURATION

Based on the above review, a 2WD, 4 wheel configuration, capable of bi-directional driving through the use of differential steering wheels and caster wheels was selected as the configuration for further development (configuration #9 in the figure above).

This configuration offered a good balance between driving performance, stability, payload capacity and complexity. 2WD differential steering is not commonly used for off-road driving because of the increased forces required to overcome obstacles. However, in the case of broadacre farm operation, where over 95% of the driving would be undertaken in relatively flat, straight terrain it was determined that 2 wheel drive with differential steering would be a suitable balance between functionality, vehicle complexity and cost. The complexity of construction and control are also greatly reduced.

Key vehicle parameter – 4 wheel configuration with 2 wheel differential steering and caster wheels.

3.13 KEY VEHICLE PARAMETERS

The following Table 6 list the key vehicle parameters outlined in this section. This information is used during the concept development phase of the project to direct the design of the vehicle. This information forms part of the SRFV design spreadsheet, a working document used to capture important information needed to help calculate the power requirements for the vehicle, inform considerations for the drive unit (motor, gearbox and brake), and the suspension system. Based on these key vehicle parameters and the accepted configuration, the conceptual design phase will progress with concept sketching, CAD modelling and rapid prototyping of vehicle designs as shown in the following pages.

Table 6. Key vehicle parameters.

Specification	Measure	Unit	Detail
Vehicle Mass	400	kg	1G Load
Payload	200	kg	
Total Vehicle Mass (m)	600	kg	Total vehicle mass
Rated Speed	5	km/h	
	1.389	m/s	
Max. Speed (v)	10	km/h	
	2.778	m/s	Maximum vehicle speed
Number of Wheels	4		
Drive Wheels	2		
Steering Wheels	2		Differential steering
Width of Wheels	0.3	m	
Width	3	m	Wheel centre to centre
Length	2.5	m	
Height (Implement Clearance)	0.75	m	Underside of implement unit
Operating Time	24	hr	
Operating Gradients	15	%	Inclination (pitch)
	10	%	Banking (roll)

Outside of the scope of this thesis and the development of the prototype SRFV is a detailed analysis of the operating forces acting on the vehicle, along with forces that may occur randomly such as during a vehicle collision.

Many of these forces were unknown at the time of design development, and still are. Further research, experimentation and analysis needs to be undertaken to establish what these forces are likely to be in the environment in which the robot will operate. By making educated estimates on the forces during the detailed design phase, the continued development of the prototype vehicle can take place to meet the tight prototype development timeframe.

3.14 CONCEPTUAL DESIGN DEVELOPMENT - SKETCHES

During the conceptual design phase of the project, many pages of sketches, such as those depicted below in Figure 27, were developed to quickly assess and communicate concepts around vehicle configurations, power storage, implement placement functionality and steering schemes. More Conceptual Design Development can be seen in the appendix.

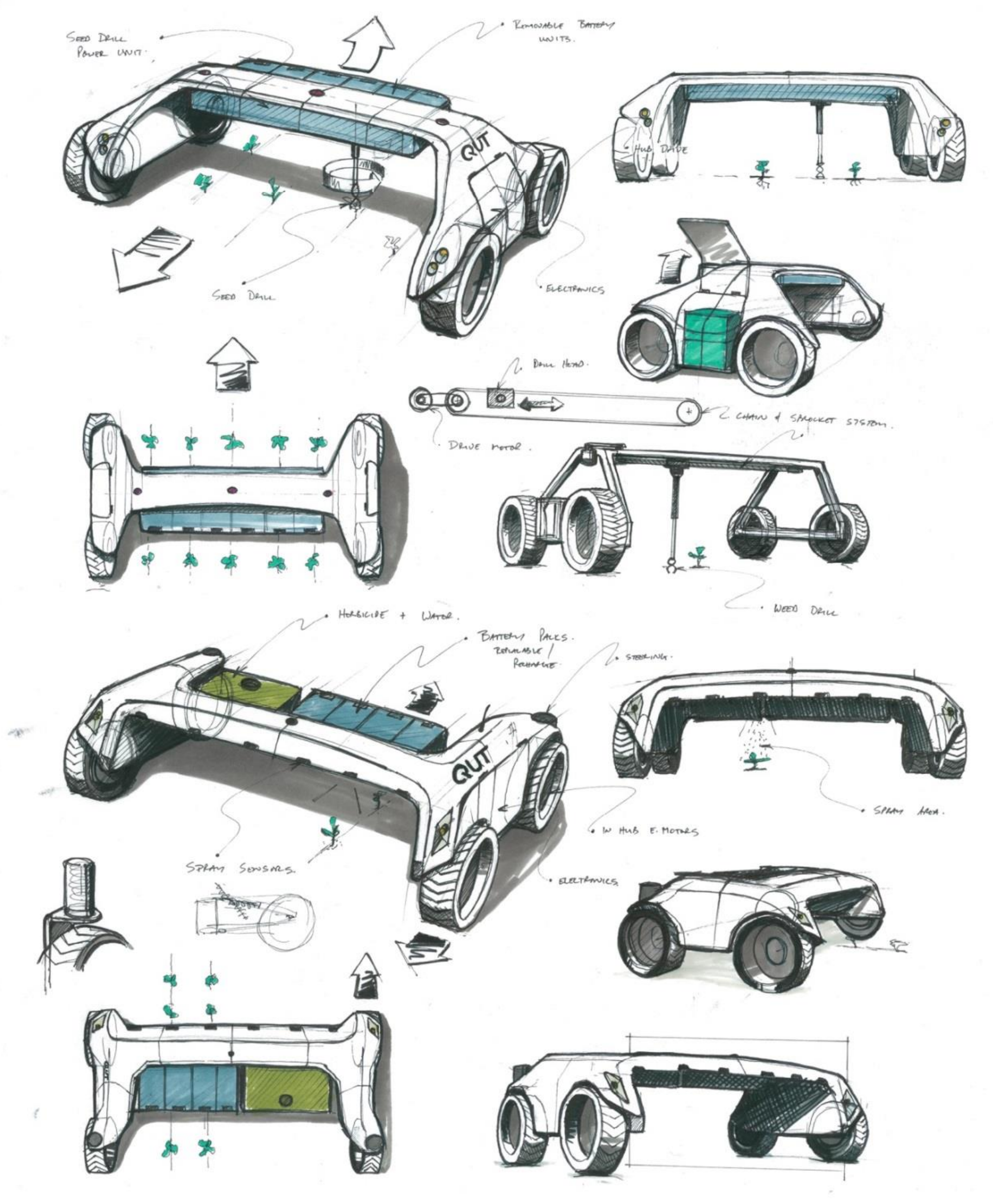


Figure 27. Early conceptual sketches of the agricultural robot illustrating some ideas about form, configuration, implement and battery placement.

3.15 CONCEPTUAL DESIGN DEVELOPMENT - RENDERINGS

Throughout the conceptual design phase, parametric CAD models were used to quickly test options for vehicle geometry along with positioning and size of components like wheels and batteries. Enough detail was worked into the model to effectively communicate the design intent of the vehicle to the project stakeholders through renders like those shown in Figure 28.

Figure 28. Concept rendering of the vehicle showing the development of the configuration, placement of the wheels, power storage, suspension and direction for the vehicle aesthetics.

3.16 CONCEPT VEHICLE DESIGN

Progressive iteration throughout the conceptual design phase refined the direction of the agricultural vehicle. As the concept design developed, more detailed research was undertaken into aspects of the vehicle such as the suspension system, wheel sizes and possible power sources. This fed back into the design to build a more realistic concept. Finally a conceptual design was developed that aligned with the configuration and key vehicle parameters which had been established.

It is important to note that the form of the vehicle concept is influenced by manufacturing and production processes, material selection for environmental optimisation and vehicle configuration for broadacre farming rather than as a result of suggestions or inspiration from the review of literature and alternative platform designs.

The conceptual design developed for the SRFV is a 4 wheeled vehicle, driven by 2WD through in-hub motors. A differential steering scheme in combination with caster wheels was selected with the vehicle being capable of bi-directional driving. The narrow modular side units, suitable for driving between crop rows, contain the vehicle batteries which are mounted between the drive and caster wheels. The interchangeable implement unit is attached between the modular side units and sits at a height that allows the implement to traverse above broadacre crops. The drive wheels are suspended with a single sided swingarm for ease of maintenance and to aid in-crop driving. The vehicle dimensions are 3m x 2.5m, enabling the SRFV to be transported on a flatbed truck.

3.17 VEHICLE SPECIFICATION

A more detailed list of functional requirements was prepared to guide the design of the vehicle during the detailed design phase. These requirements have been placed in the appendix as Table 15 and cover the following areas:

- Environmental considerations.
- Operation.
- Ergonomics.
- Chemical resistance.
- Ingress protection.
- Enclosure design.
- Sensors.
- Dimensions.
- Weight.
- Capacity.
- Locomotion.
- Materials.
- Production and manufacturing logistics.
- Manufacturing cost.
- Lifespan.
- Branding.
- Production design and form language.
- Lighting.
- Safety.
- Cleaning.
- Maintenance.
- Decommissioning

Chapter 4: Detailed Vehicle Design

This chapter describes the design, engineering and fabrication of the prototype SRFV. The vehicle consists of six major assemblies, which are then broken down into minor sub-assemblies. The Drive Unit assembly which includes the electric motor, gearbox and emergency brake will be discussed in Chapter 5:.

The six major vehicle assemblies are:

1. Modular Side Units.
2. Implement Unit.
3. Battery Boxes.
4. Swingarms.
5. Caster Wheels.
6. Covers.

Figure 29 depicts the position of the major assemblies of the vehicle. Due to the symmetrical construction of the vehicle, four of the six assemblies are mirrored and occur on both sides of the vehicle.

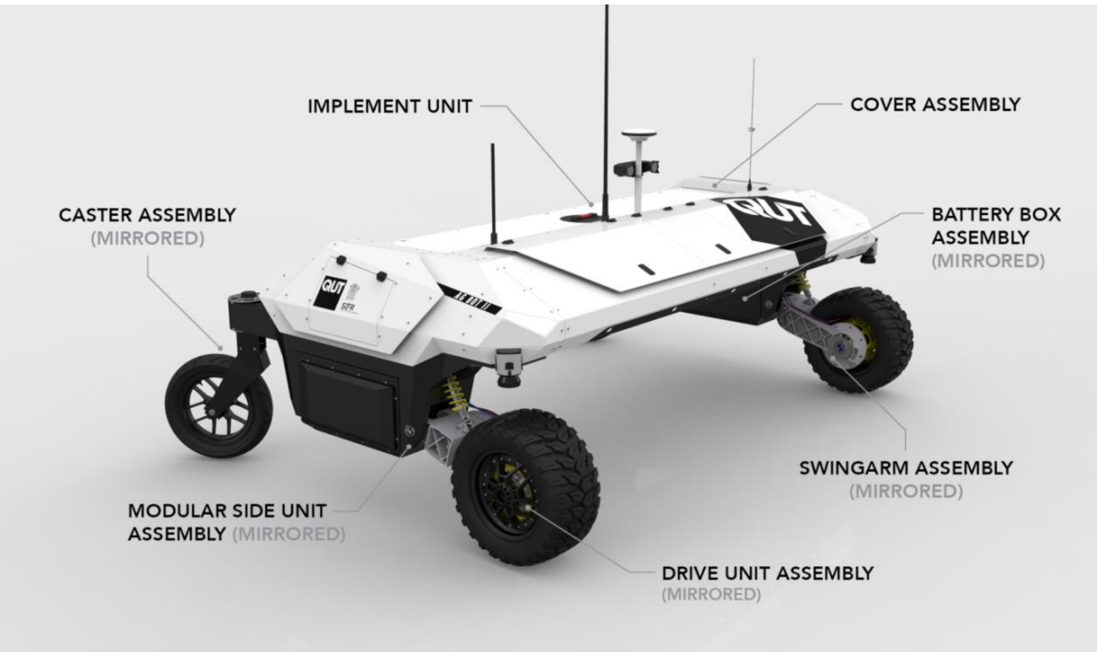


Figure 29. A complete vehicle render showing the major vehicle assemblies in the prototype.

4.1 OVERALL DIMENSIONS

Figure 30 outlines the overall dimension of the prototype SRFV:

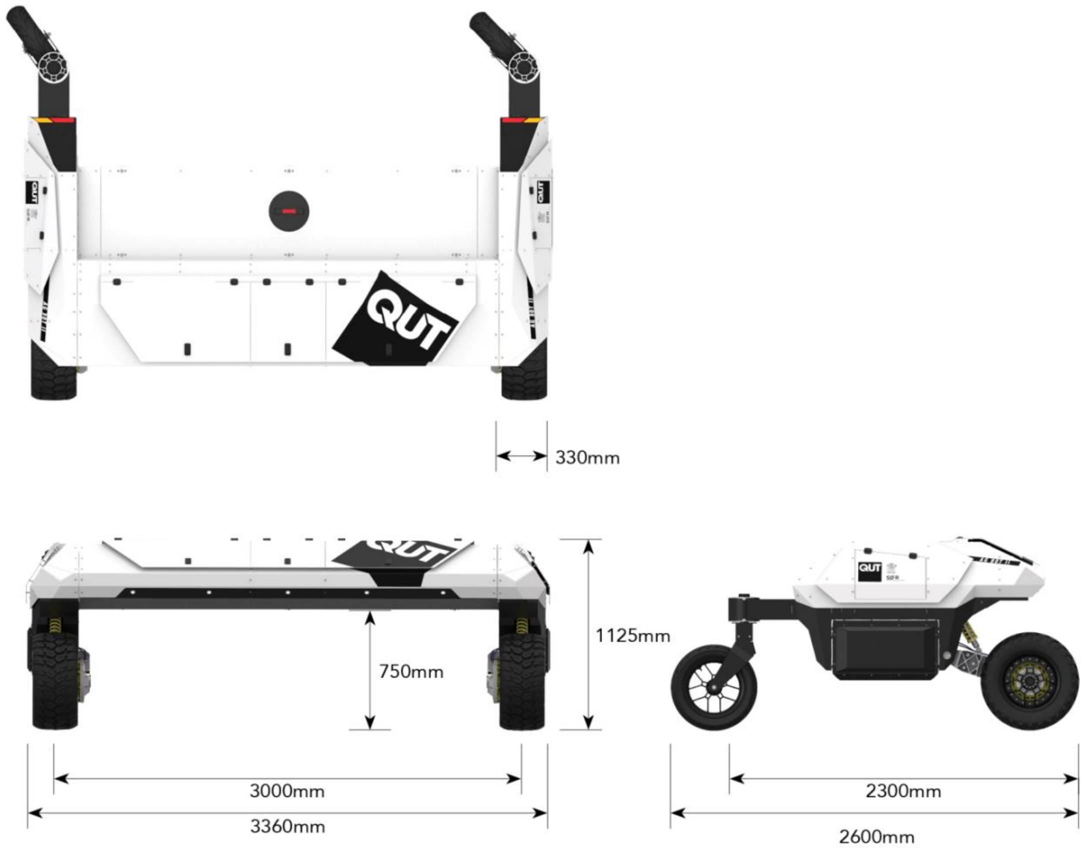


Figure 30. Vehicle dimensions of the prototype SRFV.

4.2 VEHICLE CHASSIS

This section reviews the design of the vehicle chassis developed to meet the operational requirements. During the Conceptual Design stage of the project various chassis construction methods were reviewed and tested for suitability. Designs for the vehicle chassis had to meet objectives around manufacturability, assembly, weight, strength and finish requirements. The chassis ultimately needed to be lightweight, easily and repeatedly assembled with a quality finish without specific tooling or jigs. This early consideration for manufacturing issues helped to shorten product development time, minimise cost and ensuring a smooth transition from design to prototype production.

The design of the vehicle chassis is divided into two main assemblies:

- the Modular Side Unit (mirrored on both sides of the vehicle) and,
- the Implement Unit spanning between the two side units.

An integral part of the rolling chassis is the battery box assembly, swingarm and caster wheel assembly. These will be discussed as separate assemblies later in this chapter. The following Figure 31 illustrates the position of the chassis assemblies.

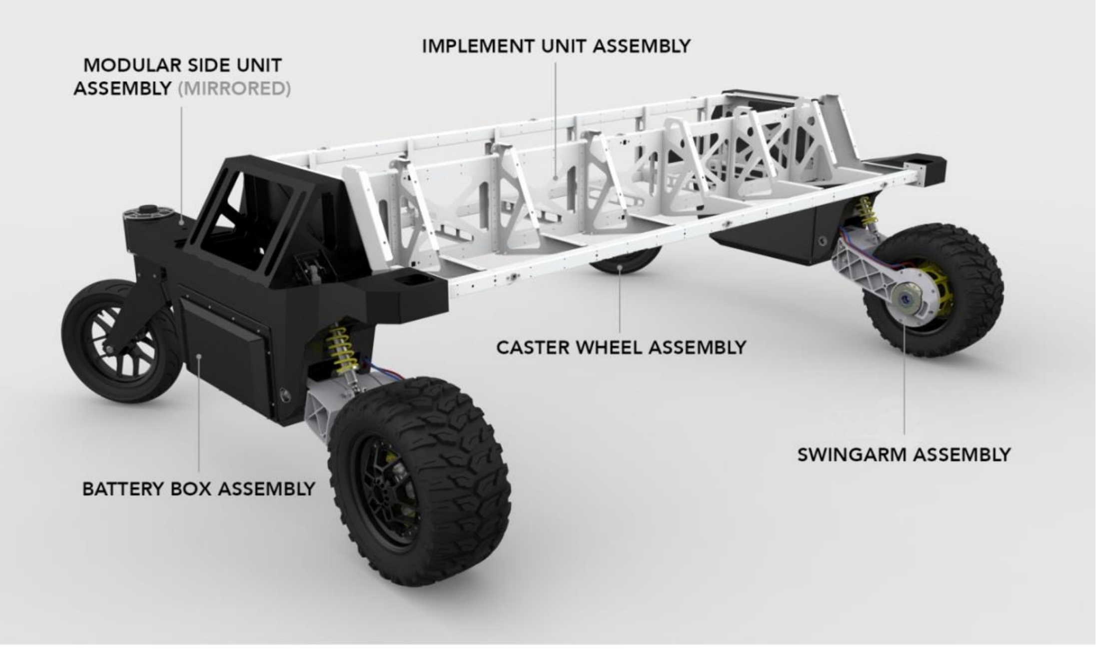


Figure 31. The position of the chassis assemblies.

4.3 MODULAR SIDE UNIT ASSEMBLY

Reference to the CAD file: PN001000a - PN001200a

Function

The modular side unit functions as the chassis for carrying the battery box, caster wheel, swingarm and implement unit assemblies. At 300mm wide the side unit is designed to fit between crop rows without damaging crops. A unibody structural approach was taken to support the vehicle loads through the external skin on the chassis. This design approach also influenced the aesthetics of the vehicle through its faceted structure.

Dimensions

The overall dimensions (L x W x Hmm) of the Modular Side Unit Assembly are 1900 x 300 x 765mm.

An objective of the vehicle design was to enable in-crop driving. A review of commonly used crop row widths in broadacre agriculture highlighted the need to produce a modular side unit that could drive between crop rows with spacing of 500mm. This dimension informed the design of the side unit which was developed to be 300mm wide, leaving 100mm space allowance on either side.

The length of the modular side unit was a factor of the overall vehicles transportability on a flatbed truck. When loaded in an orientation perpendicular to the truck the maximum length of the SRFV would be 2.5m. Other factors limited this dimension until the final length of 1.9m was reached.

Materials

The complete assembly is fabricated from 1.6 and 3mm mild steel sheet.

Mild steel was selected as the material choice for the initial prototype because of the ability to modify the chassis through cutting and welding if issues were discovered with the prototype.

Fabrication Method

Individual bulkhead and skin components are laser cutting and CNC folded. The entire assembly locks together using a “tab and slot” method. MIG welds are used to secure the panels together.

Design Details & Analysis

The side units were the first assembly to be prototyped and engineered. A variation on a unibody construction method was devised that utilised the external skin of the chassis to support the structural loads while proving the aesthetic form of the vehicle. Unibody is an automobile construction technique in which the body is integrated into a single unit with the chassis rather than having a separate body covering an internal frame [55].

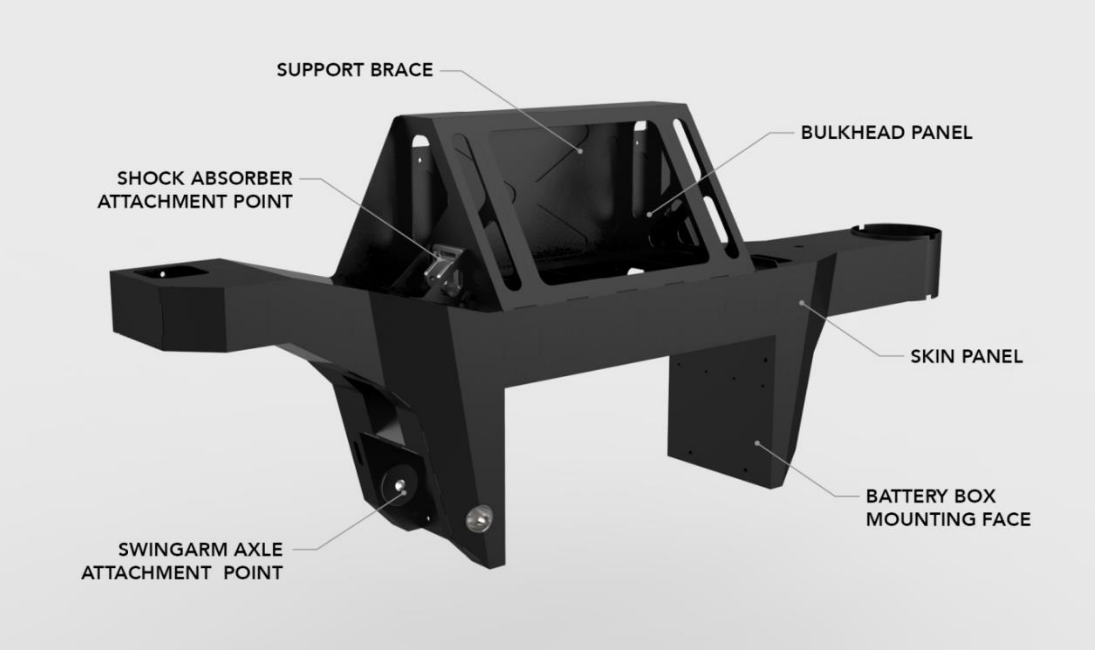


Figure 32. Overview of the modular side unit assembly.

Internal frame chassis, (also referred to as space frames) which utilise a truss structure, were reviewed during the conceptual design stage for suitability and offered a lightweight construction method. However, constructing a chassis using tubular materials involves complicated jigs to cut and align components during fabrication. This went against one of the key design considerations which was to enable quick and repeatable assembly of the vehicle chassis.

Laser cutting sheet materials directly from 2D CAD files minimises part setup and tool changes common in other fabrication methods. Re-positioning components for subsequent machining increases production time and may lower accuracy relative to machining operations made in one take. Laser cutting is also a relatively inexpensive material processing technology compared to hand fabrication or CNC machining.

The design utilises laser cut skin and bulkhead panels that interlock together with tabs and slots to create a ridged chassis. The benefit of this approach is that contact surface area between the chassis components is greatly increased and no secondary alignment jigs are required during assembly. Figure 32 depicts the componentry of the side unit.

This style of manufacturing and assembly removes the issues of alignment of the skin to the bulkheads, an area which generally require time consuming assembly procedures. Using tabs and slots features integrated into the chassis components also provided part registration and improves the speed and accuracy of assembly.

Tab and Slot prototypes in actual materials were laser cut to test a range of clearances. The results of this experiment led to the specification of required clearance between tabs and slots in the CAD model. A clearance of 0.15mm in 1.6 and 3mm mild steel was determined to be the best fit and the addition of small interference features was deemed unnecessary. Figure 33 show the prototype components used for testing.

Figure 33. Prototype tab and slot components, laser cut in 1.6 and 3mm mild steel sheet

Initially it was planned to add a small amount of transitional interference between the tabs and slots enabling the chassis panels to tightly assemble and remain interlocking while final welding was undertaken. Interference was to take the form of a small v shaped features within the slots. A characteristic of the laser cutting process is the pierce point. This is the initial point in the cutting operation where the laser first pierces the material before continuing on its path. Often the pierce point creates a small blowout in the work piece that is relative to the material thickness and laser output. This pierce point was used to act as an interference feature with the tab.

This method of chassis construction is ideal for prototyping and testing alternative materials, sheet thicknesses and panel designs. Parametric CAD models of the vehicle can be easily updated and iterative prototypes tested quickly. As part of the design process two Proof of Principle (POP) prototypes of the modular side chassis were built. These were laser cut from 3mm MDF and were used to test the design for manufacturability, assembly, strength and purpose.

The following Figure 34 and Figure 35 illustrate the process of building the side units. The laser cut parts are assembled together by interlocking the tabs and slots and a small amount of adhesive is used on the panels to represent where tack-welding would take place during assembly in mild steel.

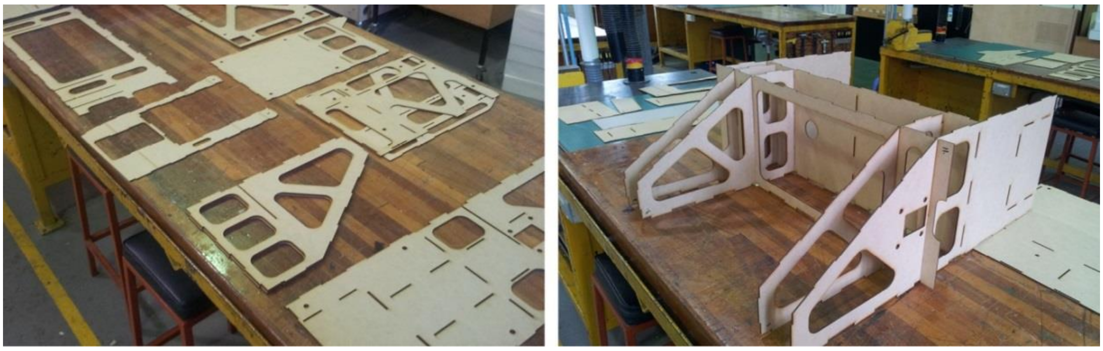


Figure 34. The left image shows the individual laser cut components laid out prior to assembly and the right image shows the assembly of the bulkhead panels prior to attaching the skin panels.

Figure 35. The completed POP prototype chassis ready for testing (left image) and the prototype in-situ (right image).

This construction method allows for intuitive assembly as instructions can be built into the design by varying the size of tab and slots on different panels. This removes the potential for directional error in assembly. Furthermore, the use of flat, laser cut panels in the design eliminates the need to create paired parts (left and right handed parts) for the chassis assembly. The same components are able to be used for both sides of the frame.

Early vehicle design and architecture decisions determine 80% of the cost of the product and significantly influence quality, reliability and serviceability. Early design decisions also determine ease of product manufacturing, along with how easily manufacturing improvements can be introduced. In the case of the side units, detailed engineering and planning was undertaken intensively over a period of several weeks, while the fabrication and assembly of components took less than a day. The laser cutting time for all the components was a little over 1hr and the assembly, welding and finishing took around 3hrs per side.

The images below show the mild steel components for the side units arriving from the laser cutting supplier. Pictured in Figure 36 are all the components required for two complete side chassis delivered flat packed on a pallet. The total weight of each side chassis was around 45kg. The right image shows a test assembly of the components on the workshop floor. All the bulkhead components slotted together accurately the first time and the external facing skin, which required the alignment of 70 tabs and slots, also assembled accurately!

Figure 36. Pallet load of laser cut mild steel components and a test assembly of the side unit.

Components were welded together using a MIG setup at the university. By laying the flat side of the assembly down on the weld table, then slotting all the bulkhead components together, the assembly of the unit took only minutes. Tack-welds were applied internally to lock all the components in place. This was the most labour and time intensive stage in the fabrication process.

The skin of the side unit, made from 1.6mm sheet was braced internally with a thicker 3mm plate around the areas where the implement unit would be fastened. The brace plates support the structural loads on the chassis and act as attachment plate for fastening the implement section. These are highlighted Figure 37 below in green.

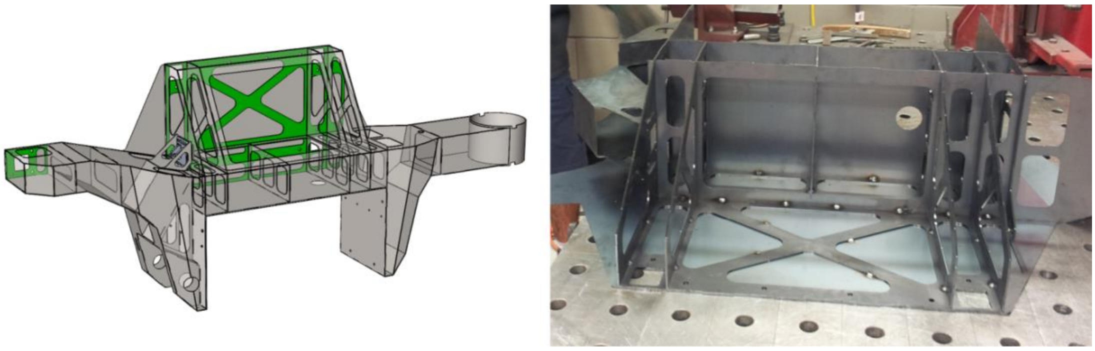


Figure 37. The internal supporting brace represented in the CAD file and as part of the side unit assembly during fabrication.

Additionally, the five cross spans that make up the main structure of the implement unit (more detail on this in section 0) were allowed to penetrate the side unit and act as further load support by working in shear against the side unit. The position of the five support holes in the side unit are indicated in blue in Figure 38 below while the image on the right shows the 50mm steel tubes inserted during the early vehicle mock-up stage.

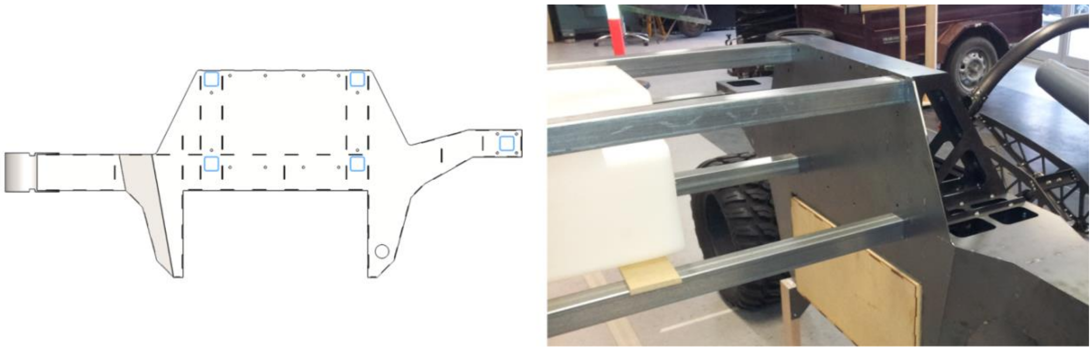


Figure 38. Illustrates support holes built into the side unit to attach the implement unit.

The future of fabrication using this method

Despite the proliferation of robotic prototypes being developed around the world over the past decade, very few have been able to transition to commercialised products. Although there are many reasons for this, the largest roadblocks are the same ones faced by all high-tech products – slow, early adoption rates by the consumer and high fabrication costs due to low initial production volumes.

It was decided that a design and manufacturing method needed to be devised that would allow a small number of units to be fabricated at reasonable cost so that early adopters were not burdened with high unit costs due to the limited initial production runs.

Visiting with farmers highlighted that the skillsets, tools and manufacturing facilities needed to construct these vehicles already existed on most farms. Due partially to their isolation, many farms in Australia are self-sufficient, enabling farmers to efficiently maintain operations, repairs and maintenance on-site. Nearly all have the ability to both fabricate and maintain their own vehicles.

This led us to formulate a design strategy incorporating CNC laser cutting, pressing and machining, to rapidly, at low volumes and low cost, produce complete prototypes or kits that could be shipped to farms and assembled on-site by the farmers themselves. Using a “tab and slot” concept, we’ve been able to create a jig-less design that requires no specialised fixturing to manufacture. Using nothing more than a welder and simple hand tools, the robot chassis itself can be assembled in less than 8 hours by one person.

By eliminating both the labour and facilities needed for producing complete vehicles, initial kits can be offered to farmers at pricing substantially below what a traditional fully assembled robot would typically cost – especially given the initial low production volumes expected. This could deliver a large number of units into the hands of farmers without the need for significant infrastructure build-up typically required for vehicles of this size. Once a revenue stream is established, it would allow for a dedicated manufacturing site to be developed and complete vehicles built for those farmers interested in purchasing fully-assembled vehicles.

4.4 IMPLEMENT UNIT ASSEMBLY

Reference to the CAD file: PN001000a - PN001450a

Function

The implement unit spans between the two side units. Its function is to set the width of the vehicle, stabilise the side units to prevent misalignment when driving, and to carry a payload of sensors, electronics, implements and liquids for various agricultural and experimental tasks.

Dimensions

The overall dimensions (L x W x Hmm) of the Implement Unit are 2700 x 1140 x 422mm.

Materials

Fabricated entirely in aluminium, the implement unit uses three specific grades - 5005 and 5083 and 6060-T5.

The 5 square hollow section (SHS) cross spans are made from 2mm 6060-T5 which is very common for extrusions. To achieve the temper of T5, the square tubes are cooled from the extrusion process and artificially aged.

All the components that have fold details have been fabricated from 5005 aluminium. The end brace plates and skin covers have been made from 5083 aluminium.

Integrated attachment points referred to as “hardpoints” were machined form 304 Stainless Steel.

Fabrication Method

The implement unit is fabricated with laser cut and pressed components. The design incorporates a semi-monocoque construction with a stressed skin bracing five longitudinal cross spans and inter-locking bulkhead components. Rivets are used to secure the cross span, bulkhead and skin panels together. Several panels have been design to be removable with the use of Nutserts and M6 fasteners.

Design Details & Analysis

The implement unit spans between the two side units. Its purpose is to set the width of the vehicle, carry a payload of implements for various agricultural and experimental tasks and house electronic and sensing equipment.

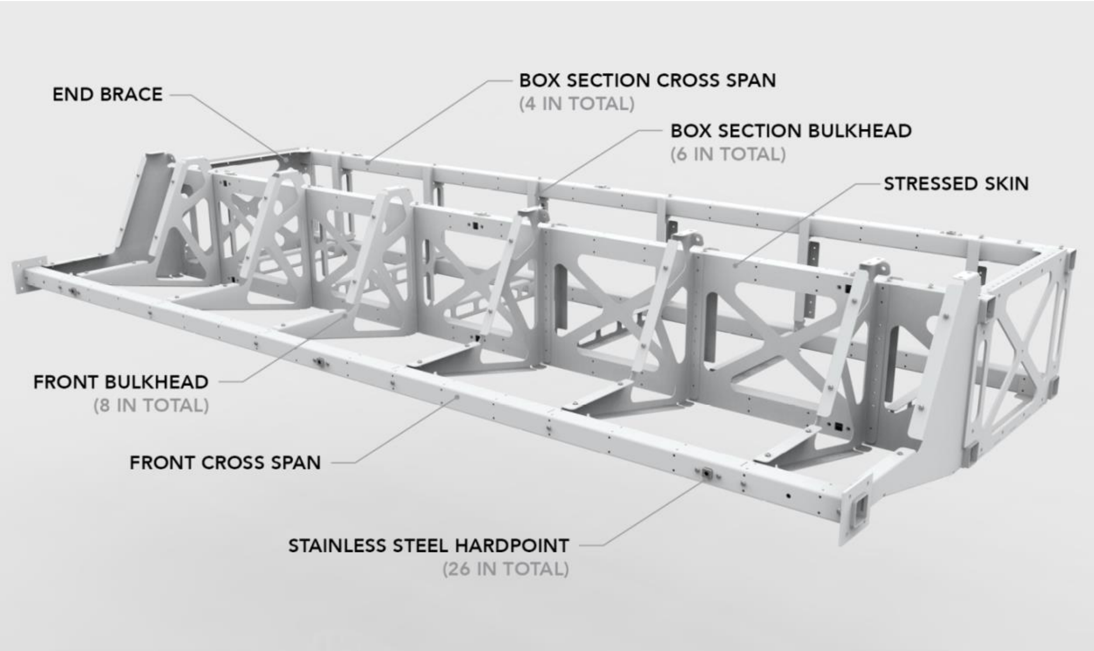


Figure 39. Overview of the implement unit frame (without skins attached).

The design for the implement unit was informed by the requirements of the specification. The width of the implement unit was determined by the overall vehicle width required to achieve in-crop driving on multiples of 500mm crop row spacing. With the 300mm side units running between crop rows, an implement unit width of 2700mm was required.

A second key requirement called for the vehicle to carry 200L of liquid payload. This was to enable testing of prototype applicators for liquid herbicide and fertiliser. 200L of liquid was calculated as an appropriate amount for testing based on a manual refill model. Utilising a 200L tank in conjunction with a WeedIT/WeedSeeker spray system would enable 40ha of coverage in approx. 4hr at a speed of 10km/hr. The tank selected for the prototype was a rectangular design, rotationally moulded in polyethylene. This was selected because it fitted the form factor of the SRFV concept, allowing the tank to span across the implement section. The tank had dimensions (L x W x Hmm) of 1710mm x 440mm x 300mm –and weighed approx. 25kg (empty) and included a 250mm vented screw lid.

A third requirement for the implement was the ability to drive in-crop. As outlined previously, a height of 1m was determined suitable for almost all of crop tasks required in broadacre farming. Analysis of a tipping model determined that the vehicle designed with a payload positioned 1m above ground level would not tip over on operating gradients up to 15 degrees.

Designing the implement unit to be lightweight was another important requirement. A mild steel construction method similar to that used on the side units was considered, however a review of the prototyped side units determined the overall weight and fabrication time could be improved by refining the fabrication and assembly process.

50mm mild steel square hollow section (SHS) tubes with a wall section of 2mm were considered for the 5 cross rails of the unit, however it was concluded that the overall assembly weight by using this material would be too high. The weight estimates for the implement unit had been approx. 50kg. Using mild steel tubing would have increased the weight of this assembly by approx. 25kg. Figure 40 illustrates an early mock-up of the vehicle with SHS mild steel tubes in place along with the 200L tank to represent the implement unit.

Figure 40. Mock-up vehicle assembly reviewing the construction of the implement section.

The implement unit is constructed using a strong but lightweight assembly of aluminium components, laser cut, CNC pressed and riveted together. This particular construction method was chosen for the following reasons:

- The accuracy of laser cutting and CNC folding materials meant that all the components would line up during assembly.
- Using rivets, as opposed to welding components together, allows for the fabrication of the assembly with simple hand tools only.
- Rivets also gave uniform strength across the assembly. Lack of weld penetration was no longer a problem.

- A riveted construction method also enabled the use of Clecos (see appendix section on Clecos) to assist with positioning components during assembly. Clecos are useful for temporarily positioning and attaching panels together prior to riveting.

The basis for the implement unit is five 6061-T6 Aluminium SHS tubes with a 2mm wall section spanning between the two modular side units. Each tube has been laser cut on all 4 sides using a CAD defined hole pattern for attaching bulkhead and side panels and mounting the stainless steel hard points.

The tubes are arranged to create a rectangular box section in the centre of the vehicle, with an additional cross support at the front of the vehicle. This arrangement served a variety of purposes. The rectangular box section across the middle of the vehicle located the two modular side units and resisted twisting and paralleling of the units in relation to one another. The front tube helped to further stabilised the vehicle.

The rectangular box section was designed to carry a 200L liquids tank with addition space on either side for other equipment or expanding the tank to 300L in the future. U-shaped internal ribs were fabricated from laser cut and CNC folded 2mm 5005 aluminium and supported the tank. These were spaced 450mm apart in the assembly and interlocked to the aluminium tubes using tabs and rivets. Particular attention was taken to reduce component weight by including weight saving cut-outs wherever possible.

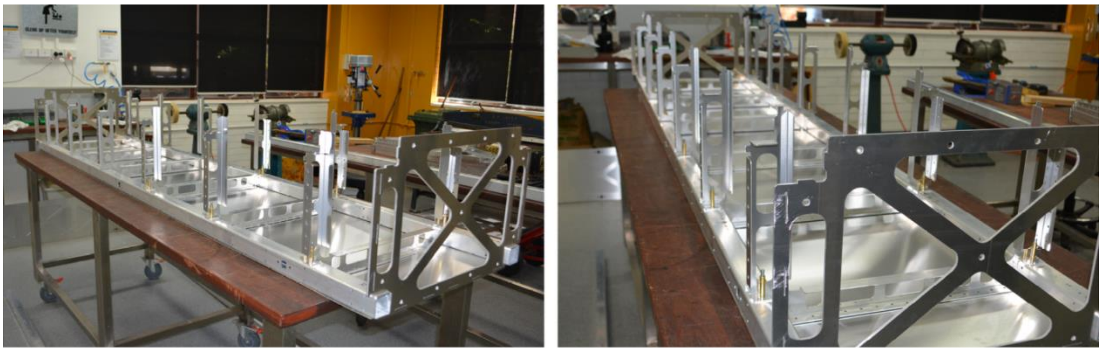


Figure 41. Shows the assembly of the implement unit box section with the bottom cross spans in place, along with the U-shaped bulkheads and the 5mm end braces.

On the attachment face between the implement unit and the chassis, a thicker 5mm 5083 aluminium plate was used. This functions as an end brace to resist twisting while providing a strong fastening surface for attaching the side units. Figure 41 highlights the bottom cross spans, bulkheads and end braces in place during assembly. After riveting the bulkhead to the cross spans, the box section was skinned on three sides in 1.2mm 5083 aluminium sheets and riveted together.

After installing the tank, the top of the box section is fitted with a skin made from 4mm DiBond, a composite sheet material of aluminium-polyethylene-aluminium (see appendix section on DiBond).

The front section of the implement unit was designed to carry an array of electronics and sensors. Although at the time of construction it was not fully known what electronic equipment would be housed on the robot, a review of the e-box on the original AgBot highlighted the need for more space, better organisation and reduced heat loading.

The front section utilises fabricated bulkhead panels that span between the central box section and the front cross span. This creates a shelf area for housing electronics. The front shelf is designed to be removable, enabling cables and other electronic equipment to be stored underneath if required. M6 Nutserts (see appendix section Nutserts) were installed in the bulkheads to allow the shelf panel to be affixed with fasteners. The following images show the inserted Nutserts and the completed implement section (without the front shelf in place, just visible on the floor to the right) ready for powder coating.

It is estimated that the aluminium skin will work to absorb many of the stresses to which the unit is subjected. During continued development and further testing of the prototype vehicle a variety of instruments including accelerometers and strain gauges will be used for monitoring the construction of the implement unit and to ascertain the actual stresses to which the unit is subjected.

Figure 42. Depicts the frame structure across the front section of the implement unit.

Hardpoints for Future Expansion

A further requirement for the implement unit was the ability to carry various implements for agricultural tasks and experimentation. These tasks include weeding, fertilising, crop scouting and seeding. At the time of designing the implement assembly it was not known what tools or sensors would need to be attached in the future, so a method of bolting components to the implement was included in the form of “hardpoints” mounted to the inside of the five cross rails.

Taken from aircraft design, a hardpoint is a location on an airframe designed to carry an external or internal load. Integration of hardpoints creates a point load on the structure. Typically a military aircraft has hardpoints under each wing and under the centre fuselage. These are rated to carry a range of weapon systems, countermeasures or drop tanks.

A total of 26 hard points were machined from 304 stainless steel. The hardpoints include a central attachment hole tapped to suit a M10 fastener and two M6 assembly holes. The hardpoints were positioned internally into the aluminium cross spans and fastened externally with M6 button head screws. Attaching the hardpoints in this manner helped to spread the load on the cross span and remove the potential for the hardpoint to pull out. A set of resulting hardpoint is visible in Figure 43 below. With these in place across the implement section a large number of mounting possibilities are now available for future applications.

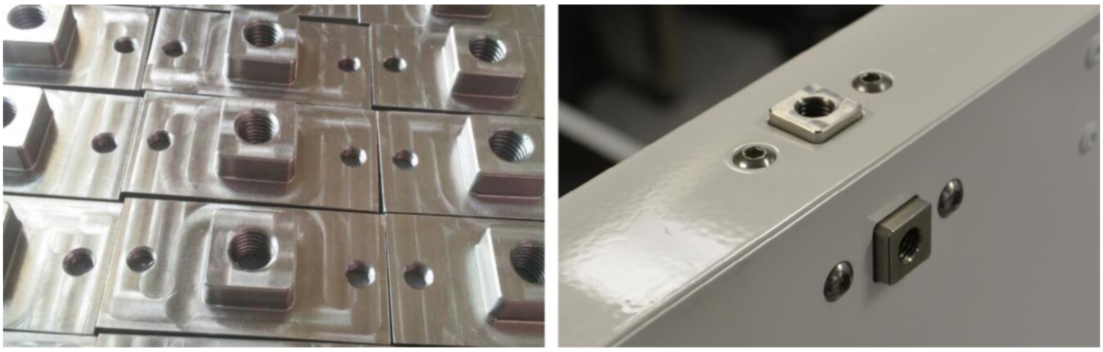


Figure 43. Hardpoints were machined in stainless steel and attached internally to the aluminium cross spans.

4.5 BATTERY BOX ASSEMBLY

Reference to the CAD file: PN001000a - PN001350a

Function

The SRFV has two battery boxes mounted centrally to the modular side units. The mounting position helps keep the vehicles overall centre of mass low. The battery boxes house the Lithium Iron Phosphate (LiFePo4) cells and electronic equipment for controlling the vehicles power supply. Both boxes are designed to be removable from the side units. Each battery box houses 4 x 12V cell packs that can also be removed and replaced if required. An integrated shelf houses the electronic control equipment at the top of the battery boxes.

Dimensions

The battery boxes each have overall dimensions of (L x W x Hmm) of 668 x 330 x 380mm.

Materials

5005 aluminium is used throughout the assembly. 1.6, 2 and 3mm sheet thicknesses are used in the fabrication of the boxes.

Fabrication Method

The assembly is fabricated from laser cut and CNC pressed sheet components rivet together. This is the same construction method used in the implement unit. The faceted door panel has been assembled and finished with internal TIG welds.

Design Details & Analysis

The SRFV has two identical battery boxes mounted centrally to the modular side units housing the LiFePo4 cells, Cell Management Unit (CMU), 2 x Battery Management Units (BMU) and various other electronic components for the control of the batteries. As shown in Figure 44, each battery box houses 4 x 12V cell packs that can also be removed and replaced if required.

Conceptually the design for the battery boxes needed to include the following features:

- Easily removable as a complete unit. This would enable interchanging with other battery boxes as a fast recharge option or swapping with another power source such as a generator for longer continuous operation.

- Strong yet lightweight to carry the weight of the cells. (Approx. 50kg per side)
- Clearly defined areas for the safe storage and operation of the power supply.

The battery boxes are positioned in the centre of the side units. To keep the vehicles centre of mass low, the boxes were integrated as close as possible to the ground while still allowing for clearance when driving over field obstacles or driving the vehicle up a ramp to a flatbed truck.

A complex assembly of components and electronics comes together in a tight dimensional envelope to make the battery boxes work. The 12V cell packs are integrated into the 300mm wide side units to allow for in-crop driving. This dimension was integral to the design of the box and influenced the selection of cells for powering the vehicle. The development of a suitable housing strategy for the cells referenced functional requirements including the ability to remove the entire box and individual cell packs. This led to the side by side 4-cell pack configuration that was adopted.

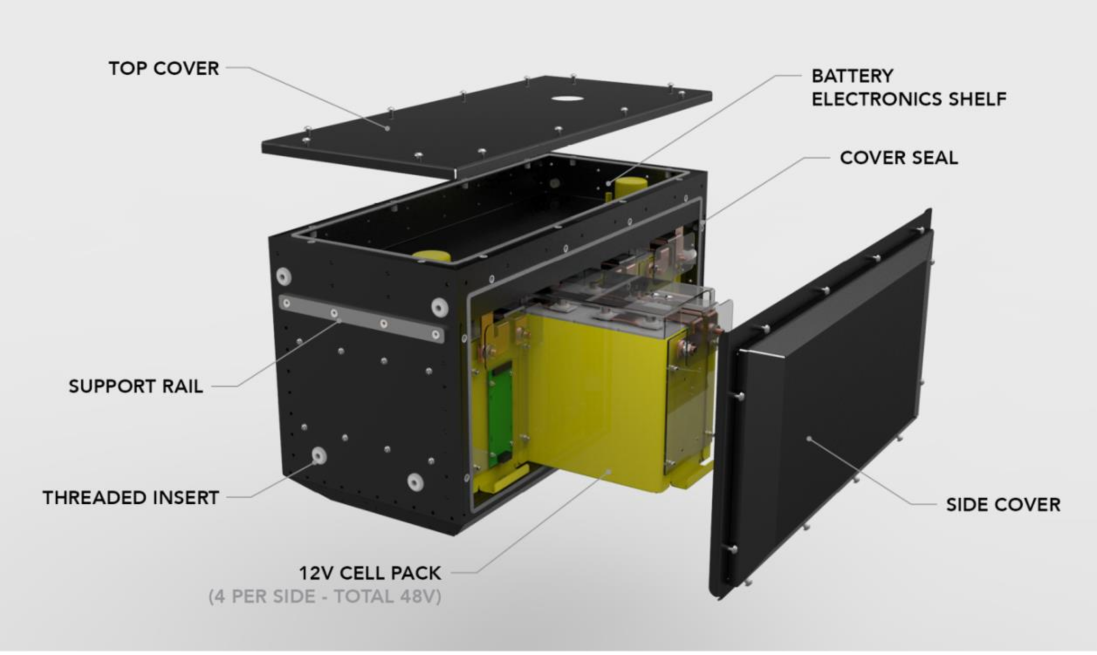


Figure 44. Exploded overview of the battery box assembly.

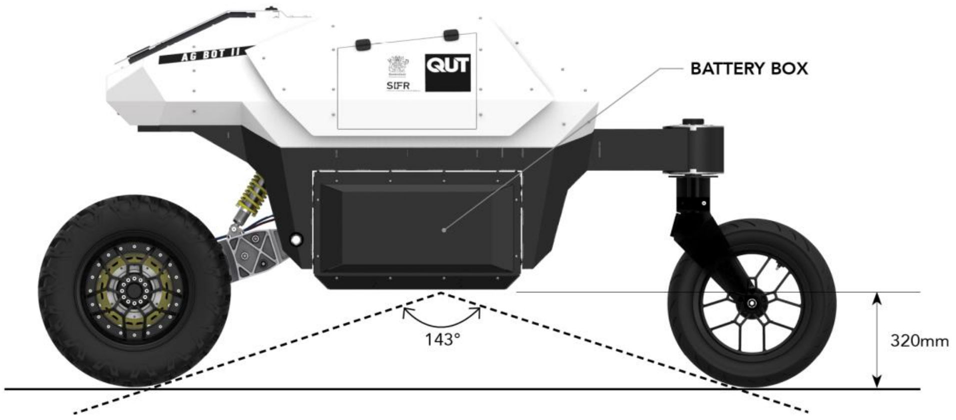


Figure 45. Position of the battery box on the vehicle and the clearance allowance.

Figure 46 depicts the boxes prior to and during assembly. The boxes carry the weight of the batteries and support electronics in a weatherproof enclosure. Seals are integrated into the front and top covers to mitigate water and dust ingress, while sealant is applied internally to further protect the components.

Stainless steel threaded inserts (as showing in Figure 47) have been designed to be retained to the sides of the boxes with a half nut. They include a tapped M8 hole and create a secure fastening point for attaching the boxes to the side units without having to reach into the box and thread on retaining nuts.

Aluminium slide rails (also shown in Figure 47) are attached to the sides of the boxes and side units to aid in the positioning and removal of the boxes. In addition to positioning, the rails also support the weight of the boxes and take the shear stress away from the M8 fasteners.

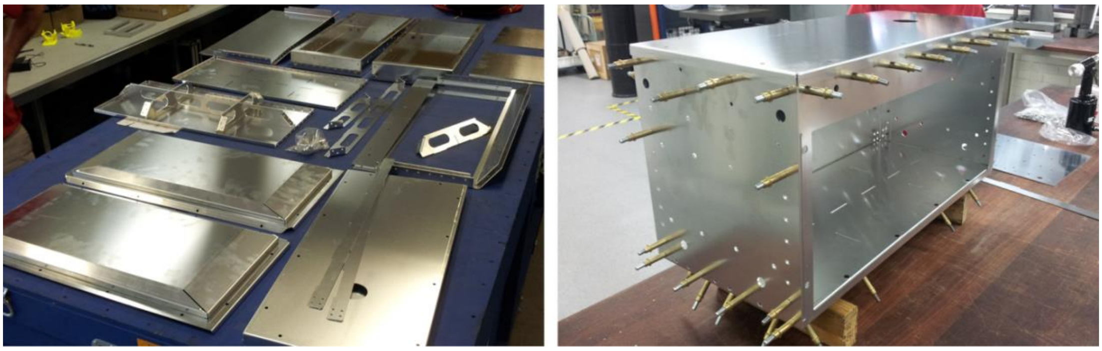


Figure 46. The individual components for the battery boxes prior to assembly and the boxes being assembled using Clecos to positioning the components prior to riveting.

Figure 47. The machined stainless steel inserts are installed into a battery box, providing a solid fastening point when mounting to the side unit. Slide rails are also integrated to aid in the positioning and load retention.

12V Cell Packs

Figure 48 gives an overview of the 12V cell packs used to house the LiFePo4 cells. These are fabricated from laser cut and folded 2mm aluminium sheet. The sides of each cell case were designed with a 90° return. When all the sides are folded up the side returns overlap the front and rear faces. These overlapping surfaces have matching holes that align when folded together. The back holes are riveted internally using countersunk 5mm rivets, while M5 countersunk fasteners are used on the front holes, which protrude through the cell case walls and a 3mm acrylic insulated mounting plate (for attaching electronic components) and are finished with dome head fasteners.

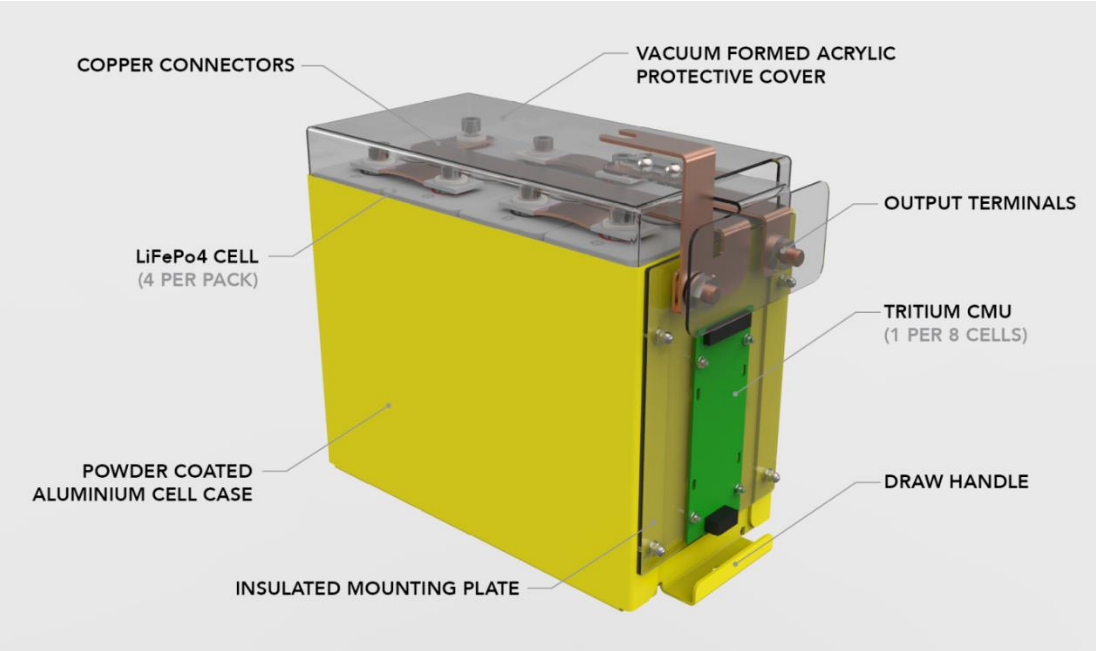


Figure 48. Overview of the 12V cell pack. Each cell pack contains four 3.2V LiFePo4 cells and four packs are installed into each battery box giving a total of 48V.

4.6 SWINGARM ASSEMBLY

Reference to the CAD file: PN001000a - PN001300a

Function

The swingarm functions as the link between the chassis and the drive unit and acts as the main suspension system for the vehicle. The swingarm assembly consists of the single-sided swingarm, axle, bushes, shock absorber and shock absorber mount. Bolted to this assembly via a support “cage” is the drive unit assembly.

The swingarm is joined to the chassis at a higher point than the wheel axle. This provides space for the monoshock to function. In an instance when the emergency brake on the drive unit is applied, the shock absorber compresses and the swingarm draw nearer to the ground. This lowers the pivot point where the swingarm joins the chassis and lengthens the wheelbase, making the vehicle more stable.

Dimensions

The overall dimensions (L x W x Hmm) of the swingarm are 720 x 335 x 700mm.

Materials

Both the swingarm and shock absorber mounts are fabricated from 6061-T6 Aluminium. The drive unit support cage is made from 3mm mild steel. The axle is made from 304 grade stainless steel while the bushes are machined from Nylon 6.

Fabrication Method

The swingarm is fabricated from CNC milled billet aluminium in three separate sections. The sections are assembled and bolted together then TIG welded and post machined.

The drive unit support cage is assembled using laser cut and step pressed components, then fabricated together and TIG welded.

Both the axle and the bushes are machined using a CNC controlled lathe to exact tolerances.

Design Details & Analysis

A detailed review is presented on the single sided swingarm and in-hub drive unit support cage in the following section. Figure 49 depicts the design of the swingarm assembly which includes the shock absorber, support cage and attached drive unit.

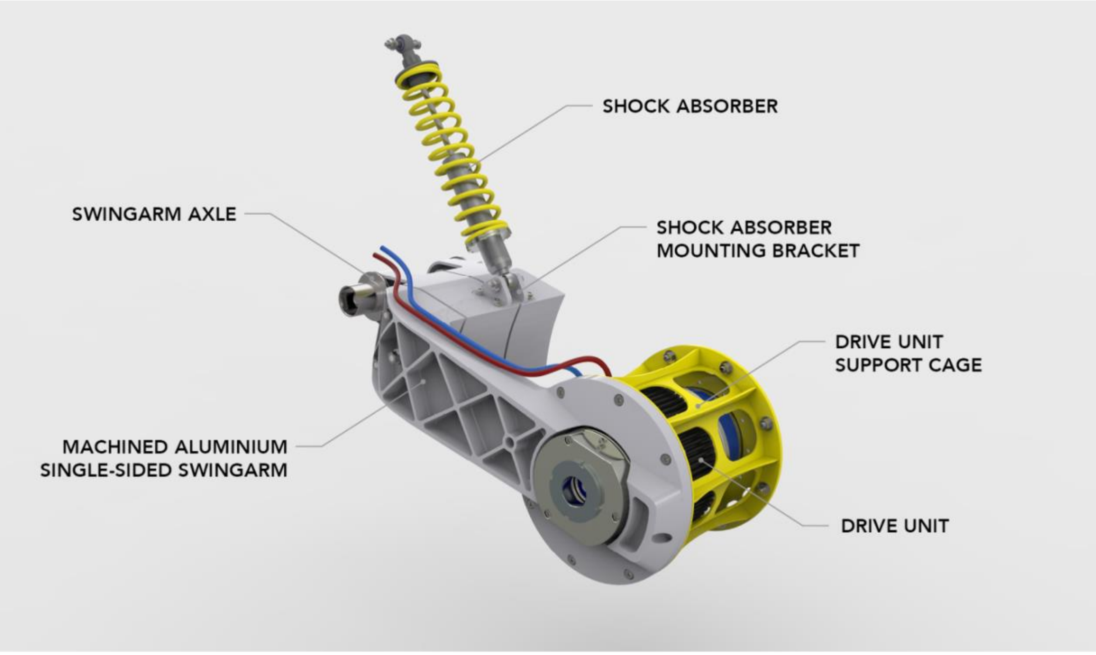


Figure 49. Overview of the swingarm assembly.

Single-Sided Swingarm

A single-sided swingarm was chosen over a double-sided swingarm to support the drive unit and wheel after analysis of various swingarm designs. Key objectives in the swingarm design included:

- Keeping the overall width of the side unit including the swingarm to a minimum to allow for in-crop driving.
- Simplifying access the drive unit by enabling the easy removal of the drive wheel.
- Trialling the fabrication of a lightweight single-sided swingarm using prototype manufacturing techniques.
- Improving the aesthetic value of the vehicle.

Generally a single-sided swingarm will need to be stiffer than a double-sided version to accommodate extra torsional forces. As a result they are generally heavier than double sided swingarms. We set about designing a lightweight single-sided swingarm using prototype manufacturing techniques to mimic what would be achievable with a diecast design used in a mass manufactured product.

The single-sided swingarm will bear all the stresses from the drive unit offset from one side. With a traditional double-sided swingarm, the design needs to have longitudinal stiffness to stop it from bending. With a single-sided design, it needs to also have torsional stiffness to stop it from twisting under the offset load. This resulted in a design that included a great deal of cross bracing.

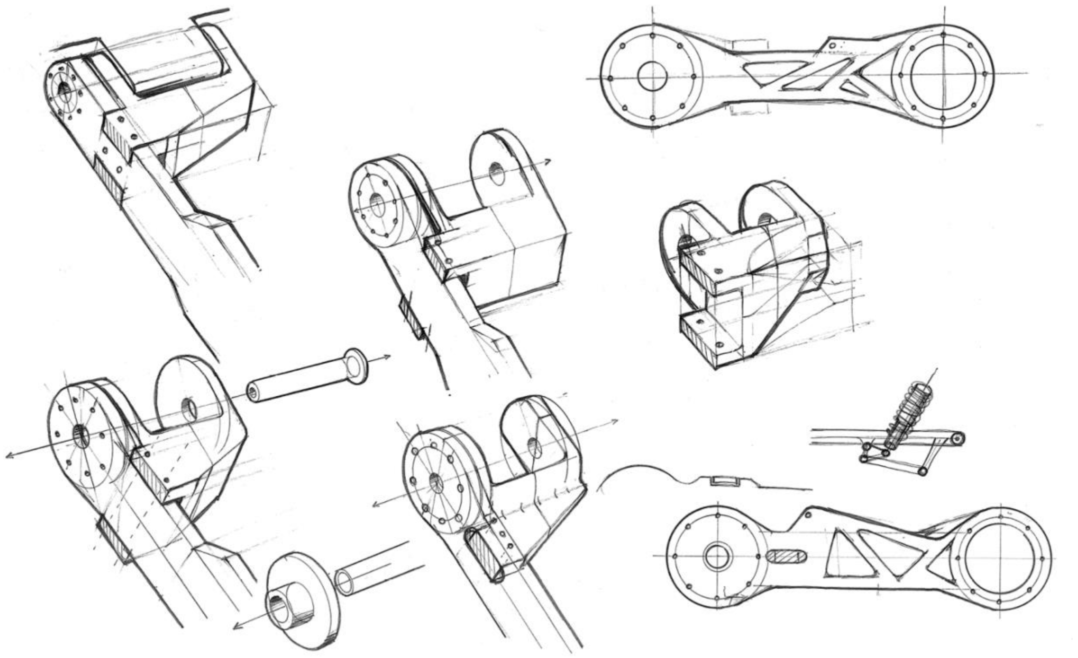


Figure 50. Concept development sketches of the swingarm design.

To keep the design as strong and light as possible, CNC milling in aluminium was chosen because of the materials weight and strength and the expediency of the CAD to CAM to machining operation. Using this process placed some limitation on the design of the swingarm. Swingarm design development was undertaken with conceptual sketches, development models and 3D prototypes to explore various design details. Figure 50 illustrates some the concept sketches for the swingarm.

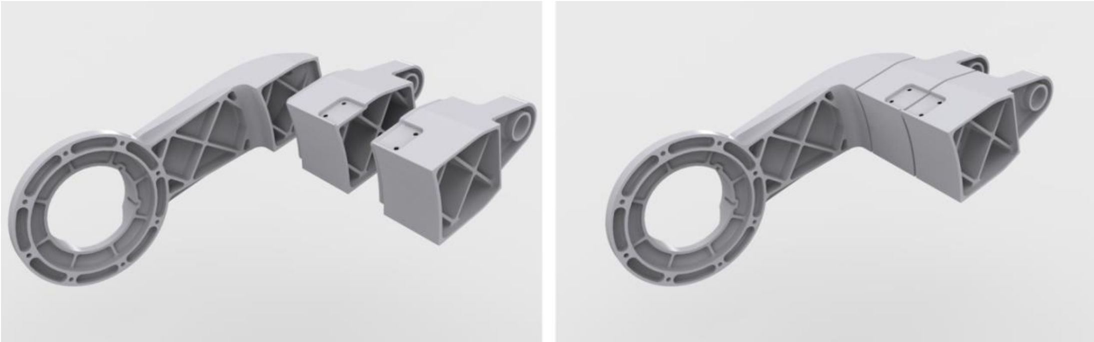


Figure 51. Assembly of the swingarm from three separate components.

Shown in Figure 51 is the final designed assembly for the swingarm. To utilise CNC machining, the swingarm was split into three separate components, each being less than 130mm wide. The three separate components were machined from both sides, creating a central I-beam with support bracing.

After each component was machined individually the swingarm was assembled for joining. Utilising an integrated step feature, the three components were locked together. Three M10 threaded rods were inserted between the components and fastened together tightly. The three components were then TIG welded together using aluminium filler rod along the two joint seams. Post machining of the part removed weld marks and left the final integrated swingarm.

Figure 52 depicts the fabricated swingarm prior to powder coating. Visible in the image are the two weld lines where the three separate components came together. The image on the right shows a test assembly of the parts.

Figure 52. Shows the prototype swingarm prior to powder coating and a test assembly of the swingarm to the MDF prototype chassis to test fitment and mounting of the shock absorber.

In-Hub Drive Unit Support Cage

The In-Hub Drive Unit, (described in more detail in Chapter 5:) consists of the motor, gearbox and emergency brake. To enable the in-hub arrangement to function effectively, the entire assembly needed to be firmly affixed to the vehicle via a swingarm, whilst allowing the drive wheel to attached to the gearbox output face and rotate freely. The method devised for attaching the drive unit to the swingarm was via a support cage as shown in Figure 53.

The drive unit support cage attaches to the gearbox mounting flange, encloses the drive unit and bolts to the swingarm. The support cage utilises the same interlocking tab and slot method employed in the other mild steel assemblies. This creates a very strong but lightweight assembly for mounting the drive unit. The cage has been designed to handle the tension, compression and torsion forces expected upon it during use.

The assembly was broken down into four key components as illustrated in the Figure 53.

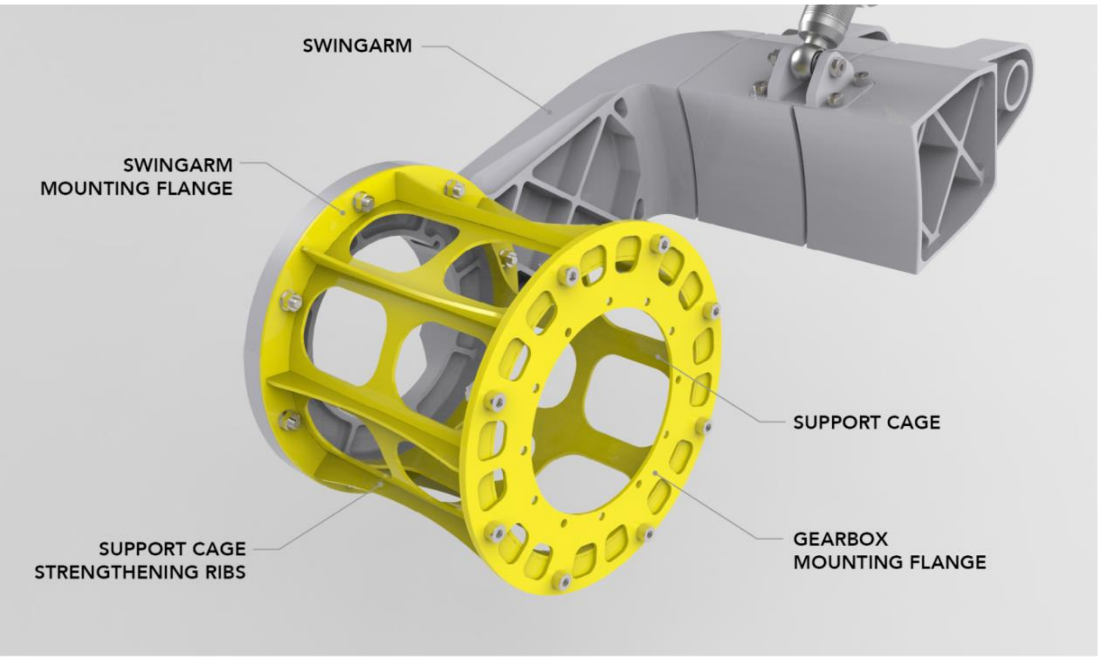


Figure 53. The support cage mounted to the swingarm suspends the drive unit in place.

4.7 CASTER ASSEMBLY

Reference to the CAD file: PN001000a - PN001150a

Function

The caster assemblies work to provide stabilisation and manoeuvrability to the vehicle. A swivel caster design was chosen to provide 360° of rotation, enabling the wheels to roll in any direction. With the used of differential steering on the drive wheels, the caster wheels will pivot and automatically align themselves to any direction of travel.

Dimensions

The overall dimension (L x W x H) for each caster assembly is 563 x 210 x 870mm.

The tyre size is 120/70 x 14" to fit the 14" x 3" rims.

Materials

The 14" rims for the caster wheels have been borrowed from an Aprilia "Sports City" motorcycle and are manufactured from an aluminium alloy such as A380.

The caster fork assembly is manufactured from 6mm and 8mm mild steel sheet, while the swivel bearing housings are manufactured from 6061-T6 Aluminium.

The swivel shaft is made from hardened 40mm precision ground round tube of 52100 carbon steel. The wheel axle is machined from 304 Stainless Steel.

Fabrication Method

The wheel forks for the casters are fabricated using laser cut and CNC pressed components and assembled using fasteners and MIG welding in various areas.

The Aprilia "Sport City" rims are most likely produced using either high pressure die casting (HPDC) or low pressure die casting (LPDC). The internal bearing races have been post CNC machined to provide a precision surface for the insertion of 6202 - 2RSH / C3 bearings.

The caster wheels and frames have been powder coated while the swivel bearing housings have been clear anodised.

Design Details & Analysis

The specification for the caster wheel assembly (as depicted in Figure 54) called for a lightweight, easily manufacturable and robust design. A 360° rotating swivel caster was chosen, enabling the wheels to roll in any direction.

Figure 54. The complete caster wheel assembly is broken down into several minor sub-assemblies including the caster bearing housing, caster fork assembly, spacer and axle assembly and the wheel and tyre assembly.

Two wheel drive differential steering in combination with caster wheels is not commonly used for off-road driving because of the increased forces required to overcome obstacles. However in the case of broadacre farm operation, where over 95% of the driving would be undertaken in relatively flat straight terrain, it was determined that using caster wheel would give the vehicle a suitable balance between manoeuvrability, stability and complexity.

With the use of caster wheels the requirement for precise steering motors on the wheels is removed because the casters will tend to maintain a straight direction. Traversing an agricultural field in a straight line, the caster will tend to automatically align to and rotate to be parallel to the direction of travel. The consequence of this will be the vehicle naturally tending to travel in linear direction.

During turning the caster rotates perpendicular to the turning radius and provides a smooth turn. When executing a turn, the in-hub drive motors will rotate at different velocities and result in different turning radius for each caster.

For the design of the caster assembly a wheel diameter of 14” is used, resulting in a tyre O.D of 550mm. The larger wheel diameter positively affects the ability of the caster wheel to roll over rough agricultural terrain. The ground contact area made by the tyre was minimised by selecting tyres with a very round profile. This had the positive affect of reducing the tyres turning resistance.

Concern about caster flutter or the oscillation side-to-side of the caster was also reviewed. It was suggested that uncontrolled caster flutter may negatively affect driving performance and result in damage to crops. Generally caster flutter is a factor of the speed and weight born by the caster. Based on the speed the vehicle would be travelling (5-10km/hr), the potential that flutter would occur was deemed to be of low risk.

Caster Fork

The design for the caster fork included 190mm of offset (from the centre axis of the vertical swivel shaft and the centre axis of the caster wheel). This equated to a fork angle of 60° and permitted the wheel to rotate around the axis of the swivel shaft and follow behind the direction of movement.

The caster fork assembly is fabricated from laser cut and CNC pressed 6 and 8mm mild steel sheet. Locating tabs and slots are used along with M8 stainless steel fasteners to lock the components together. MIG welding is used during the final assembly of components including the swivel shaft. The left image in Figure 55 show the fork assemblies during fabrication with the swivel shafts attached ready for powder coating. While the right image illustrates the 190mm of vertical offset between the wheel centre axis and the swivel axis, along with the round profile of the tyre selected for the caster.

Figure 55. The caster frame during fabrication and mounted to the vehicle showing the vertical offset.

Swivel Bearing Housings

The swivel bearing housings are designed to attach to the top and underside of the 200mm caster mounting tubes on the modular side unit. These are engineered to be strong yet lightweight components and a feature of the overall vehicle design. A splayed spoke pattern was integrated into the design, in keeping with the context of other vehicle components, particularly the caster and drive wheel centres.

3D prototypes of the swivel bearing housing were produced using Fused Deposition Modelling (FDM). The prototypes were built to test the fitting of the 40mm bearings, while also checking to see how the housing fit to the chassis. The prototype also enabled the form to be assessed for aesthetic purposes. After testing the prototypes, a machined location key was added to the housings that interlocked with slots in the 200mm caster mounting tubes to stop unwanted rotation.

The final design for the swivel bearing housing was CNC machined from billet 6061-T6 Aluminium, giving the component a total weight was 0.5kg. 6908 2RS deep groove ball bearings with an internal diameter of 40mm were used for the swivel. The bearing pockets were machined to H7 g6 fit. In assembly the bearings required a light tap to seat with the housings.

The bearing housings are shown below in Figure 56.

Figure 56. The CNC machined bearing housing prior to having the bearing fitted, and the final assembly with the 40mm bearing seated in the machined pocket.

The swivel shaft was made from a 40mm precision ground round tube of 52100 carbon steel. A ceramic cut-off tool was used to dock the tube to length. An additional 5mm section at the end of the hardened tube was removed before welding to the fork assembly to insure against possible cracking.

A 2mm spacer and 40mm shaft collar was used to secure the swivel shaft above the top bearing housing. This was capped off with a CNC machined Delrin (Acetal) polymer cover. A small amount of Sikaflex (polyurethane sealant) was applied to the outside surface of the bearing housing during assembly to remove any play between it and the side unit.

Machined aluminium spacers were designed to balance the offset of the Aprilia "Sport City" rims. These spacers offset the brake rotor attachment feature present on one side of the rim wheel, which pushed that side out farther than the other. Although discussed during the vehicle specification stage, it was decided not to run a brake on the caster wheel for the initial prototype because it was calculated that the braking force of the drive wheel unit would be sufficient to stop the vehicle.

A 15mm O.D wheel axle in 304 Stainless Steel with a machined 14 x 1.5mm pitch fine metric thread completed the caster wheel assembly.

The images in Figure 57 show the assembly of the swivel bearing housing to the chassis.

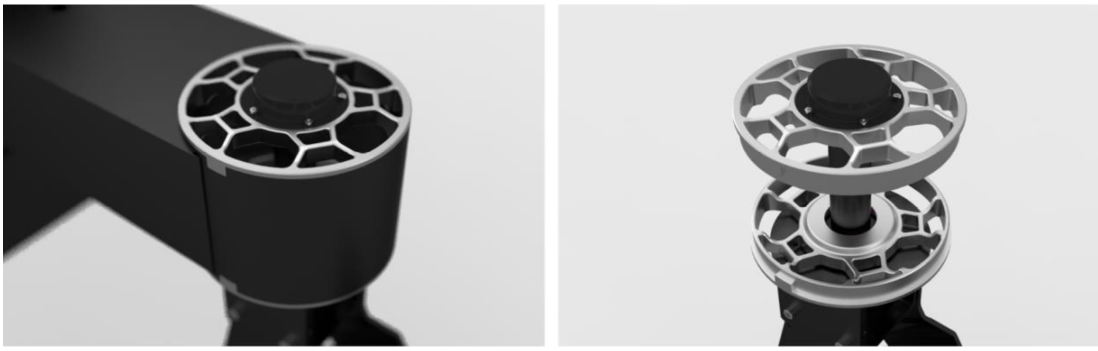


Figure 57. The final machined swivel bearing housing shown seated to the chassis and illustrated with the chassis removed.

4.8 COVER ASSEMBLY

Reference to the CAD file: PN001000a - PN001450a

Function

The cover assembly has two roles in the overall vehicle design, function and aesthetics. Functionally it protects computing, lighting and sensing equipment within an IP rated enclosure. This equipment is accessed via integrated doors providing sealed access. The covers also help reduce the heat-load on the electronics equipment by reflecting a large amount of direct sunlight. Aesthetically the covers imbue the vehicle with a great deal of its form and personality. The faceted shape creates a feeling of purpose and strength about the robot while the light and dark colour scheme produces a clean, futuristic direction.

Dimensions

The covers have an overall dimension (L x W x Hmm) of 1570 x 3300 x 450mm.

Materials

The covers are made from 4mm Dibond, an aluminium-polyethylene-aluminium composite material manufactured in sheets. Internal brackets to support the doors and position the covers are fabricated from 2mm 5005 aluminium. The unequal angle used for the door seals is made from aluminium 6060-T5.

Fabrication Method

The cover sections fabricated in Dibond are CNC routered and manually hand-folded then fastened into their final position. The aluminium brackets positioning the covers from the chassis are laser cut and pressed while the door brackets creating the sealing face against the doors are hand cut and formed.

Design Details & Analysis

The covers have several requirements in the overall vehicle design:

1. Provide environmental protection to the on-board electronics.
2. Define the vehicles character and purpose.

These requirements, along with many others, needed to be balanced during design and engineering development. Earlier conceptual design stages had created a direction for the cover form that was then developed and refined until the final design was reached.

There were many constraints and trade-offs to the cover form that could be implemented. The side and implement units, along with the requirements for housing electronics drove many of the dimensional and angular decision around the covers. The fabrication method and material properties were also critical in defining the shape. These features influenced the size of angles and the shape of facets that could be implemented.

The covers are broken down into 3 separate assemblies show in Figure 58:

1. The central implement cover assembly encloses the implement section and provides a large volume of space at the front of the vehicle for sensing and electronics equipment storage.
2. The right modular side unit cover assembly.
3. The left modular side unit cover assembly. (Mirrors the right cover assembly).

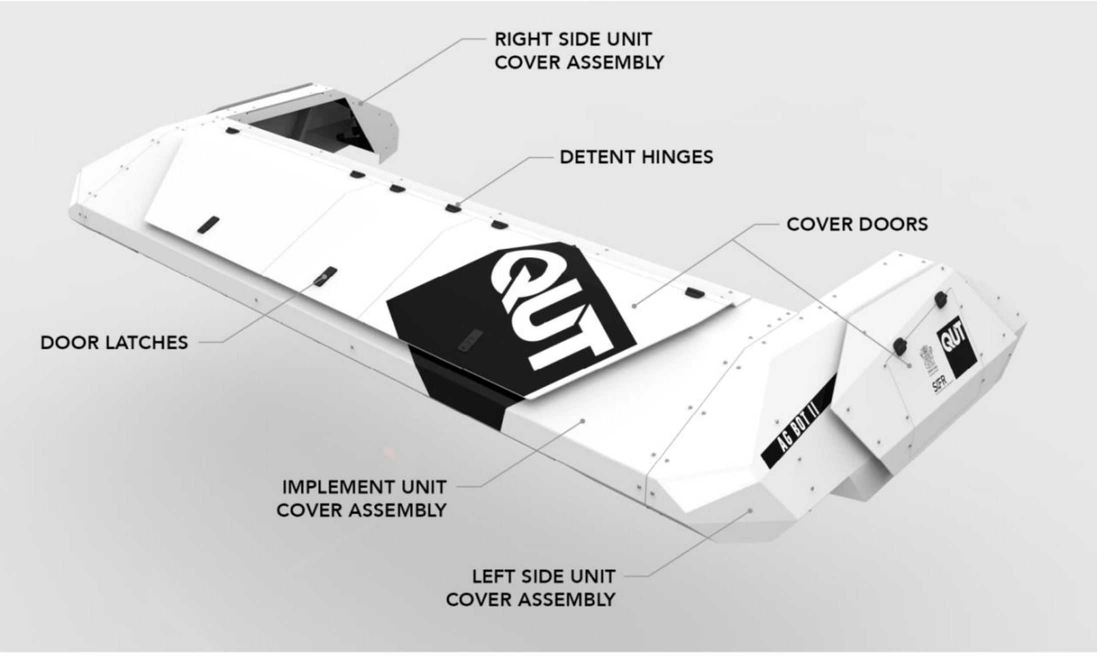


Figure 58. Depiction of the cover assembly

Separating the covers into three sub-assemblies means disassembling the vehicle became less complex. The implement section can be unbolted from the side units without needing to remove the covers. All three assemblies include integrated lift up doors. These are hinged from the top using a lightweight, injection moulded Southco hinge with inbuilt detents. The detents permit the door to remain in an open position at a set angle of 90° and 120°. The doors are also fitted with lockable compression latches.

Aluminium Attachment Brackets

Laser cut and pressed aluminium components were used to create internal compartment walls and stand-off brackets for attaching the covers to the chassis. These were powder coated prior to being installed. Figure 59 illustrates the attachment brackets on the front implement section (left image) and on the side unit (right image). 50mm holes for running cables were included in the design and during fabrication M6 threaded Nutserts were installed in the brackets. These inserts were later used to fastener the covers down to the brackets.

Figure 59. Attachment brackets for the covers mounted to the implement and chassis section.

Door Sealing

To create the sealing geometry for the doors, an overlaying compression seal was chosen. The doors are offset from the body of the covers by 20mm and from a length of unequal aluminium angle a lip was fabricated running around the edge of the cover opening (illustrated in Figure 60 below). The angle was attached to the inside of the covers using VHB 4941 (double sided adhesive tape). The vertical lip created by the angle was capped with neoprene rubber edge trim that sat several millimetres higher than the doors resting position. This meant that when the doors were closed and latched, the neoprene rubber compressed, creating the door seal.

Figure 60. Aluminium edge lip being installed and with neoprene rubber edge trim attached.

Dibond Fabrication

The prototype design involved fabricating a complex 3D form from flat sheet material. This method of fabrication enabled the creation of a high quality finish without the need of producing expensive moulds for the cover in a material such as fibreglass.

With this requirement in mind, research led to the selection of a material called Dibond (see appendix section on DiBond). The material was favoured over standard aluminium sheet because it provided good impact resistance, rigidity and insulation, three qualities required in the prototype design. Using a thicker panel material instead of a thinner sheet material required a method for folding the material accurately without damaging its integrity. It also limited possible fabrication methods and meant that CNC routing became the best option.

The design for the covers started with sculpting the shape in CAD, at first with general forms encompassing the areas of the vehicle which needed to enclosed, and then slowly refining the position and angle of the facets until the general form was created.

Utilising the sheet metal features within Solidworks, the 3D form could be transformed into a 2D flat pattern. By selecting edges of the form to split and faces to fold, various combinations could be tried until a suitable flattening pattern was found. This method of 3D to 2D transfer ensured the design intent was being met by the constraints of the fabrication process.

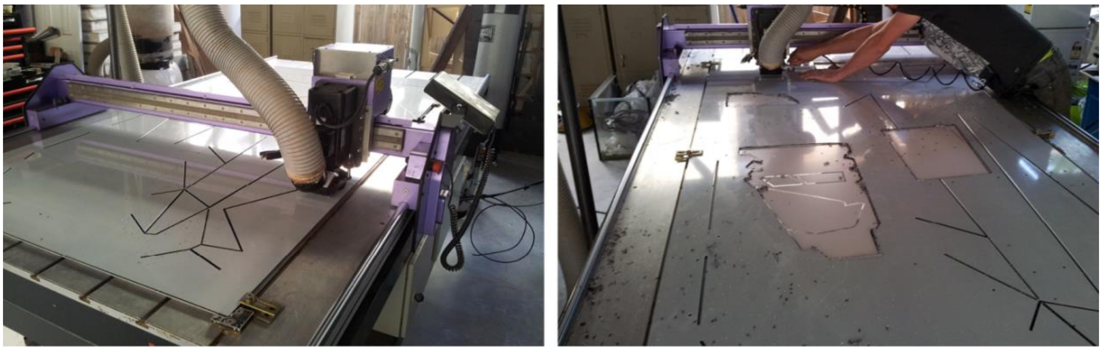


Figure 61. Routing the 45° grooves into the Dibond sheet and then cutting the outside profile.

Using a CNC router table allowed for the accurate position and cutting of each cover profile. 2D CAD data was exported for CNC routing that included information on both cut and fold lines. This meant that the position and relief of folds could be accurately routered into the Dibond sheet. To create sharp folds in the material, a 45° angle cutter was used to cut a groove approx. 3.4mm deep through the underside aluminium and polyethylene layers while leaving the external aluminium layer intact. A 6.35mm router bit was used to route the outside profile and was also plunged into the material where M6 clearance holes were required. Figure 61 shows Dibond sheets being CNC routed.

18 individual panels were cut using this method. These were then folded by hand to create the 3D form before being attached to the vehicle. In order to achieve many of the bends in the covers and have them sit at the correct angle during assembly, it was necessary to over-bend the angles by about 10%. Once the panels were roughly in the right shape they were positioned on the chassis and fastened to the attachment brackets. This pulled the cover panels down firmly against the chassis and locked everything in its final position.

The faceted design of the covers meant that a bend crossed each of the 5 door panels at a particular point. After routing the fold relief groove to create the bend, an aluminium bracket was attached to the inside surface of the door to strengthen the form. This is illustrated in the Figure 62 below. During the routing operation, all holes for fasteners, hinges and compression latches were cut into the Dibond. These lined up precisely with Nutserts in the attachment brackets and enabled the rapid assembly of the covers. The entire assembly was fastened down using M6 button head screws.

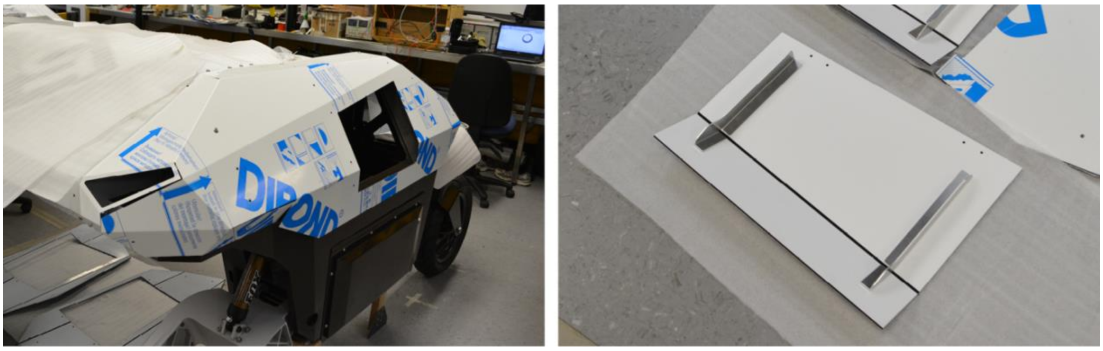


Figure 62. The left image illustrates the side cover panel in position on the chassis prior to being fastened down. The right image show the door structure with aluminium support brackets attached to the inside surface. VHB 4941 was used for attaching the brackets.

4.9 VEHICLE COLOUR

The interior of electronic enclosures under direct sunlight can get hot enough to ruin electronic equipment if not properly shaded or designed to reflect heat. Inlets and outlets for convection mitigate the problem if the ambient air is cool enough, however they may draw in dust and moisture. Active cooling using either thermoelectric or air conditioning, is an alternative but incurs power, installation and weight costs.

In the design of the covers for the SRFV, consideration was made as to the impact of surface colour and ways to reflect the incident solar radiation. Using white covers to reflect sunlight reduces the requirement for artificial air cooling within the electronics areas and may eliminate it completely. White is also a highly visible colour. A study by the Monash University Accident Research Centre demonstrated white as being statistically the safest vehicle colour in all types of light conditions (night/overcast/bright sun) [56].

Solar exposure in Australia

Sunlight is intense near the equator and weaker at the poles. There's also a coastal/moisture effect: cloudy regions experience less solar radiation. Australia has the highest average solar radiation per square metre of any continent on earth. Within Australia, heat loads can be estimated from Bureau of Meteorology maps showing average daily solar exposure. In most of the farming areas across Australia this varies from 12-21 MJ/m2 per day [57].

Sunlight and heat will also reflect off surrounding surfaces. This can increase the solar loading. So, even a shaded surface might experience significant heating. The surface finish plays a part, too. Older and rougher finishes absorb more radiation.

Absorption and reflection

Albedo is the diffuse reflectivity or reflecting power of a surface. It is the ratio of reflected radiation from the surface to incident radiation upon it. Its dimensionless nature lets it be expressed as a percentage and is measured on a scale from 0 for no reflection of a perfectly black surface to 1 for perfect reflection of a white surface.

When light falls on an opaque surface, it's either reflected or absorbed. Reflection is what gives objects their colour. Sunlight contains all wavelengths of visible light. However object appears a particular colour because only that light wavelength is reflected off the surface. Red paint reflects red light, blue paint blue light and so on. Something that looks white is reflecting all the light falling on it. For a black surface, the opposite is true; it's absorbing all that energy. The best way to minimise solar load on an electronics enclosure is to paint it white, with the effects being substantial.

Practicalities

White isn't always the most practical colour and it will become dirty on the farm. It was decided that the functional benefits of using white in respect to the protection of sensors and electronics equipment outweighed the negative visual consequences of the vehicle getting dirty. Also, as mention previously white is statistically the safest vehicle colour, an important practical consideration for an autonomous vehicle.

Chapter 5: Drive Unit Design

This chapter describes the design of the in-hub drive unit, consisting of the motor, gearbox and electric emergency brake after describing the power requirements, component specification and calculations. This chapter also discusses the design and assembly of the two drive units for the prototype SRFV.

5.1 DRIVE UNIT CONSIDERATIONS

When specifying the drive requirements for the vehicle, the following questions in Table 7 were considered. These considerations were used to help refine the search for motors and gearboxes.

Table 7. Drive unit considerations.

Considerations	Answers
What is the rated speed of the vehicle?	5km/h
What is the maximum speed of the vehicle?	10km/h
What should the acceleration of the vehicle be?	2m/s^2
How often will the vehicle be accelerated (% of total drive time)?	1%
How often will the maximum torque be used?	10%
What will the mass of the vehicle be including payload?	600kg
How will the vehicle be driven, central motor, paraxial or wheel hub?	Wheel hub
How many wheels are to be propelled?	2
Will the propelled wheels be equipped with a brake?	Yes
Options: Brake mounted to gearbox and wheel	First option
Options: Brake mounted onto non-propelled wheels	Second option
Will the vehicle be equipped with a switchable gearbox?	No
What slope gradient should the vehicle be able to climb?	15%
On what kind of ground conditions shall the vehicle be able to achieve the climbing power?	Loose Soil

5.1.1 Drive System Selection

A detailed review was undertaken of different types of drive systems including diesel-hydraulic, petrol-electric hybrid and full electric systems. An electric motor solution was preferred as it gives the ultimate flexibility in the choice of the robot's power system. All power technologies such as commonly used diesel, petrol, battery, and solar can be converted into electrical energy.

Highly efficient motors could be sourced at relatively low cost and supplying additional power to other electric systems on-board the vehicle was simplified. Some of the drawbacks of fully electric systems included the current cost of batteries and components, operating and recharge times and many farmers inexperience in dealing with electric vehicles. With careful design consideration, many of these issues can be diminished.

Analysis was undertaken of the power requirements to traverse agricultural environments. These requirements are then used to design an appropriate drive and power system. Agricultural vehicles will operate in a wide variety of field conditions such as loose soil, compacted soil, paved roads and wet soil. They also need to handle a range of varying gradients, including sloping fields, contour banks, small slopes between fields, and steep ramps around workshops.

Rolling Resistance

Rolling resistance is the force that resists the motion of a body rolling on a surface. In the case of an agricultural tyre rolling on soil, the resistant force is a combination of the deformation of both the soil and tyre, and the slippage between the surfaces. Similar to soil bulk density, the rolling resistance is difficult to theoretically calculate due to the number of factors affecting the rolling resistance. Errors in estimating the rolling resistance can greatly affect the energy consumption required and reduce the productivity of the vehicle[58]. The rolling resistance is influenced by the following variables most notably: tyre inflation pressure, applied torque, applied load and the soil structure. The rolling resistance of driven tyres varies significantly with the applied torque, and at high ranges may be several times higher than a free wheel [58]. Table 8 outlines the coefficients of friction for various surface types, from smooth concrete through to sand.

At small vertical loads the deformation through the soil remains elastic; however, as the vertical load on the tyre increases the deformation becomes plastic. This plastic deformation creates soil compaction and rutting of the tyre tracks, increasing ground contact and the rolling resistance. During this loading, the tyre will also deform generating heat loss, a component of the rolling resistance [59]. In contrast to the proportionally increasing loading and rolling resistance, the tyre inflation pressure has an inverse relationship to the rolling resistance. This is directly due to the reduced contact pressure of the tyre. For this reason, pneumatic radial tyres have up to 20% lower rolling resistance than bias plies tyres [60]. In comparison to conventional tyres, bogie tracks have similar rolling resistances with less soil deformation. The rut depth is reduced by up to 40% and the soil compaction by 10% compared to wide and soft tyres. This is evident even with the increased mass of the tracks over tyres [61]

Table 8. Rolling resistance coefficients (C_r) [62]

Action	Surface	Coefficient of Friction
Rolling	Smooth Concrete	0.01
Rolling	Packed Soil, Dirt Road	0.02
Rolling	Grassy Field – Dry Crop	0.08
Rolling	Loose Soil, Gravel	0.1
Rolling	Fresh Deep Snow	0.15
Rolling	Wet Soil, Mud	0.2
Rolling	Sand	0.2 - 0.3

Tyres

Radial tyres have internal plies arranged at 90 degree to the direction of travel (or radially from the centre of the tyre). The design of radial tyre avoids having the internal plies rub against each other as the tyre flexes, reducing the tyres rolling friction. This enables vehicles with radial tyres to achieve better fuel efficiency then biased ply tyres.

Bias tires possess plies which run diagonally across the width of a tire. These diagonal plies crisscross beneath the tread and sidewall, running from bead to bead. Generally, these plies are run between 30 and 40 degree angles. The benefit of bias tires is in their ability to tackle rough roads without sacrificing ride comfort. However, these tires also have some negatives. The rolling resistance of biased tires, for example, is diminished due to the angled ply construction.

5.1.2 Specification

The following Table 9 expands on the specification for the vehicle outlining the critical information need to calculate the power requirements for the drive unit and batteries.

Table 9. Detailed vehicle specification

Specification	Measure	Unit	Detail
Vehicle Mass	400	kg	1G Load
Payload	200	kg	
Total Vehicle Mass (m)	600	kg	Total vehicle mass
Rated Speed	5	km/h	
	1.389	m/s	
Max. Speed (v)	10	km/h	
	2.778	m/s	Maximum vehicle speed
Acceleration (a)	2	m/s²	
Deceleration	1	m/s²	
Number of Wheels	4		
Drive Wheels	2		
Steering Wheels	2		Differential steering
Width of Wheels	0.3	m	
Max. load per drive wheel	195	kg	
	1912.95	N	
Drive Wheel (r)	0.660	m	O.D. (Tyre)
Width	3	m	Wheel centre to centre
Length	2.5	m	
Height (Implement Clearance)	0.75	m	Underside of implement
Frontal Surface Area (S_a)	2.25	m²	Side unit and implement unit
Operating Time	24	hr	
Operating Gradients	15	%	Inclination (pitch)
	10	%	Banking (roll)
Coefficient of Friction (C_r)	0.1		Loose soil
Coefficient of Drag (C_d)	0.3		
Density of Air (at sea level)	1.225	kg/m^3	

The following calculations were used to establish the requirements for the drive unit and power supply. There are two important power requirements, the first is the average power required under normal conditions which is used to calculate the total energy storage required. The second is the peak power required under the worst case conditions and specifies the drive size.

First the average typical power is calculated.

The rolling resistance F_{rr} to overcome the coefficient of friction is given by:

$$F_{rr} = C_r mg$$

where,

C_r is the coefficient of friction,

m is the robot mass,

g is the force of gravity.

This was calculated as **588.6N**

The air resistance F_{air} on the vehicle is given by:

$$F_{air} = \frac{S_a}{2} C_d D_a v^2$$

where,

S_a is the vehicles frontal surface area,

C_d is the coefficient of drag,

D_a is the density of air at sea level,

v is the vehicles maximum speed.

This was calculated as **3.19N**

As the effect of air resistance on the vehicle is negligible due to very low operating speeds it isn't included in further calculations.

Further development of the vehicle and testing of the prototype in operational environments may require more detailed analysis of strong wind loads on the vehicle. Australian Standard AS1170 on wind loading can be used to provide guidance during this analysis.

The power P required to move the vehicle is given by:

$$P = Fv$$

Where,

F is the force required to move the vehicle,

v is the vehicles rated speed.

This was calculated as **817.5W.** At 75% power and drive system efficiency this is a continuous power of 1090W. Allowing some power for computing, the average continuous power is estimated at 1.2kW.

The peak force F_{peak} when accelerating was given by:

$$F_{peak} = F + F_{rr}$$

where,

F is the force required to accelerate the vehicle,

F_{rr} is the rolling resistance.

And accounting for gradient the total mechanical power required to propel the vehicle is given by:

$$P = P_{rolling} + P_{gradient} + P_{acceleration}$$
$$P = (C_r mg\cos\theta + mg\sin\theta + ma)v$$

where,

C_r is the coefficient of rolling resistance,

m is the robot mass,

θ is the gradient of the terrain,

a is the desired acceleration and

v is the vehicle velocity.

The worst case power requirement is when the vehicle is required to accelerate on wet soil up a gradient of 15%. Using the previous equation the power requirement increases to 8.9kW.

5.2 DESIGN OF ELECTRO-MECHANICAL DRIVE UNIT

The main drive unit for the SRFV consists of a customised motor, gearbox and emergency brake assembly mounted inside a 14” wheel hub. Significant research failed to identify a suitable commercially available complete drive unit, especially considering the requirement of an emergency brake. Without a suitable off-the-shelf solution available a custom drive unit was designed.

When designing the drive unit, the vehicles drive and power requirements were considered. These where then matched against the torque, efficiency and load specification of the individual components being reviewed. This enabled the construction of a drive unit capable of meeting the vehicle’s specification.

A 5kW electric motor with an efficiency of 75 - 85% at 3200 - 4500 rpm was chosen in conjunction with a 50:1 two stage planetary gearbox to provide energy efficient locomotion at the desired speed range of 5-10km/hr. The electric brake, defined by its maximum braking force was integrated on the design to provide emergency braking. Table 10 outlines the suppliers and part numbers for the drive unit components.

Table 10: Drive Unit Components

Component	Supplier	Part #
Motor	Golden Motor	HPM5000L-48V
Gearbox	Wittenstein	TP050 MF2 50 0G1
Electric E-Brake	Warner Electric	ERD-035-20-M32-024-22-0

Customised mounting plates were designed and CNC milled from 6061-T6 aluminium. These were used for attaching the motor and gearbox intimately, reducing the overall width of the assembly.

The motor shaft was redesigned to extend beyond the rear case of the motor and interface with the electric electronic brake, which is mounted directly to the motor via a modified friction plate.

The entire drive unit assembly is mounted to the vehicle’s single sided swingarm via a support ‘cage’ which transfers the load between the mounting flange on the gearbox and the swingarm. The wheel centre, machined from billet aluminium, is mounted directly to the gearbox output flange which turns the wheel.

Figure 63 presents the overview of the drive unit assembly showing the e-brake, motor and gearbox.

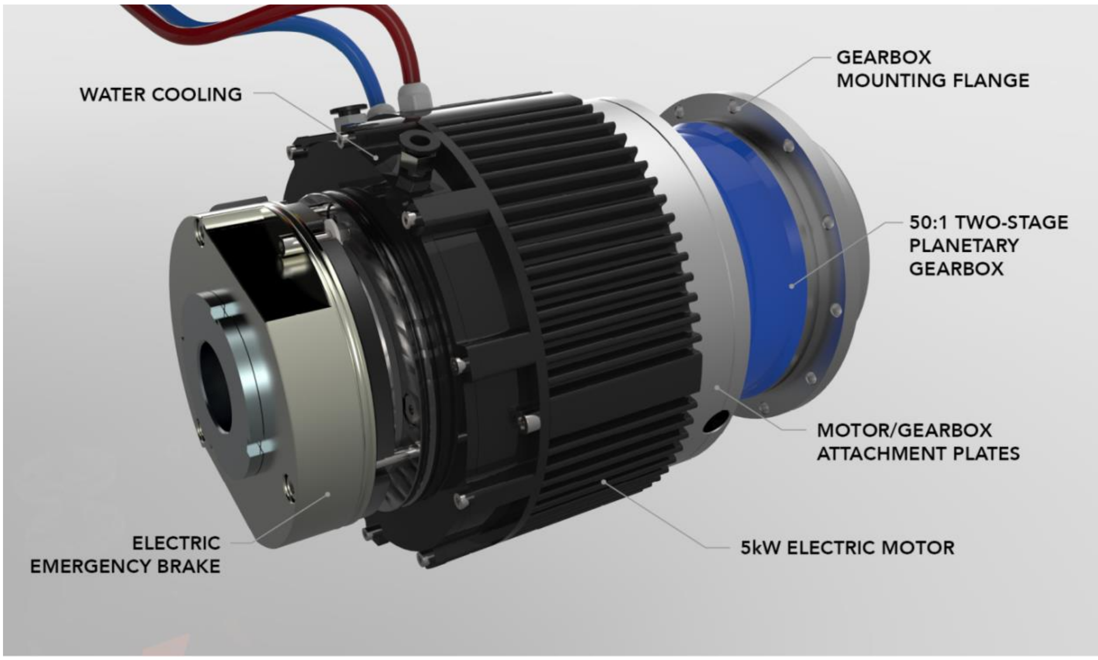


Figure 63. Drive unit assembly showing the e-brake, motor and gearbox.

Modified Drive Shaft

To enable a compact interface between the e-brake/motor/gearbox, modifications to the drive shaft were required. On the gearbox side, the shaft needed to be shortened and reduced in diameter to attach to the gearbox. On the e-brake side, the motor shaft needed to be extended and keyed to enable the mounting of the brake spline. The original and modified motor shafts can be seen in Figure 64 below. Various prototypes of the shaft were made and installed to test the modification and mounting of components. The CAD for the final design was then sent directly to the motor manufacturer (Golden Motor) who machined and installed the custom shafts to the two motors.

Figure 64. Original motor shaft (left image) and the modified motor shafts (right image).

Motor-Gearbox Mounting Plates

Custom mounting plates were designed and CNC milled from aluminium 6061-T6 for mounting the motor and gearbox. Individual plates were attached to the gearbox and the motor and then fastened together. Figure 65 shows the machined mounting plates prior to assembly.

Figure 65. Custom mounting plates for attaching the motor/gearbox.

Drive Unit Assembly

The following images in Figure 66 show the assembled drive unit for the prototype vehicle before and after mounting to the drive unit support cage.

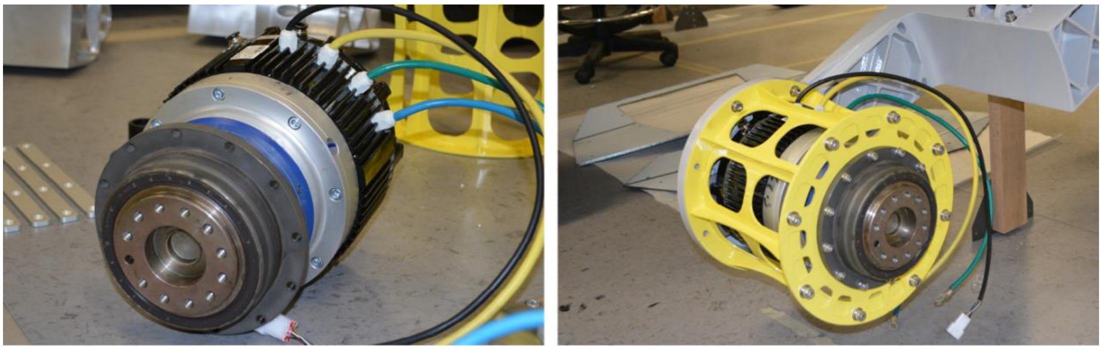


Figure 66. The following image in the complete drive unit before and after installation to the drive unit support cage.

Motor Selection

Table 11. Motor details

Part Detail	Description
Brand	Golden Motor
Model	HPM5000L – High Power
Voltage	48V
Power	5kW (3-8kw)
Cooling	Liquid
Speed	2000-6000rpm
Efficiency	91%
Protection Class	Water Resistant
Diameter	206mm
Width	145mm
Weight	11kg
Motor Shaft	Customisable

Gearbox Selection

Table 12. Gearbox details

Part Detail	Description
Gearbox	Wittenstein 050 Planetary
Translation	50:1 – 2 Stages
Input Speed	5000rpm
Output Torque	350Nm
Torque	Nm
Diameter	179mm (O.D. of the mounting flange)
Width	150mm
Weight	10.4kg

Electric Emergency Brake Selection

Table 13. Emergency brake details

Part Detail	Description
Brake	ERD 35 - 24V DC
Diameter	147mm
Width	65mm
Weight	10kg

5.3 BATTERIES

The batteries are located in the vehicle's two side units between the wheels which will keep the centre of mass low. The two battery boxes are connected in parallel to achieve the desired capacity. There are many different battery chemistries suitable for a robotic farm vehicle. In order of increasing energy densities, the chemistries considered were Lead-acid, NiMH, Lithium metal and Lithium-ion. The main considerations are safety, weight, cost, charge times and ease of packaging. Lithium metal cells are safe under most conditions and fail much more safely than Lithium ion and Lead-acid batteries. Furthermore, Lithium cells are readily available in enclosures meeting UN38.3 – Lithium battery transport safety standards. Lithium metal cells have an energy density of 95Wh and cost AUD$1.6/Wh, comparing favourably to Lead-acid and NiMH chemistries. Lithium-ion cells have a higher energy density although are significantly more expensive. Additionally, Lithium metal cells are typically manufactured as rectangular prisms which make for easier packaging. The illustration in Figure 67 outlines the hierarchy components in the battery box assembly.

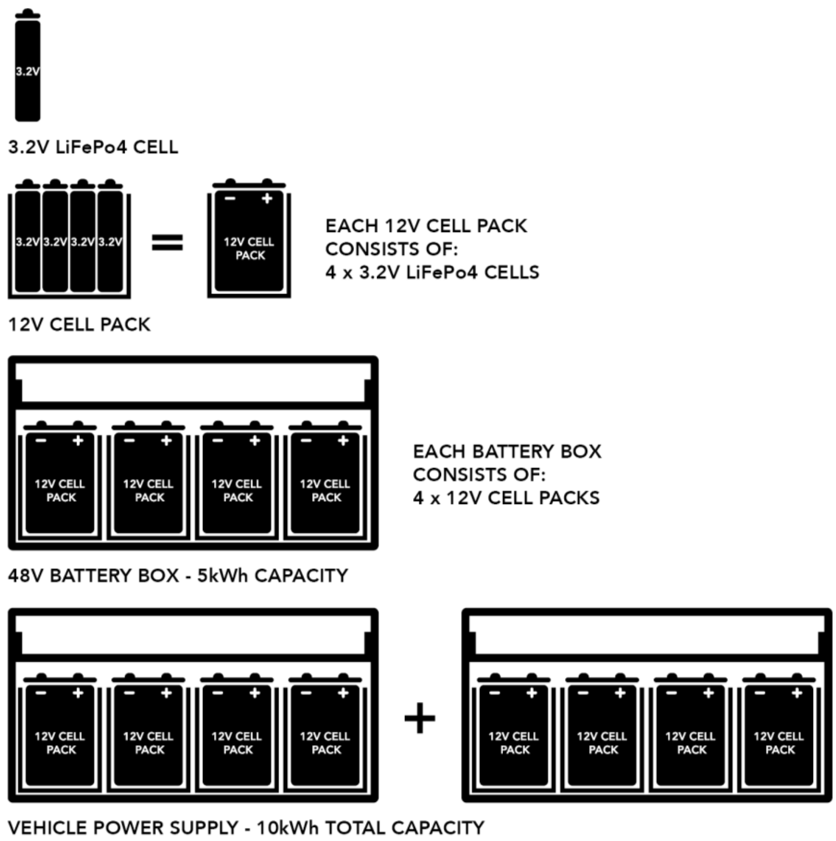


Figure 67. Illustration of the battery box hierarchy of components.

To make the vehicle safe for operators a maximum voltage of 60V was selected. This is below most definitions of extra-low voltage, as defined in AS/NZS 3000. The power requirements from the previous section of 1.2kW typical and 5.4kW peak specify a typical current of 20A and a peak current of 92A.

The vehicle is required to operate for 10 hours on a single charge. Therefore, the vehicle needs to have a battery capacity of around 10kWh. To accommodate this, the batteries are split into two 100Ah battery boxes and placed in each side unit. Each battery box consists of 16 cells in series to yield a nominal voltage of 51.2V and a capacity of 5kWh. The two battery boxes in the side units are then connected in parallel to give a total of 32 cells and an overall battery capacity of 10kWh.

Analysis of battery capacity and resistance was undertaken before specifying the type and size of the battery packs to be used on the vehicle. This looked at the capacity of the battery and drive control system to provide the required current for the motors, taking into account voltage losses from resistance both within the batteries and in the cabling, as well as voltage losses in the control circuitry. As a result of this analysis the vehicle was designed to house the motor, motor controller and battery closely together to mitigate the issue of voltage losses from resistance. This is part of the reason for developing a split battery pack design.

Further research and detailed analysis will be conducted looking into voltage losses in the system as the project progresses and the development of the vehicle prototype continues. This detailed level of analysis was outside of the scope and timeframe of this thesis.

Chapter 6: Summary

6.1 DISCUSSION

Lightweight robotics vehicles integrated into broadacre farming have the potential to enable the sustainable intensification of agriculture by offering solutions to challenges faced by farmers. These include: subsoil compaction, caused by large vehicles designed to optimise an individual farmer's productivity, and herbicide resistance in weeds cause by excessive reliance of chemicals with zero-till farming practices.

Integrating autonomous vehicles into farming will require a systems approach which includes the robotic vehicles, recharging/refuelling stations; safety, navigation and communication systems. Each one of these areas needs to be considered in relation to the other for the system to be well integrated. However, for the system to be successful, the needs, wants and desires of the project stakeholder must be incorporated.

Applying a user-centred design process focuses the requirements of the project on the needs of the project stakeholders (see Figure 1). If done well, solutions emerge that intersect the areas of feasibility, viability and desirability.

The majority of agricultural vehicles which have been developed until now have centred on the functional requirements of the researchers using them. Their purpose has been to test sensor systems, software, driving and steering operations and assess experimental tools for agricultural tasks. These projects have identified the researcher as the major stakeholder and end user and designed accordingly. While including the functionality mentioned above, this project has shifted the focus for the development of the vehicle towards farmers, concentrating on their needs and wants as the ultimate end-user.

A user-centred design process requires the understanding and integration of the needs of the stakeholders during every phase of the project. It also requires insight and lateral thinking to effectively map the needs of the stakeholders and distil these into opportunities for innovation. A key learning from this project has been a heightened appreciation for managing the timing of this process, specifically the importance of ensuring that you are collecting and distilling the information in an appropriate manner, so it becomes useful to the current phase being explored.

With this project, more work needed to be done during the research and conceptual design phases to integrate the requirements of the key stakeholders. Not taking into account the time required to prepare for and receive ethics approval for user research meant that contextual interviews and observational studies with farmers could not be included till after the completion of the prototype design. Developing robots of any kind require multi-disciplinary teams. When pursuing a development project utilising a user-centred approach it's important that the philosophy, if not the details, are well understood and accepted by all members of the team. Defining shared goals and expected outcomes are critical, as is constant communication.

At the time of writing, the prototype SRFV is being prepared for field trials, which will enable the testing of the vehicle's performance to see how it stacks up against the functional requirements (see Table 15). A discussion on whether the outcomes of the prototype design are successful or not based on the vehicle's performance is premature. What can be discussed are the considerations for the design and the methods and outcomes of the prototyping process.

The method utilised during this project for synthesising robotic locomotion configurations was based on a conceptual design method used for rapid product development that begins by defining the objectives of the design and setting criteria against which multiple vehicle configurations can be compared. Criteria include stability, manoeuvrability and the number of driving and steering motors required. Configurations are scored in a matrix against these criteria. The advantage of using this method is that it structures the assessment process and forces the designer to look at alternative solutions and this decreases the probability of heuristic bias and increases the quality of the outcome.

The work of Apostolopoulos [28] on configuration equations may prove to be a more rational method for configuration analysis in the design of future robotic vehicles for agriculture. Configuration equations are mathematical functions capturing quantitative relationships among configurations parameters (e.g. wheel diameter, chassis articulation location), performance parameters (e.g. drawbar pull, maximum gradable slope) and environmental/tasks parameters (e.g. soil geophysical properties, density and size of obstacles). This approach may offer a practical approach to rationalizing configuration design of robotic locomotion through qualitative studies.

The specification and design of the drive unit was of major importance to the vehicle. It was also the source of considerable challenges for the design team. An electric drive unit suitable for low-speed high-torque locomotion, in a compact package, capable of managing the axial loads of the vehicle, with an integrated emergency brake for safety, was not commercially available. At present very few manufactures are making low-speed, high-torque electric motors because the market is requiring the opposite for passenger vehicles and bikes. The companies that were developing these kinds of motors were custom solutions and expensive for an initial prototype.

The design that was developed for this vehicle integrates three components: the motor, gearbox and electric brake. It meets many of the requirements for the drive unit including the output speed and torque, while fitting within the dimensional requisite of the vehicle. Early lab trials have shown the design is capable of efficiency around 85% which was the target. However there are several drawbacks to the solution, notably the lack of a clutch or mechanism to disengage the wheel from the gearbox. It is too early to tell what may result because of this, as no field trials have yet been undertaken, however it is easy to imagine a scenario where the vehicle has stopped in a field due to a failure and is unable to be rolled away. The application of an emergency brake to the rear of the motor shaft is also an unknown factor. Prototyping then testing the application of this brake in lab and field trials will establish the effectiveness of the design.

The first assembly tackled for detailed design was the modular side unit. These were so important because all other assemblies attached to them at some point. Consideration was put into the method of construction, the materials and the requirements for fabrication. The side units were prototyped in 3mm MDF, tested and the design updated with changes before moving to production.

Mild steel was selected for this assembly for several reasons. Firstly, it allowed parts to be welded together easily using standard ARC, MIG or TIG welding equipment. Secondly, it simplified the design and manufacturing process for the components. All the components, except for the outside skins were flat and required no bending operations. Thirdly, using mild steel was seen a guarantee against incidents where components may fail and require repairs. Using mild steel meant the chassis would be easily repaired by welding, even in the field if required.

A review of the side units after prototyping was completed made several things clear: using mild steel as opposed to aluminium increased the weight of the side unit assembly by two-thirds and welding the parts together was time consuming and relied on the skill of the individual to produce quality welds. Although these things were well understood before developing the design, it became obvious that an improved method of construction could be found that better met the requirements for the design. As the design proceeded with the implement unit, construction methods evolved to include lighter materials and a more repeatedly secure fastening method.

Like the rest of the prototype vehicle, the swingarm assembly was a challenging design built on a tight timeline. To meet critical deadlines for developing the prototype we were unable to undertake more in-depth analysis on this assembly. Although outside the scope of this Masters, with more time and resources it would have been possible to undertake finite element analysis on the design to review where stresses and strains were occurring. With this information it may have been possible to create a more refined design for the swingarm. This will be an important next step in the testing and refinement of the vehicle design to be undertaken over the coming months. Integrating this into the design workflow will help to reduce the need for prototypes, eliminate rework and delays, and save time and development costs.

6.2 CONCLUSION

This thesis expands the field of research into agricultural robotics by presenting the design and development of a lightweight, modular, low cost platform specifically applicable to broadacre farming. Prior research into agricultural robotics has focused heavily on solutions for high value crops in the horticulture sector. This thesis looks at the opportunities in broadacre farming and low value crops for the application of robotic vehicles operating in fleets to undertake precision agricultural tasks, such as weed mitigation, fertiliser application and seeding.

As can be seen in the Amazone BoniRob [35], Ladybird [46] Zeus [36], Hortibot [33] and Weedy Robot [34], previous research has focused predominantly on four wheel drive, four wheel steered platforms that come at a high cost and complexity due to the number of drive and steering motors inherent in the design. A major component of this project was researching and implementing an alternative vehicle configuration suitable for broadacre farming that offers optimum traction and steering using the minimum of components.

This project has concentrated on developing a platform solution for broadacre agriculture directed on the end user, the farmer, which is modular, lightweight and low cost, using a variety of manufacturing methods, materials and assembly techniques. The objectives of this project were threefold: firstly, research, specify and design an autonomous vehicle suitable for a range of agricultural tasks (weeding, spraying, crop scouting, seeding); secondly, engineer, prototype and fabricate one vehicle before thirdly, beginning testing, field trials and design refinement for further research and commercialisation.

Research into broadacre farming and the range of present and future challenges facing farmers helped establish general requirements which the design of the vehicle would need to meet. Key components of these requirements are detailed in the specification, a working document which continues to capture features the vehicle must embody to achieve the project objectives.

By its nature, design process is a continual dialogue of trade-offs and compromises, whether it is between power and weight, material strength and manufacturing capabilities or form. The evidence of how well these criteria were met is embodied in the fabricated prototype vehicle. Many aspects of the design require detailed testing and assessment to determine which particular decisions were poor, acceptable or excellent. This period of testing and reflection is required to provide the best feedback on the design development and will help to inform the design of the next vehicle.

The key requirements for the design of the SRFV were set out at the beginning of this thesis in section 3.2 General Robot Requirements. The following is a brief summary of how each requirement was considered in the vehicle design and what the outcomes of each of these requirements were.

The robot must be suitable for a range of precision agricultural tasks related to weed management, fertiliser application and seeding.

This requirement was achieved in several different ways with the design of the SRFV. Firstly, integrating a 200L liquids tank enabled the vehicle to carry a range of liquids for fertilising and weed mitigation. Secondly, incorporating hardpoints into the implement unit will allow the flexible attachment of a wide range of different tools and implements in the future. Thirdly, the modular design allows the vehicle to adjust in width and height to conform to specific farming applications, while allowing for in-crop driving and clearance while driving over crops.

The robot must be capable of autonomous driving over a variety of agricultural terrain including in-crop driving, along farm roads and in fallow fields.

Research and analysis led to the decision to develop a platform based on a 2WD, 4 wheel configuration with differential steering. This can be reviewed in section 3.11 Configuration Analysis. Testing of this platform will give insights into how well this configuration works across a variety of agricultural terrain. At the stage of writing this thesis, the sensor and software integration that will enable autonomous driving of the SRFV had not yet been integrated. This will form part of the next stage of work on the platform and is outside the scope of this thesis.

The robot must be lightweight to reduce or remove the impact of soil compaction.

Designing the vehicle to be lightweight was an important consideration throughout the concept and detailed design and engineering phases. The use of lightweight materials, predominantly aluminium and DiBond (a composite of aluminium and polyethylene) along with weight saving construction techniques gleaned from aircraft design, helped to achieve the weight targets for the vehicle. The experimental use of mild steel in the modular side units was important to test the hypothesis of farmer assembly and reparability with welds. Reviewing this material selection and assembly method helped to move the design towards riveted, laser cut aluminium components, which proved most successful in providing lightweight strength, durability and repeatable assembly.

The robot must be transportable on a standard road-going flatbed trailer.

Reviewing Australian Standards on trailer sizing, in conjunction with information on common crop row spacing and control traffic lane sizing, a vehicle dimension envelope of 3m (width) and 2.5m (length) was chosen. This sizing allowed the vehicle to be transportable via standard road-going trailer. Information in this requirement can be found in section 3.4 Vehicle Dimensions.

The robot must be able to carry payloads of liquid including herbicide, fertiliser and water as well as seeds.

A 200L liquids tank was integrated into the design of the vehicle, spanning between the two modular side units. This allows liquids in the form of herbicides and fertiliser to be stored on the vehicle for direct application to crops. The considerations for the 200L liquid requirement were defined through trade-off in the vehicle weight, coverage, operating speed and operating time. A review of sections 3.6 Vehicle Coverage will highlight the considerations for payload volume as they relate to vehicle speed, refill time, coverage and time to completion. If required the space used by the tank can be made available for alternative storage of seeds or other items, depending on the application requirements.

The robot must be able to carry various implements for agricultural tasks and experimentation. These will include weeding, fertilising, crop scouting and seeding.

This is achieved with the inclusion of 26 stainless steel M10 hardpoints into the implement section frame. These hardpoints enable the attachment of a range of implement and tools for agricultural and experimental tasks. Section 4.4 Implement Unit Assembly discusses the addition of the hardpoint into the design and the benefits of this system for the incorporation of various implements.

The robot must be able to identify (detect and classify) weeds in order to select and apply the most appropriate weed treatment, which includes the integration of novel non-chemical destruction methods.

This requirement forms part of the sensor, actuator and software integration tasks which are currently underway as part of the continued development of the platform. Non-chemical weed destruction methods such as mechanical actuators and microwaves are being considered as part of this project. It is envisioned that the SRFV will be able to carry a variety of weed treatments methods at any one time, selecting the most appropriate method for treating weeds based on a set of predetermined factors.

The robot should be low cost.

The overall cost of the SRFV will be determined through a variety of areas and it is too early to say what the final cost of the working platform will be. By designing the chassis to be constructed using laser cut and CNC formed components, we have created a vehicle which can be quickly and repeatedly assembled. This method of construction minimises production and labour costs. The use of low cost electric motors and standard wheel components has also helped to minimised the vehicle costs. A detailed breakdown of prototyping costs for materials, manufacturing, finishing and assembly has been captured in the Bill of Materials (BOM) for the SRFV and this will be used to analysis the overall costs of the build at a later date.

The robots must be mechanically reliable and easy to maintain.

A great deal of design and development time was put into considerations for reliability and maintenance with an eye on the end user undertaking maintenance tasks themselves. This included designing component assemblies for easy disassembly, building in hatches and openings for access to all areas of the vehicle and selecting materials that could be repaired in the field. Mechanical reliability will be thoroughly tested once the vehicle is running and operational trials commence.

The robot must operate safely in farming environments.

Safety was integrated into the design of the vehicle by minimising catch and pinch points throughout the design, including self-locking latches on the doors, integrating an emergency stop system into the vehicle, and giving consideration for the use of bumpers and perimeter safety systems. Colour and material selection was also important, with white being selected partly to improve visibility in operating environments. Vehicle signage was also considered and integrated into the design to inform users about the dangers of vehicle operation. The integration of obstacle avoidance as part of the sensor and software integration will also enhance the safety of the SRFV.

The robot must be energy efficient; delivering increased levels of efficiency compared to existing technologies as well as incorporating renewable energy power options.

The requirement of energy efficiency was met through a combination of factors in the design of the vehicle. As part of the drive system, a 5kW electric motor with an efficiency of 75 - 85% at 3200 - 4500 rpm was chosen in conjunction with a 50:1 two stage planetary gearbox to provide energy efficient locomotion at the desired speed range of 5-10km/hr. The motors we paired with LiFePo4 cell packs mounted in close proximity to the drive units to reduce losses through resistance. Additionally, the selection of a 2WD, differential steering scheme works to reduce the energy usage of the vehicle by eliminating the requirements for power to other steering and drive motors.

Highly reflective Dibond material in the cover design works to passively reduce the heat load on the electronics enclosure, reducing or potentially eliminating the need for cooling systems on the SRFV. Furthermore, the vehicle was designed to be as light as possible, helping to increase energy efficiency. The future incorporation of renewable energy power options such as solar has also been considered to help offset the power requirements of the computing system.

The overall system must be scalable, allowing farmers to utilise SRFV's on farms of all sizes. Single operators will be able to manage a fleet of robots across large areas

Scalability forms part of the system environment in which the SRFV can operate. This system allows the use of the SRFV platform on farms of all sizes, including single units on small farms to multi-unit deployments on larger farm operations. Multi-agent systems will be used to enable the cooperation of fleets of vehicles across farms. The multi-agent system will form part of the sensor and software integration and will be undertaken in the next stage of the platform development.

By incorporating aspects of both engineering and industrial design practices, this project has been undertaken using a user-centred design process, weaving human factors into technical problem solving. This has led to the design and prototyping of a robotic vehicle informed by the requirements of the key project stakeholders. The solution that emerged from this process intersects the areas of feasibility, viability and desirability. The result is a complete vehicle prototype for agricultural robotics, addressing the requirements defined through research and an understanding of user-needs. The vehicle aims to achieve all of the benefits that have been outlined as follows:

- Lighter impact on the environment.
- Reduced occurrence of soil compaction.
- Multi-purpose vehicle for weed mitigation, crop scouting, seeding, fertilizing and harvesting.
- More manoeuvrable vehicle, reducing the amount of unused land.
- Scalable, allowing farmers to utilise robots on farms of all sizes.
- No single point of failure (multi-robot redundancy).
- Lower vehicle and implement stresses, reducing the complexity of the engineering and the overall cost.
- Variable rate application of inputs for weed mitigation.
- Reduced energy consumption per hectare - reduced fuel costs.
- Better understanding of soil - crop requirements.

Bibliography

1. United Nations, *How to Feed the World in 2050*, Food Agriculture Organization of the United Nations, Editor. 2009.
2. Future Directions International. *Global Food Demand and Supply to 2050: Workshop Summary*. in *Future Directions International*. 2011.
3. Alakukku, L., et al., *Prevention strategies for field traffic-induced subsoil compaction: a review: Part 1. Machine/soil interactions.* Soil and tillage research, 2003. **73**(1): p. 145-160.
4. Raper, R.L., *Agricultural traffic impacts on soil.* Journal of Terramechanics, 2005. **42**(3–4): p. 259-280.
5. GRDC, *Adoption of no-till cropping practices in Australian grain growing regions*, Grains Research and Development Corporation, Editor. 2010.
6. Sinden, J., et al., *The economic impact of weeds in Australia.* Technical Series, 2004. **8**.
7. Day, W., *Engineering advances for input reduction and systems management to meet the challenges of global food and farming futures.* Journal of Agricultural Science, 2010(149): p. 55-61.
8. Kassler, M., *Agricultural Automation in the new Millennium.* Computers and Electronics in Agriculture, 2001. **30**(1–3): p. 237-240.
9. Engineers, I.-I.o.A., *Agriculture Engineering: A key discipline enabling agriculture to deliver gloval food security.* . 2013: p. 58.
10. Newcombe, R., *From client to project stakeholders: a stakeholder mapping approach.* Construction Management and Economics, 2003. **21**(8): p. 841-848.
11. Gulliksen, J., et al., *Key principles for user-centred systems design.* Behaviour & Information Technology, 2003. **22**(6): p. 397-409.
12. National Farmers Federation, *The Blueprint for Australian Agriculture | 2013-2020* 2013.
13. Godfray, H.C.J., et al., *Food Security: The Challenge of Feeding 9 Billion People.* Science, 2010. **327**(5967): p. 812-818.
14. UK Government Office for Science, *Foresight. The Future of Food and Farming - Final Project Report*, The Government Office for Science, Editor. 2011: London.
15. Commission, P., *Trends in Australian agriculture*. 2005.
16. Report, T.R., *Are Agricultural Robots Ready - 27 Companies Profiled*, F. Tobe, Editor. 2014: The Robot Report.
17. Research, W., *Agricultural Robots: Market Shares, Strategies, and Forecasts, Worldwide, 2014 to 2020*. 2014.
18. Smart, W., 2013.
19. Beckie, H.J. and F.J. Tardif, *Herbicide cross resistance in weeds.* Crop Protection, 2012. **35**(0): p. 15-28.
20. Preston, C., *What has herbicide resistance taught us?*, in *GRDC - Global Herbicide Resistance Challenge*. 2013: Perth.
21. Hobbs, P.R., *Conservation agriculture: what is it and why is it important for future sustainable food production?* Journal of Agricultural Science - Cambridge, 2007. **145**(2): p. 127.

22. Bindi Isbister, P.B., Glen Riethmuller, Stephen Davies, Andrew Whitlock and Tim Neale, *Controlled Traffic Farming Technical Manual*. 2013.
23. Chamen, T. *Control Traffic Farming Europe Ltd.* . 2013; Available from: http://www.controlledtrafficfarming.com/Home/Default.aspx.
24. Bekker, M.G., *Theory of land locomotion: the mechanics of vehicle mobility*. 1956: University of Michigan Press.
25. Bekker, M.G., *Off-the-road locomotion: research and development in terramechanics*. 1960: University of Michigan Press Ann Arbor.
26. Wong, J.Y., *Theory of ground vehicles*. 2001: Wiley. com.
27. Wong, J.Y., *Terramechanics and off-road vehicle engineering: terrain behaviour, off-road vehicle performance and design*. 2009: Butterworth-Heinemann.
28. Apostolopoulos, D., *Analytic Configuration of Wheeled Robotic Locomotion.* 2001.
29. Madsen, T.E. and H.L. Jakobsen, *Mobile Robot for Weeding.* Department of Control and Engineering design - Technical University of Denmark, 2001.
30. Åstrand, B. and A. Baerveldt, *An Agricultural Mobile Robot with Vision-Based Perception for Mechanical Weed Control.* Autonomous Robots, 2002. **13**(1): p. 21-35.
31. Jensen, K., et al. *A low cost, modular robotics tool carrier for precision agriculture research*. in *Proceedings 11th International Conference on Precision Agriculture Indianapolis, USA*. 2012.
32. Bakker, T., et al., *Systematic design of autonomous platform for robotic weeding*. Journal of Terramechanics, 2009.
33. Jorgensen, R.N., et al., *HortiBot: A System Design of a Robotic Tool Carrier for High-tech Plant Nursing* CIGR, 2007. **Volume 9**.
34. Ruckelshausen, A., et al., *Autonome Roboter zur Unkrautbekämpfung - Autonomous robots for weed control.* Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz, 2006: p. 173-180.
35. Ruckelshausen, A., et al., *BoniRob–an autonomous field robot platform for individual plant phenotyping.* Precision agriculture, 2009. **9**: p. 841.
36. University of Thessaly. *Zeus*. 2011; Available from: http://www.savage.gr.
37. Tabile, R.A., et al., *Design and development of the architecture of an agricultural mobile robot.* Engenharia Agrícola, 2011. **31**: p. 130-142.
38. University of Southern Denmark. *Omnirota*. 2013; Available from: http://www.youtube.com/user/CornIsKing.
39. Corporation, A.T. *Spirit - Tractor platform*. 2014; Available from: http://www.autonomoustractor.com/.
40. Kongskilde Industries A/S. *Kongskilde Vibro Crop Robotti*. 2013; Available from: http://www.kongskilde.com/ro/en/News/Year%202013/09-09-2013%20-%20New%20automated%20agricultural%20platform%20-%20Kongskilde%20Vibro%20Crop%20Robotti.
41. Clearpath Robotics. *Grizzly*. 2013; Available from: http://www.clearpathrobotics.com.
42. Harvest Automation. *HV-100*. 2014; Available from: http://www.harvestai.com.
43. Rowbot. 2014; Available from: http://rowbot.com.
44. Manufacturing, K. *Autonomous Harvest System*. 2014; Available from: http://www.kinze.com/.

45. ecoRobotix. *Concept field robot*. 2014; Available from: http://www.ecorobotix.com/.
46. Robotics, A.C.f.F. *Field robotics research*. 2013; Available from: http://www.acfr.usyd.edu.au/.
47. Tristan Perez, P.H., Ben Hutchins, David Ball, *On the Economic Benefits of Broadacre Farm Robotics in Queensland*. 2014, Queensland University of Technology: School of Electrical Engineering and Computer Science.
48. GRDC, *Machinery Investment and Costs*, Grains Research and Development Corporation, Editor. 2014.
49. Australian Government, *Australian Vehicle Standards*. 1999.
50. Queensland Government. *Vehicle Standards*. 2014; Available from: http://www.tmr.qld.gov.au/Safety/Vehicle-standards-and-modifications/Loads-and-towing/Projecting-loads.aspx#dimensions.
51. GRDC, *Crop Placement and Row Spacing - Fact Sheet*, Grains Research and Development Corporation, Editor. 2011.
52. Queensland Government, *Deciding row spacing for wheat in central Queensland*. 2007.
53. States., F.a.A.O.F.o.t.U. *Guidelines for computing crop water requirements*. 2014; Available from: http://www.fao.org/docrep/x0490e/x0490e0b.htm.
54. Trimble, *WeedSeeker® spot spray system*. 2014.
55. Wikipedia. *Vehicle Frame - Unibody*. 2014; Available from: http://en.wikipedia.org/wiki/Vehicle_frame.
56. Newstead, S. and A. D'Elia, *An investigation into the relationship between vehicle colour and crash risk.* Prevention, 2007. **17**(1): p. 47-56.
57. Sandu, S., et al., *Australian energy resource assessment*. 2010: ABARE.
58. Karaftath, L., *Rolling Resistance of Off-Road Vehicles.* Journal of Construction Engineering and Management, 1988. **114**(3): p. 458-471.
59. M. Gharibkhani, A.M.F.V., *Determination of wheel-soil rolling resistance of agricultural tire.* Australian Journal of Agricultrual Engineering, 2012. **3**(1): p. 6-11.
60. J. Kurjenluoma, L.A.J.A.a., *Rolling resistance and rut formation by implement tyres on tilted clay soil.* Journal of Terramechanics, 2009. **46**: p. 267-275.
61. G. Bygden, L.E.I.W., *Rut depth, soil compaction and rolling resistance when using bogie tracks.* Journal of Terramechanics, 2004. **40**: p. 179-190.
62. Carvill, J., *Mechanical engineer's data handbook*. 1994: Butterworth-Heinemann.
63. Atlas Aluminium, *Aluminium Alloy - Data Sheet - 5005*. 2013.
64. Atlas Aluminium, *Aluminium Alloy - Data Sheet - 5083*. 2013.
65. Standard, A.N.Z., *Hot-rolled steel flat products*. 1997.

Appendices

Appendix A

Note on Detailed Feature Explanations

It would be a complex and time consuming task to communicate the thousands of integrated design decisions that were made while engineering the prototype SRFV.

To aid in your understanding of the design development I have included a copy of the CAD file for the prototype vehicle (in STEP format). Please review this along with the discussion on each assembly of the design. It will help to explain many of the minor details you may have interest in.

Each section will include reference to a particular CAD assembly to assist in navigating the CAD files. These appear below the heading of each section and look like this:

Reference to the CAD file: PN001000a - PN001450a

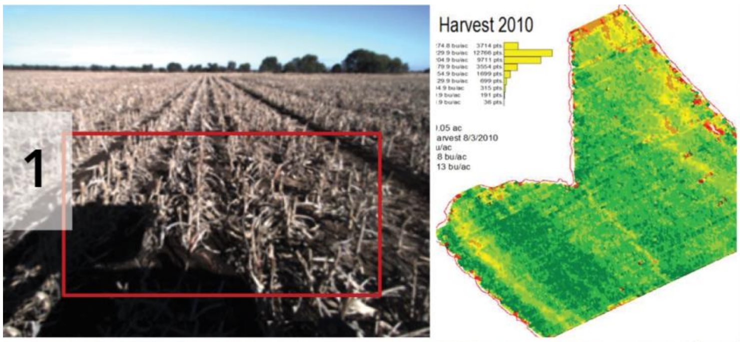
Table 14. CAD Assembly naming convention.

File Name	Assembly
PN001000a	Master SRFV Assembly
PN001100a	Drive Unit Assembly
PN001150a	Caster Wheel Assembly
PN001200a	Side Unit Assembly
PN001300a	Swingarm Assembly
PN001350a	Battery Box Assembly
PN001400a	Cover Assembly
PN001450a	Implement Unit Assembly

A USB key saved with the CAD file of the prototype SRFV has been prepared. Please open up the Master Assembly file PN001000a and start browsing the individual build assemblies from there.

SIFR Vision

The vision for the SIFR program will encompass the 5 following areas:



MODELLING, LEARNING & DECISION MAKING

- Fleet Planning
- Obstacle Detection & Avoidance
- Localisation & Navigation
- Motion Control
- Crop State Estimation
- Variable Rate Application (Inputs)

SENSING & PERCEPTION

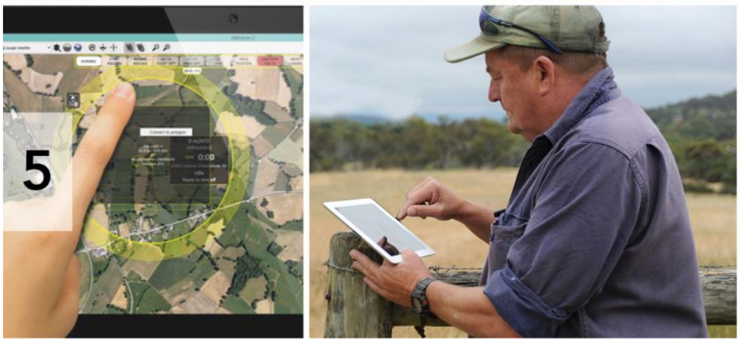
- GPS
- Cameras (Weed Detection, Nav.)
- Environmental Sensors (Soil, Pest)
- IMU
- Laser, Sonar, Radar
- Encoders (Wheel, Motor)

SYSTEMS & ARCHITECTURE

- Autonomous Refilling/Recharge
- Emergency Systems
- UAV & UGV Interaction
- Communication

PLATFORM DESIGN & ENGINEERING

- Autonomous Vehicles
- Implement Systems (Weed Mitigation, Scouting, Seeding)
- Locomotion (Electric / Hydraulic)



HUMAN MACHINE INTERACTION & USABILITY

- Interfaces (GUI)
- Communication (Lights, Sounds)
- Modularity
- Maintenance

User Research

Ethics Approval for Participant Research

The following is the ethical approval document emailed to farmers as part of the user research undertaken during this project.

QUT Queensland University of Technology
Brisbane Australia

PARTICIPANT INFORMATION FOR QUT RESEARCH PROJECT
– Observation, Interview, Questionnaire –

Bringing the Farmer Perspective to AgBot

QUT Ethics Approval Number 1400000676

RESEARCH TEAM

Principal Researcher: Dr Dhaval Vyas

Associate Researchers: Prof Tristan Perez, A/Prof Ben Upcroft, Prof Margot Brereton, Dr Fiona Redhead, Mr Steve Snow, Mr Owen Bawden, Mr Ray Russell.

Science and Engineering Faculty, Queensland University of Technology (QUT)

DESCRIPTION

This project is being undertaken as part of a grant awarded by the School of Electrical Engineering and Computer Science. This is a collaborative project between the Robotics and Aerospace Systems and the Computer-Human Interaction disciplines.

The purpose of this project is to better understand the farmer perspective of agricultural robots in order to design effective applications of Small Robotic Farm Vehicles (SRFV): i.e. understand farmer attitudes towards robots, how farming practices might need to shift to incorporate robots, and how best to marry the skills and knowledge of the farmer with the capability of the robot.

You are invited to participate in this project because you can help us to understand farming practice and how to best design agricultural robots.

PARTICIPATION

Your participation will involve a site visit to your farm for researchers to observe the work that you do on the farm, and an audio recorded interview at your farm. We expect the visit to take up to 3 hours, including the interview that will take approximately 1 hour of your time. During the site visit and interview we will ask questions about farming practice, relationships between farming practice and home activities, and for your thoughts about how robots might help with your farming work.

In addition, we will leave a questionnaire and other materials for you to record any other insights related to farming practice and robots that you might think of during your day to day activities. The questionnaire will take approximately 45 minutes of your time and will include questions about your farm, farming practices, weed mitigation, machinery and other equipment, and energy and fuel use. The questionnaire and other materials will be collected after about 2 to 3 weeks.

The materials will include a booklet, disposable camera, maps and other printed images. We will also provide stationery (pens, glue stick, etc). The booklet will prompt you to record ideas of how robots might help with your farming tasks, how you would like to control the robot, and the things the robot would need to know to complete work on your farm (the intelligence and sensors needed). You can use the camera, maps and printed images to record these ideas. We expect you would need to spend about 2 hours (over the time you have the probe kit) to record your ideas.

Your participation in this project is entirely voluntary. If you do agree to participate you can withdraw from the project without comment or penalty. If you withdraw within 2 weeks, on request any identifiable information already obtained from you will be destroyed. Your decision to participate or not participate will in no way impact upon your current or future relationship with QUT.

EXPECTED BENEFITS

It is expected that this project will not benefit you directly. However, it may benefit farmers that use future agricultural robots.

RISKS

There are minimal risks associated with your participation in this project. These include the inconvenience of giving time to participate in the research, and the minor discomfort of anxiety induced by an interview. It is likely that you will have farming work to complete while we are visiting and we will break from our research activities to allow you to manage the farm without interruption to your required daily work. We intend to make the interview a comfortable and enjoyable experience for you.

PRIVACY AND CONFIDENTIALITY

All comments and responses will be treated confidentially unless required by law. This project does involve an audio recording.

You will have the opportunity to verify your comments and responses prior to the final inclusion in our research data. The audio recording will be destroyed as soon as it is transcribed and only the researchers will have access. It is possible to participate in the project without being audio recorded however in that case the interviewer may need extra time to write notes.

CONSENT TO PARTICIPATE

We would like to ask you to sign a written consent form (enclosed) to confirm your agreement to participate.

QUESTIONS / FURTHER INFORMATION ABOUT THE PROJECT

If have any questions or require further information please contact one of the research team members below.

Dr Dhaval Vyas	07 3138 9564	d.vyas@qut.edu.au
Mr Owen Bawden	0406 773 008	o.bawden@qut.edu.au

CONCERNS / COMPLAINTS REGARDING THE CONDUCT OF THE PROJECT

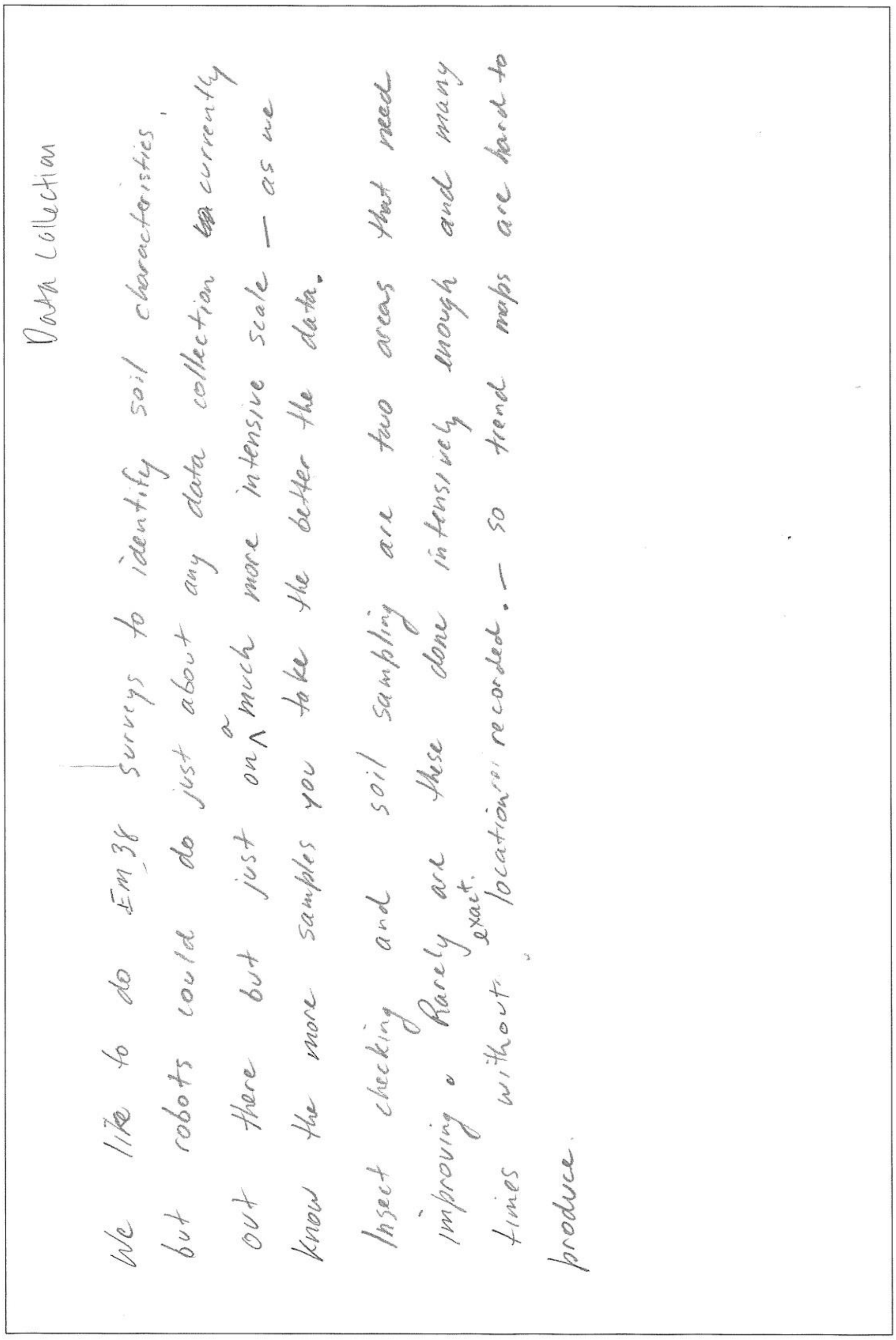
QUT is committed to research integrity and the ethical conduct of research projects. However, if you do have any concerns or complaints about the ethical conduct of the project you may contact the QUT Research Ethics Unit on 07 3138 5123 or email ethicscontact@qut.edu.au. The QUT Research Ethics Unit is not connected with the research project and can facilitate a resolution to your concern in an impartial manner.

Thank you for helping with this research project. Please keep this sheet for your information.

Figure 68. Ethics approval for participant research.

Field Visit Responses from Farmers

The following figures show notes prepared by Nev Boland, a farmer from Moonie in the Darling Downs. This is part of the probe material left with the farmers.



Data Collection

We like to do EM38 surveys to identify soil characteristics, but robots could do just about any data collection currently out there but just on a much more intensive scale — as we know the more samples you take the better the data.

Insect checking and soil sampling are two areas that need improving. Rarely are these done intensively enough and many times without exact locations recorded. — so trend maps are hard to produce.

Figure 69. Notes from Nev Boland on the applications for agricultural robotics.

Field Visit Responses from Farmers

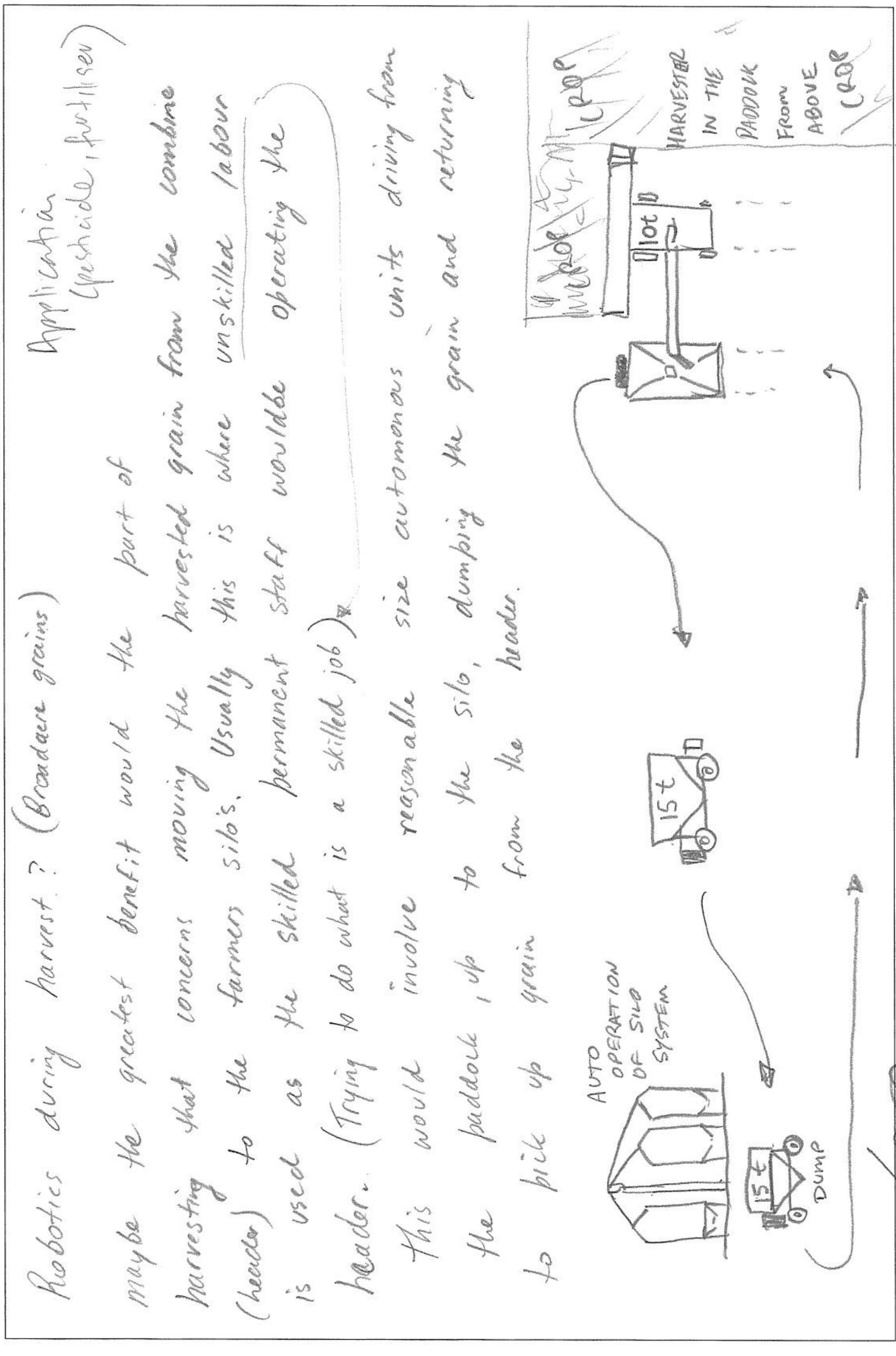
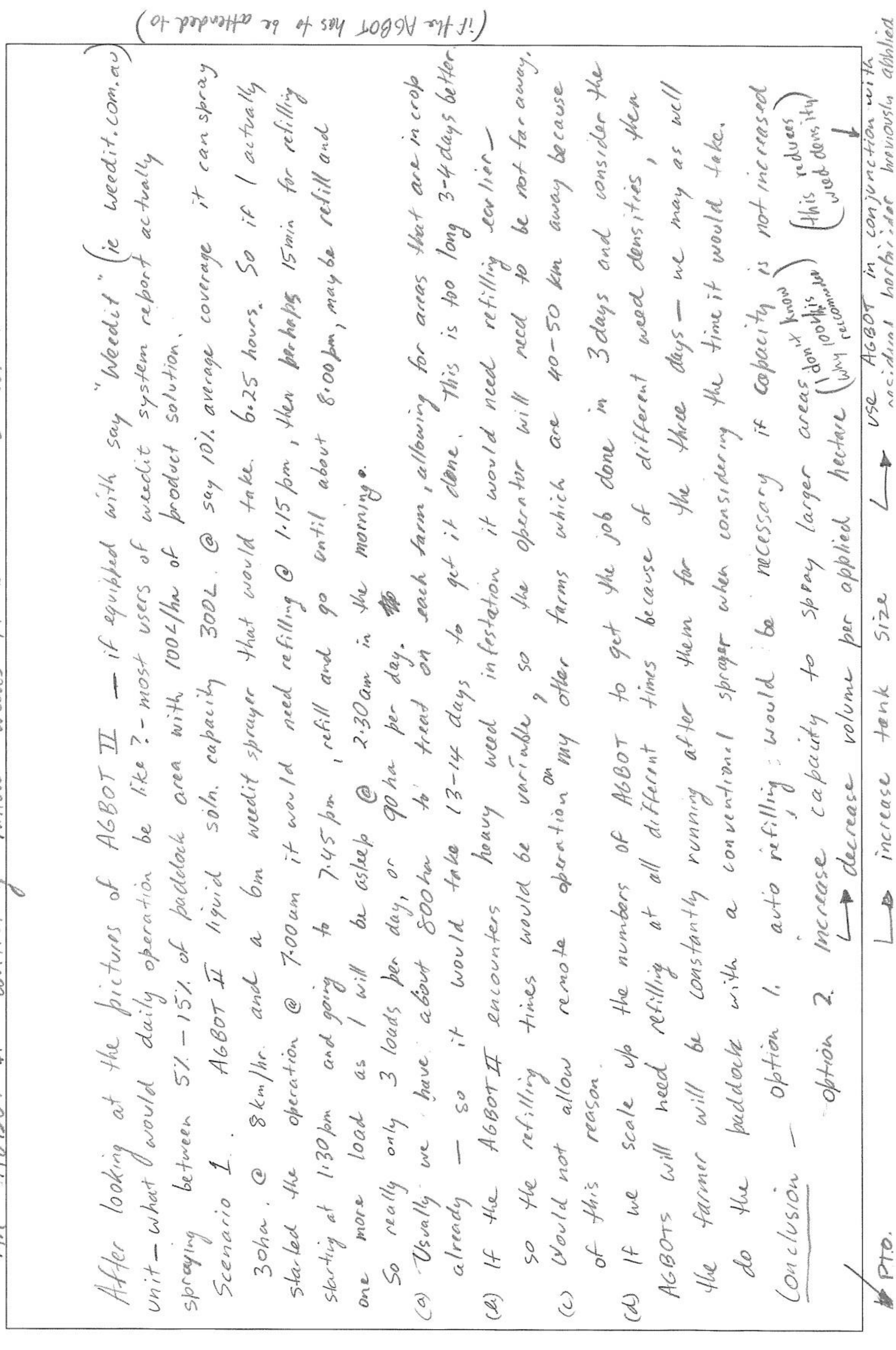


Figure 70. Notes from Nev Boland on the applications for agricultural robotics.

Field Visit Responses from Farmers



An AGBOT II controlling fallow weeds in broadacre situation

After looking at the pictures of AGBOT II — if equipped with say "Weedit" (ie weedit.com.au) unit — what would daily operation be like? - most users of weedit system report actually spraying between 5% – 15% of paddock area with 100L/ha of product solution.

Scenario 1. AGBOT II liquid soln. capacity 300L. @ say 10% average coverage it can spray 30ha. @ 8km/hr. and a 6m weedit sprayer that would take 6.25 hours. So if I actually started the operation @ 7.00am it would need refilling @ 1.15pm, then perhaps 15min for refilling starting at 1:30pm and going to 7.45pm, refill and go until about 8.00pm, maybe refill and one more load as I will be asleep @ 2.30am in the morning.

So really only 3 loads per day, or 90 ha per day.

(a) Usually we have about 800ha to treat on each farm, allowing for areas that are in crop already — so it would take 13-14 days to get it done. This is too long 3-4 days better.

(b) If the AGBOT II encounters heavy weed infestation it would need refilling earlier — so the refilling times would be variable, so the operator will need to be not far away.

(c) Would not allow remote operation on my other farms which are 40-50 km away because of this reason.

(d) If we scale up the numbers of AGBOT to get the job done in 3 days and consider the AGBOTS will need refilling at all different times because of different weed densities, then the farmer will be constantly running after them for the three days — we may as well do the paddock with a conventional sprayer when considering the time it would take.

Conclusion — option 1. auto refilling would be necessary if capacity is not increased

— option 2. increase capacity to spray larger areas

→ decrease volume per applied hectare (I don't know why 100L is recommended)

→ increase tank size

→ use AGBOT in conjunction with residual herbicides previously applied (this reduces weed density)

(if the AGBOT has to be attended to)

P.T.O.

Figure 71. Notes from Nev Boland on the applications for agricultural robotics.

Vehicle Specification

The following specification outlines all the major considerations for the SRFV:

Table 15. Outlines the specification for the vehicle.

Environmental Considerations			
Item	**Requirement**	**Rating**	**Comment**
1.1	Temperature range	Must	Cope with temperature range of -10°C to +50°C
1.2	Temperature cycling	Must	Withstand temperature cycling of -10°C to +50°C over a 12 hour period.
1.3	Humidity	Must	Cope with relative humidity range of 5% - 95%
1.4	Precipitation	Must	Capable of operating during rainy conditions.
1.5	Wind Speed	Must	Resist wind speeds, from multiple directions up to 60kph, while vehicle is static.
1.6	Pressure exposure	Must	Protect from exposure to low pressure hoses used in wash down - working pressures of up to 350kPa (50psi).
1.7	UV exposure	Must	Protect from prolonged exposure to sunlight (UV).
1.8	Vibration and Impact	Must	Withstand vibration and impact associated with standard machine operation. Vehicle driving on farm terrain and vehicle driving on farm roads (speeds up to 15kph).
1.9	Terrain Gradient	Must	Gradients of -15% to +15% are expected during some operations.
1.10	Soil Conditions	Must	Operate in a variety of soil conditions.
1.11	Fallow Operation	Must	Operate during fallow crop periods.
1.12	In-Crop Operation	Must	Operate in a variety of broadacre crops - Wheat, Sorghum, and Chickpea.

Operation			
Item	**Requirement**	**Rating**	**Comment**
2.1	Autonomous Driving	Must	Required to drive autonomous over a variety of agricultural terrains.
2.2	10hr (minimum) operating time	Must	Average operating time of 10hrs. required between recharging/refuelling the power supply.
2.3	0-10kph vehicle operation speed	Must	Operating speeds of 0-10kph are required for general usage.
2.4	Steering	Must	Capable of turning 180° within a space of

			$9m^2$
2.5	Spraying	Must	Autonomous driving over a variety of agricultural terrain - This will include traversing fields without damaging crops (In-Crop driving), utilising existing CTF tracks, driving from field to field within a farm, driving to replenishment (power/liquid) and driving out of the fields in some failure modes.
2.6	Autonomous Weeding	Must	Autonomous weeding capabilities both in-crop and during fallow periods. Including detection, identification, decision making and action with chemical and non-chemical weed removal methods.
2.7	Autonomous Fertilising	Desired	Autonomous applications of variable rate fertiliser using the same GNC as weeding operations.
2.8	Autonomous Crop Scouting	Desired	Autonomous crop scouting for a variety of pests and crop diseases.
2.9	Autonomous Seeding	Desired	Autonomous seeding of crops.

Ergonomics			
Item	**Requirement**	**Rating**	**Comment**
3.1	No sharp edges, catch points or protrusions	Desired	No sharp edges, catching points, or other protrusions that might otherwise cause damage or injury when being used.
3.2	Ergonomic and semantic instructions	Desired	Ergonomic and semantic instructions will be designed into the product. The user must understand the function of particular parts by the suggestive instructions provided by the parts colour, form, position and any notation and symbols placed on it. The ability for the use to instinctively use the SRFV, safely and correctly will greatly improve customer satisfaction.
3.3	Moving doors and panels	Must	All actuated (moving) doors or panels are to be designed to allow easy operation by a single user. Height off the ground plane is to be reviewed. Ideally the doors and access panels should be operable with one hand allowing ease of access and use as operators often carry objects in the other hand.
3.4	Access to the vehicle	Must	Users will have access all sides of the SRFV.

3.5	Physical ergonomic validation	Must	Physical ergonomics will be validated through pre-production prototypes. User trials will be undertaken by different size users.

Chemical Resistance			
Item	**Requirement**	**Rating**	**Comment**
4.1	Materials review for SRFV	Must	QUT will conduct a materials review process to determine suitable materials for the project. The materials selected for the SRFV should be resistant to significant chemical attack from the following chemicals both individually and in combination.
4.2	Diesel fuel / oil	Must	Materials resistant to Diesel fuel / oil.
4.3	General salt / corrosion	Must	Materials resistant to general salt / corrosion
4.4	Herbicide	TBC	Materials resistant to generally used herbicides.
4.5	Pesticide	TBC	Materials resistant to generally used pesticides.

Ingress Protection			
Item	**Requirement**	**Rating**	**Comment**
5.1	Limited water ingress	Must	Allow limited water ingress during operational use and cleaning with low pressure water cleaners.
5.2	IP64	Must	The drive unit sealed to IP65 to protect the internal components from dust and low pressure water ingress.
5.3	IP64	Must	The electronic enclosure (e-box) sealed to IP64 to protect the components from dust and splashing water.
5.4	IP64	Must	The battery enclosure sealed to IP64 to protect the components from dust and splashing water.
5.5	Sensors	TBC	The required level of IP protection for sensors will be reviewed on a case by case basis.

Enclosure (Cover) Design - General			
Item	**Requirement**	**Rating**	**Comment**
6.1	Removal	Must	Removable enclosure for access to the chassis of the SRFV for transport, maintenance, modifications and repairs.
6.2	Storage for	Must	Adequate storage for commonly used tools

	commonly used tools		must be allowed for in the design of the SRFV.
6.3	Cables	Must	The cable channels must be easily accessible by removal of the enclosure.
6.4	Temperate control	Must	The enclosure must passively reduce the heat gain by reflecting as much heat away from the vehicle as possible.

Enclosure Design - Electronics			
Item	**Requirement**	**Rating**	**Comment**
7.1	Storage for electronics (e-box)	Must	Provide protection to the electronics on the SRFV. Computers will be housed within an e-box that may be part of the general enclosure or a separated sub-enclosure.
7.2	Cooling	TBC	The level of cooling will be determined through temperature analysis of the prototype.
7.3	Access for connectors and power supplies	Must	Allow for user access to the connectors and power supplies for all components.
7.4	Sensors	TBC	To be confirmed - Level of protection required.
7.5	Batteries	TBC	To be confirmed - Level of protection required.

Sensors			
Item	**Requirement**	**Rating**	**Comment**
7.1	Camera	TBC	Camera sensors will be used for navigation, obstacle detection and weed detection.
7.2	Laser	TBC	Laser sensors will be used for navigation and obstacle detection.

Dimensions			
Item	**Requirement**	**Rating**	**Comment**
8.1	Driving between crop rows - In-Crop Driving	Must	Capable of driving between crop rows without damaging the crop by crushing or shearing. Crop row spacing of 500mm is common in broadacre crops. Drive unit width <350mm acceptable.
8.2	Driving over crops - Clearance	Must	Able to drive over a crop without causing damage. Current analysis has indicated that a height of >750mm will be suitable.
8.3	Drive over multiple crop	TBC	Suited to driving over multiple crop rows. Vehicle width will depend on type of crop

	rows at once		and farm setup.
8.4	Utilise Control Traffic Farming (CTF) paths	Desired	Standard width of CTF paths - 3m.
8.5	Driving on farm roads	Must	Drive between fields to access crops and replenishments.
8.6	Transportable on a flatbed trailer	Must	Transportable on a flatbed trailer. Trailer dimensions - 2.5m is the max. width, 4.3m is the max. height, 3.7 is a common trailer length.
8.7	Sprayer Height	Desired	Sprayer height should be constantly maintainable 500mm above crop
8.8	Spray Width	Desired	Up to 7m utilising an extended spray boom.

Weight			
Item	**Requirement**	**Rating**	**Comment**
9.1	Vehicle Weight (including Payload)	Must	Target vehicle weight of 600kg - based on empirical evidence from farmers of soil compaction from similar sized vehicles.
9.2	Payload Weight	TBC	Payload weight of the vehicle will be 200kg.

Capacity			
Item	**Requirement**	**Rating**	**Comment**
10.1	Water for herbicide spraying	Must	Able to carry a payload of 200 litres of water for spraying
10.2	Herbicide	Must	Suitable to carry herbicide for spraying.
10.3	Fertiliser	Desired	Carry fertiliser for autonomous fertilising
10.4	Seed	Desired	Carry seeds for autonomous seeding
10.5	Power capacity	Must	Have capacity, either as battery charge or liquid fuel to meet the operational time of 10hrs.
10.6	Sensors	Must	Carry a range of sensors for autonomous operations.
10.7	Implement	Must	Carry a range of implement for various agricultural and experimental tasks

Locomotion			
Item	**Requirement**	**Rating**	**Comment**
11.1	Standard driving conditions	Must	Capable of traversing agricultural environments including unsealed roads,

			fields, contour banks and workshop areas.
11.2	Soil Compaction	Must	Standard vehicle movements resulting in soil compaction.

Materials			
Item	**Requirement**	**Rating**	**Comment**
12.1	Lightweight components and materials	Must	Reduction of weight and using lightweight materials where possible. These materials are required to have a proven history in related markets and applications. (Military use of Kevlar composites would be an example of this).
12.2	UV stable materials	Must	Material specification must be UV stable for the lifetime of the product.
12.3	Robust materials	Must	Robust and durable to withstand typical usage / environmental conditions.
12.4	Chemical exposure	Must	Withstand the full range of chemical exposure commonly occurring during general usage. See Chemical Resistance section.
12.5	Paintable	Must	Readily paintable.
12.6	Cleanable	Must	Easily cleanable by mild detergent and water.
12.7	Repairable	TBC	Materials should be easily repairable by commonly available means.
12.8	Low impact manufacturing and use of recyclable materials	Desired	The manufacture of the SRFV should have minimal impact upon the environment, and incorporate materials that may be reclaimable at the end of its product lifecycle.
12.9	Material codes	Desired	Where possible include material codes on all plastic and metal parts for identification and recycling purposes.

Production and Manufacturing Logistics			
Item	**Requirement**	**Rating**	**Comment**
13.1	Method of manufacturing	Must	Use readily available manufacturing methods.
13.2	Multiple vendors	Must	Use processes available from multiple vendors (not locked to single source or manufacturing entity).
13.3	Repeatable and reproducible parts	Must	Manufacturing method provides repeatable and reproducible parts that will meet QUT's QA levels regardless of manufacturer.
13.4	Sourcing	Must	Use easily sourced materials, available from multiple vendors or supply sources where

			possible.
13.5	Components	Must	Use easily available standard components where possible.
13.6	Component availability	Must	Readily available components at point of manufacture and assembly of the SRFV.
13.7	Replacing components	Must	Standard components specified for use are easily replaced with a similar product if supply source of original is not possible.
13.8	Assembly ease	Must	Integrate features such as crane lift points and forklift tine receptacles for shipping and assembly.

Manufacturing Costs			
Item	**Requirement**	**Rating**	**Comment**
14.1	Manufacturing and part costs	TBC	No guidance on actual manufacturing or part costs have been provided at this time.

Life Span			
Item	**Requirement**	**Rating**	**Comment**
15.1	Review of lifecycle cost model	TBC	The life span of the SRFV will be determined by a lifecycle cost model. Life span will depend on whole of life cost optimisation.

Branding			
Item	**Requirement**	**Rating**	**Comment**
16.1	QUT Branding	Desired	Incorporation of QUT branding, including livery and signage will be displayed prominently on the SRFV.
16.2	Livery	Desired	In conjunction with the QUT branding, a suitable livery for the SRFV will be implemented that embodies the themes of accuracy, technology and power.
16.3	Brand Perception	Desired	The brand will deliver the perception that the SRFV is the very latest in agricultural machinery innovation, product technology and service.

Product Design and Form Language			
Item	**Requirement**	**Rating**	**Comment**
17.1	Establish distinctive form language	Desired	The design for the SRFV should be contemporary with relevance to agricultural technology. It must have wide appeal and draw from influences of automotive design

			aeronautics, robotics and high-end consumer product design. The goal will be to establish a strong design form that can be multiplied across a range of vehicles.

Signage			
Item	**Requirement**	**Rating**	**Comment**
18.1	Vehicle use signage	Must	Vehicle use signage must be displayed on the SRFV to appropriately communicate the correct operation requirements of the vehicle.
18.2	Mobile signage	Must	Mobile signage should be used when SRFV is in operation to communicate that work is being undertaken, safe work areas and danger areas.
18.3	Vehicle warning signage	Must	All points of danger on the vehicle should show clear warning signs to protect users from injury.

Lighting			
Item	**Requirement**	**Rating**	**Comment**
19.1	Indicator lights	Must	Incorporate left and right side indicator lighting to indicate when the vehicle is turning.
19.2	Brake lights	Must	Utilise brake lighting to indicate when the vehicle is slowing down or stopped.
19.3	Communication Lights	Must	Include communication lighting to visually project when a task is being undertaken. This will be used in conjunction with a sound notification system.

Safety			
Item	**Requirement**	**Rating**	**Comment**
20.1	Self-locking doors	Must	All panels and doors shall be self-locking.
20.2	Emergency stop (e-stop) buttons	Must	Emergency stop (e-stop) buttons will be positioned on all corners of the vehicle.
20.3	Bumpers	TBC	Emergency stop bumpers should be positioned on the front of the vehicle.
20.4	Signage		Refer to Signage section.

Cleaning			
Item	**Requirement**	**Rating**	**Comment**

21.1	Cleaning	Desired	Cleaning of the SRFV must be a process involving a minimum of effort. The SRFV should facilitate this where possible i.e. no dirt traps.
21.2	Low Pressure Cleaning	Must	Only low pressure hoses should be used to clean the SRFV. The SRFV must not incur damage from exposure to low pressure hoses used during cleaning – this included working pressure of up to 350 KPa (50 PSI)

Maintenance			
Item	**Requirement**	**Rating**	**Comment**
22.1	Service Intervals	TBC	The SRFV will be serviced at intervals to be determined.
22.2	Scheduled maintenance	TBC	A set maintenance schedule for the SRFV is to be determined.
22.3	Summary of maintenance items	TBC	A summary of maintenance items will be compiled at the end of the SRFV prototyping stage.
22.4	Battery Maintenance	Must	Battery maintenance will be carried out at intervals as specified by the manufacturer.

Decommissioning - Disposal			
Item	**Requirement**	**Rating**	**Comment**
24.1	Proper disposal	TBC	If the SRFV is decommissioned, then proper disposal procedures will be followed including a validation of destruction.

Conceptual Design Development - SRFV

Concept Sketches

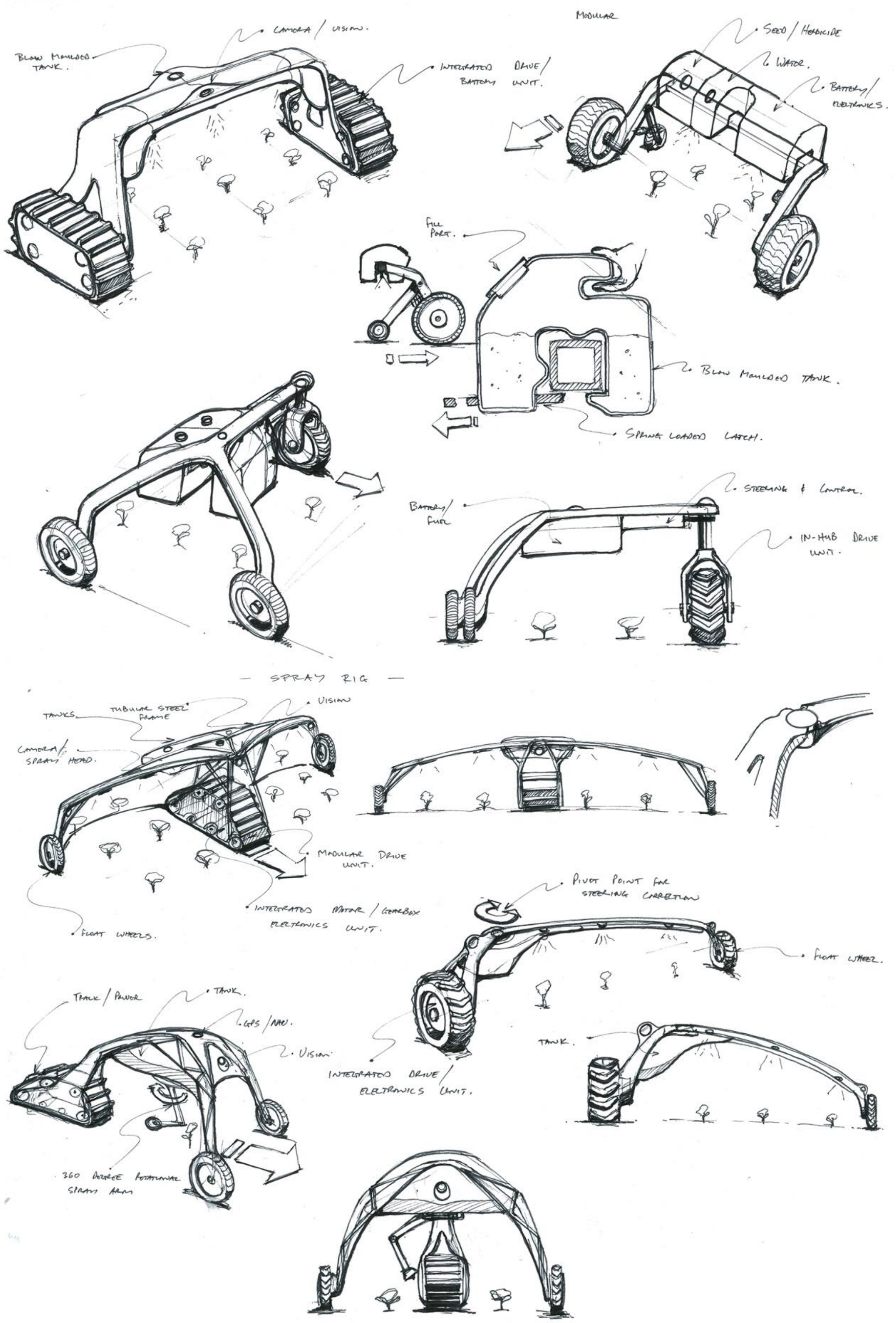


Figure 72. Concept sketches.

Concept Sketches

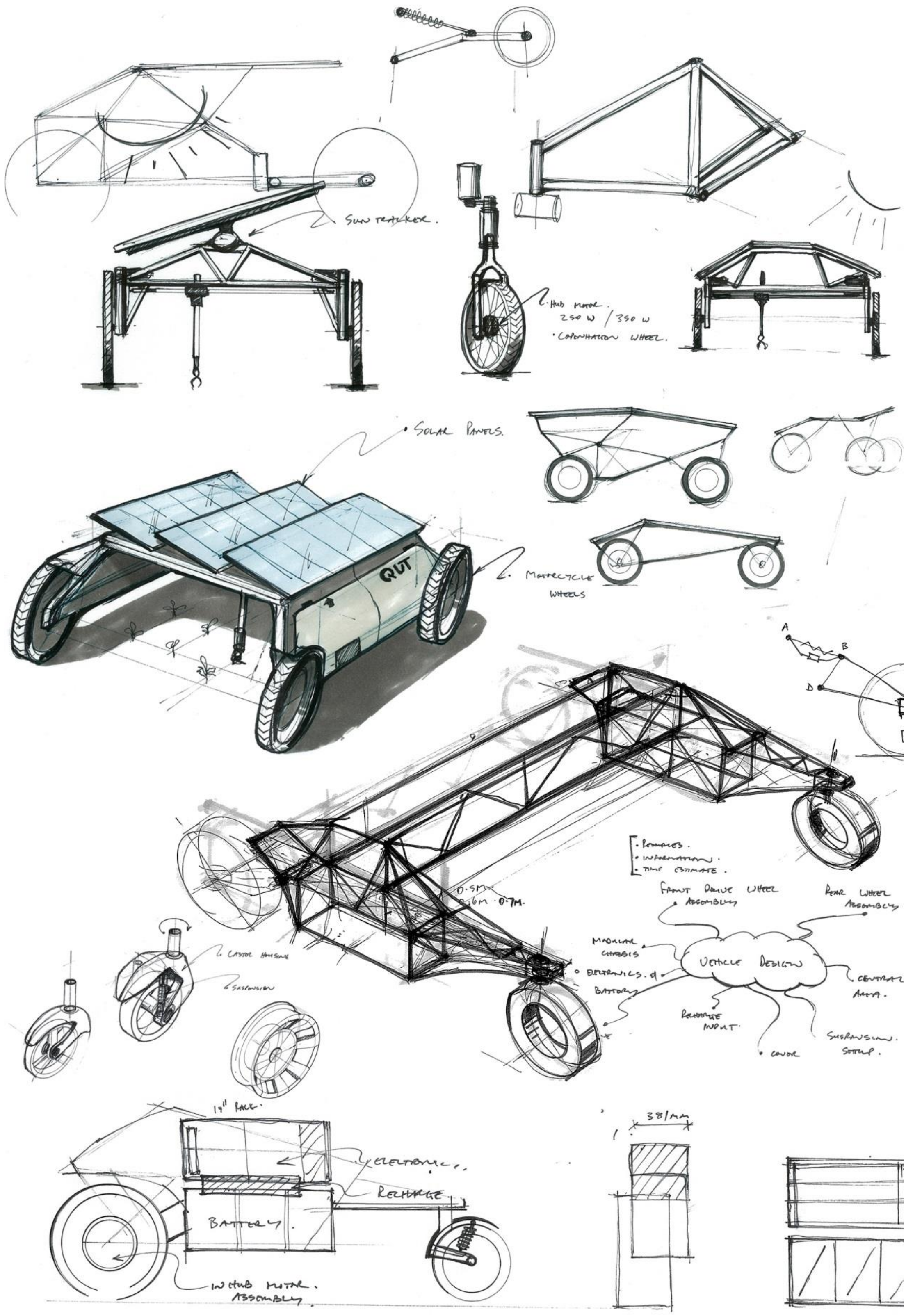


Figure 73. Concept sketches.

Concept Sketches

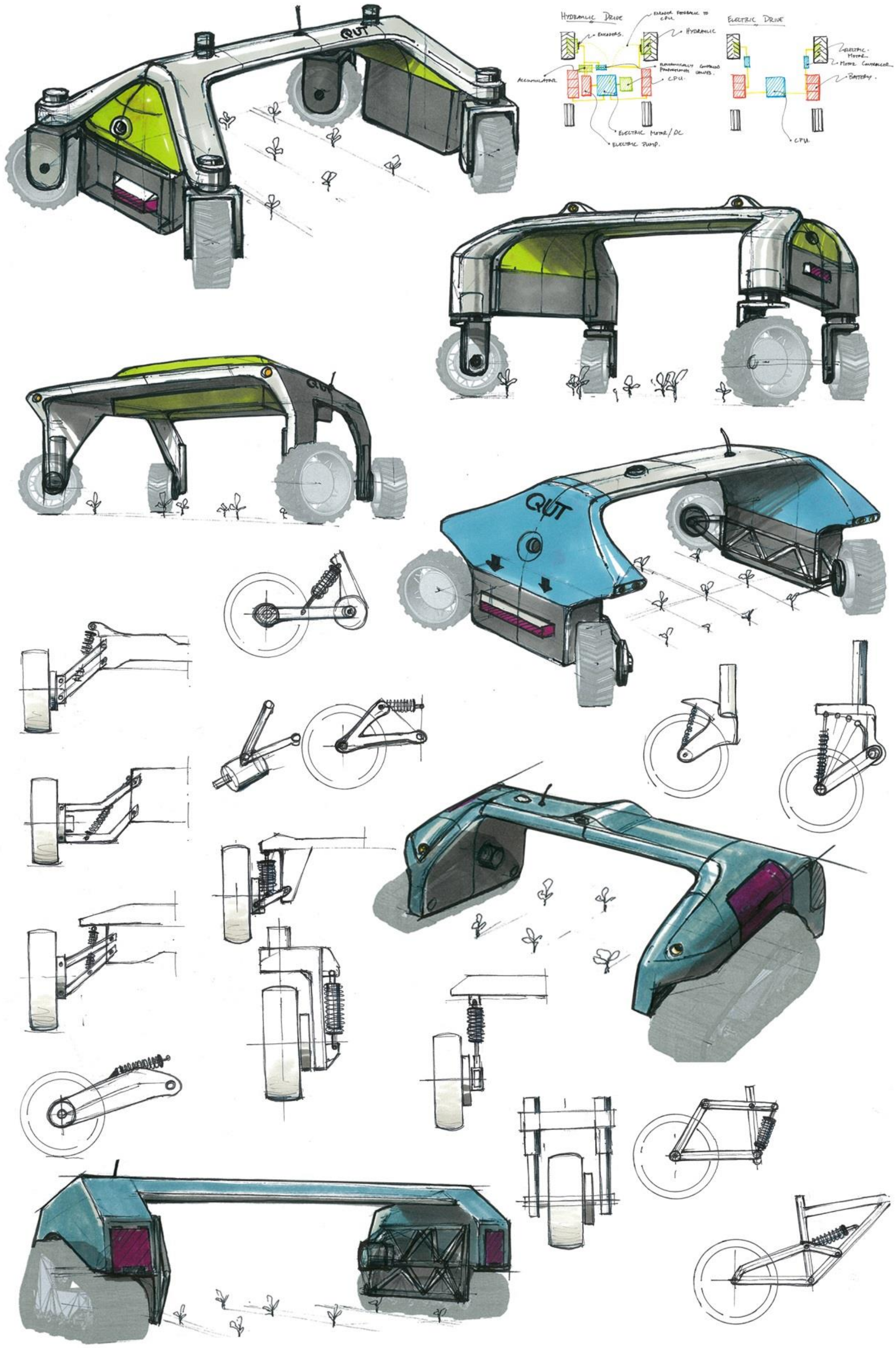


Figure 74. Concept sketches.

Concept Sketches

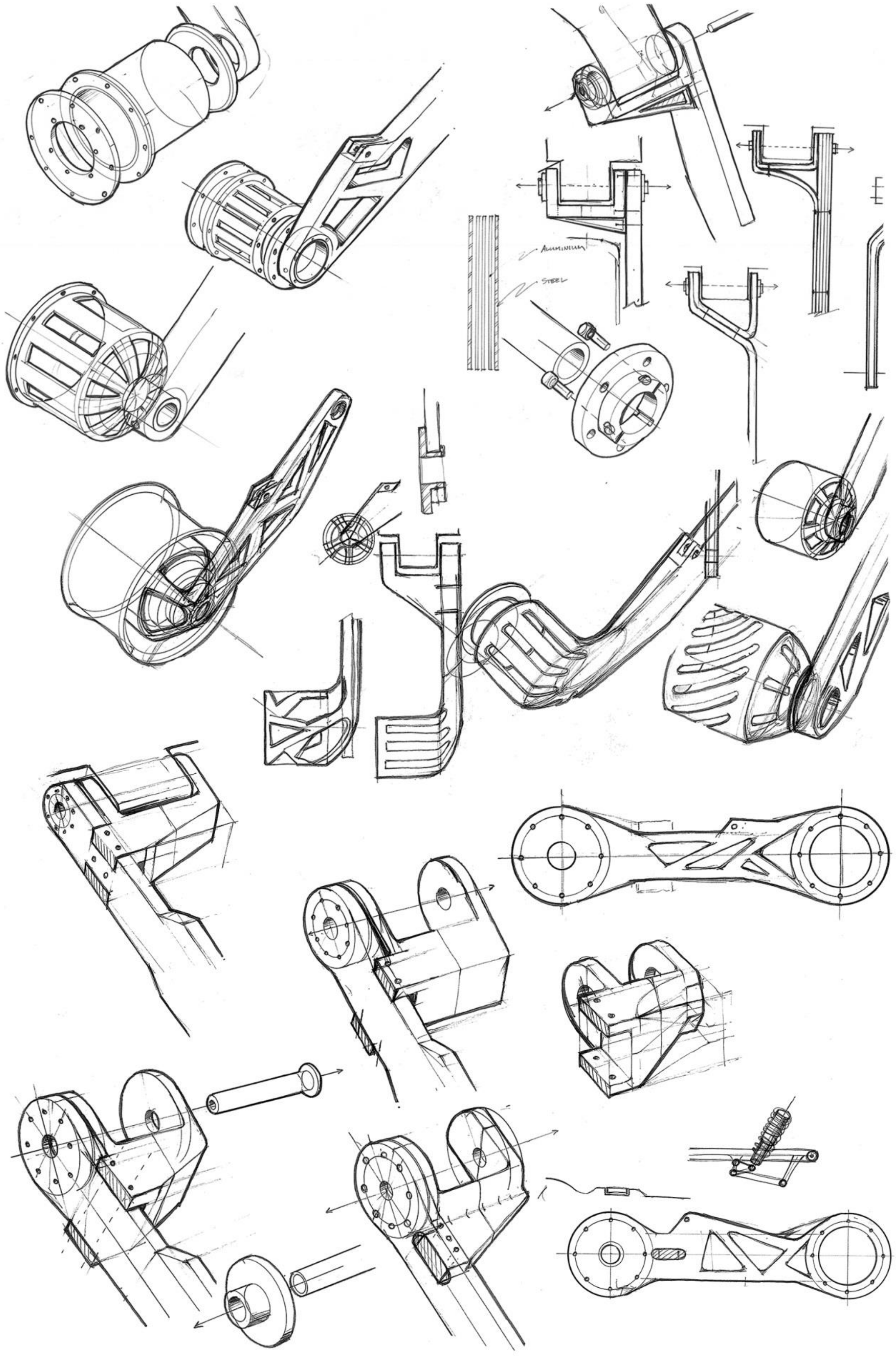


Figure 75. Concept sketches.

Concept Sketches

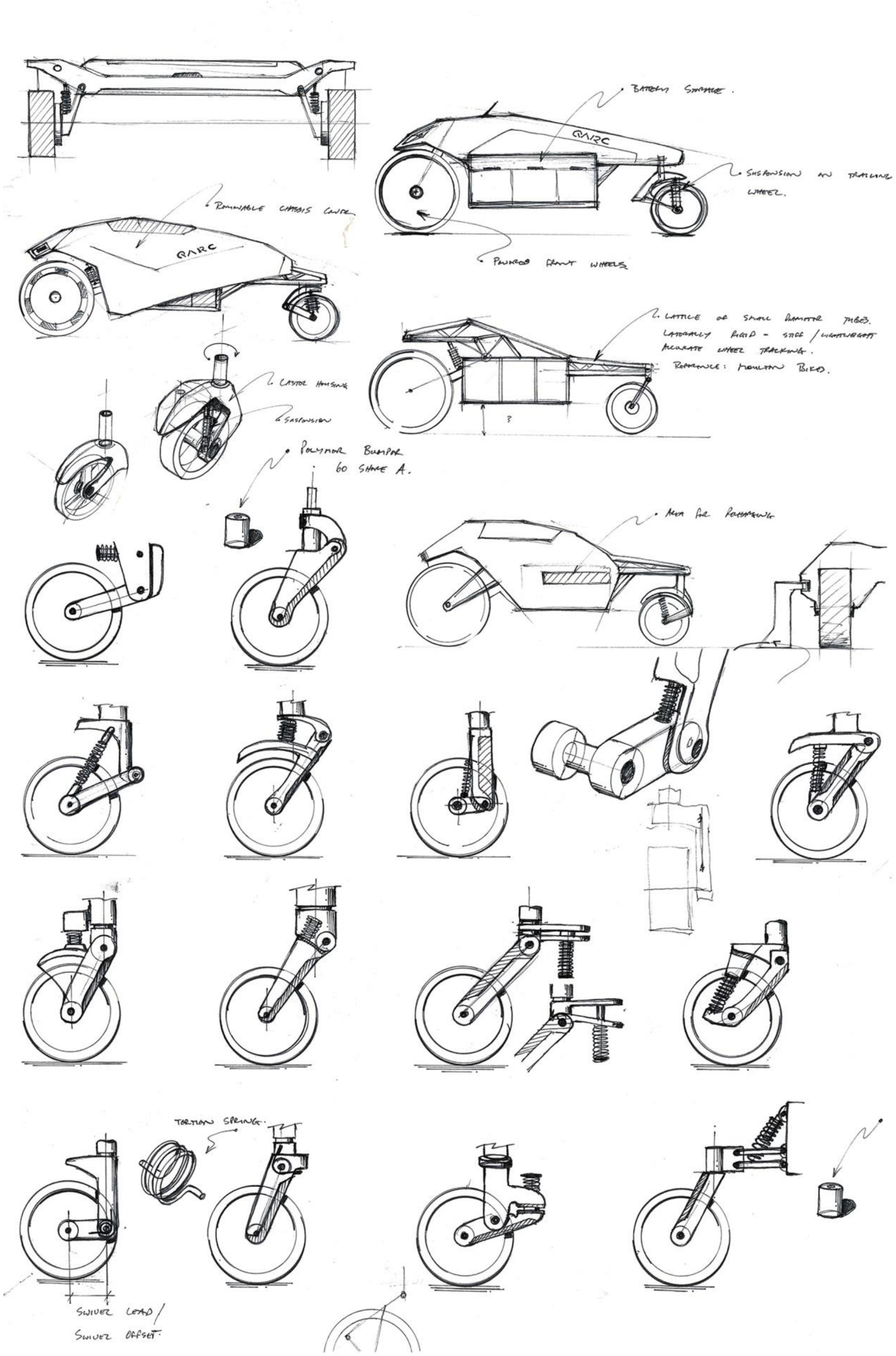


Figure 76. Concept sketches.

MATERIALS AND FASTENERS

Materials (Aluminium, Mild Steel, Stainless Steel, Dibond)

Aluminium

Aluminium was used extensively throughout the vehicle to reduce weight, energy consumption and increase load capacity. Aluminium has properties such as low weight, high strength, superior malleability, easy machining and naturally offers excellent corrosion resistance by generating a protective oxide layer. It is also very easy to recycle.

A variety of aluminium grades and manufacturing methods were used during the fabrication of the vehicle to take full advantage of the materials properties.

- Laser cut and folded aluminium was used extensively in the implement section and the battery boxes. 5005 and 5083 aluminium was used for these assemblies.
- CNC Machined 6061-T6 aluminium was used in the swingarm, caster bearing assembly, shock absorber mounts, motor-gearbox attachment plates and wheel centres.
- Spun aluminium in was used for the 14” wheel hubs. 6061-T0 Aluminium was used in this process, which was later hardened to T6.

5000 Series Aluminium

5000 series Aluminium are alloyed with *magnesium*.

5005 - Aluminium alloy 5005 nominally contains 0.8% magnesium. It has medium strength, good weldability, and good corrosion resistance in marine atmospheres. It also has the low density and excellent thermal conductivity common to all aluminium alloys. It is the most commonly used grade of aluminium in sheet and plate form.

Typical applications include architectural applications, general sheet metal work, and high strength foil.

Table 16. Material properties of Aluminium 5005 [63]

Aluminium 5005	
Alloy and Temper	5005-H34
Tensile Strength (MPa)	160
Yield Strength 0.2% Proof (MPa)min	105 min
Density (kg/m³)	2700
Elastic Modulus (GPa)	69.5
Mean coefficient of thermal expansion 20-100°C (µm/m/°C	23.5
Thermal Conductivity at 25°C (W/m.K)	201

5083 - Aluminium alloy 5083 contains 5.2% magnesium, 0.1% manganese and 0.1% chromium. In the tempered condition, it is strong, and retains good formability due to excellent ductility. 5083 has high resistance to corrosion, and is used in marine applications. It has the low density and excellent thermal conductivity common to all aluminium alloys.

Typical applications require a weldable alloy of high to moderate strength, with good corrosion resistance. Marine applications, unfired welded pressure vessels, TV towers, drilling rigs, transportation equipment, armour plate.

Table 17. Material Properties of Aluminium 5083 [64]

Aluminium 5083	
Alloy and Temper	5083-H116
Tensile Strength (MPa)	305 min
Yield Strength 0.2% Proof (MPa)min	215 min
Density (kg/m³)	2700
Elastic Modulus (GPa)	71
Mean coefficient of thermal expansion 20-100°C (µm/m/°C	23.8
Thermal Conductivity at 25°C (W/m.K)	117

6000 Series Aluminium

6000 Series Aluminium is alloyed with *magnesium* and *silicon*, is easy to machine, and can be precipitation hardened.

6061 - Aluminium alloy 6061 is a medium to high strength heat-treatable alloy. It has very good corrosion resistance and very good weldability, although reduced strength in the weld zone. It has medium fatigue strength. It has good cold formability in the temper T4, but limited formability in T6 temper.

Typical applications include heavy duty structures in aircraft and marine fittings, couplings, brake pistons, ship building and aerospace applications including helicopter rotor and skins.

For all of the components that were CNC machined in the assembly 6061-T6 Alloy was used. 6061-T6 has been heat treated and artificially aged.

Table 18. Material Properties of Aluminium 6061.

Aluminium 6061	
Alloy and Temper	6061-T6
Tensile Strength (MPa)	345
Yield Strength 0.2% Proof (MPa)min	290
Density (kg/m^3)	2700
Elastic Modulus (GPa)	70
Mean coefficient of thermal expansion 20-100°C (µm/m/°C	23.4
Thermal Conductivity at 25°C (W/m.K)	167

Mild Steel

Mild steel was used for the fabrication of the modular side chassis, drive unit support cage and the caster wheel forks. Some of the advantages of mild steel over other metals are cost, malleability and weldability. It can also be readily laser cut and pressed. We used mild steel made to Australian Standard AS1594 - HA250. This is a fine grained low-medium carbon steel with good combination of strength, formability, toughness and weldability. It has excellent galvanising performance (low silicon and phosphorus content) and higher strength compared with normal soft forming steels such as HA1, A1006.

Typical applications include automobile parts, furniture, fixtures, tubing water heaters and machine parts.

Table 19. AS1594 - HA250 hot roll steel plate properties [65].

Mild Steel

Alloy and Temper	AS1594 - HA250
Tensile Strength (MPa)	392
Yield Strength 0.2% Proof (MPa)min	269
Density (kg/m³)	7850
Elastic Modulus (GPa)	205
Mean coefficient of thermal expansion 20-100°C (µm/m/°C	33
Thermal Conductivity at 25°C (W/m.K)	51.9

Stainless Steel

Stainless steel was used for the fabrication of the caster wheel axles, swingarm axle, for the hardpoints and for the motor drive shafts.

Typical uses include surgical tools, kitchen utensils, fasteners, and furniture.

304 Austenitic stainless steel offers good strength and good corrosion resistance. It is the most versatile, and the most widely applied of the 300 series commonly known as 18/8 Stainless Steel. It also has excellent welding characteristics, and post weld annealing is not necessary. It offers corrosion resistance and exhibits good resistance to a wide range of chemical, petroleum, textile, and food industry exposures.

Typical applications include architectural purposes, household appliances, catering equipment, cutlery industry, medical equipment, automotive components and sanitary equipment.

Table 20. Material properties for 304 Stainless Steel.

304 Stainless Steel	
Alloy and Temper	304
Tensile Strength (MPa)	600
Yield Strength 0.2% Proof (MPa)min	190
Density (kg/m³)	7900
Elastic Modulus (GPa)	200
Mean coefficient of thermal expansion 20-100°C (µm/m/°C	16
Thermal Conductivity at 25°C (W/m.K)	15

DiBond

Dibond is a composite of Aluminium-Polyethylene-Aluminium. It comes in a variety of sheet sizes and thicknesses for different applications. It is highly corrosion resistant and optimised for long term outdoor use.

Typical applications include signage and architecture cladding.

Table 21. Dibond properties for 4mm sheet thickness.

Dibond	
Material	Dibond
Tensile Strength (MPa)	145-185
Yield Strength 0.2% Proof (MPa)min	110-175
Density (kg/m²)	4.75
Elastic Modulus (N/mm²)	70’000
Mean coefficient of thermal expansion 20-100°C (µm/m/°C	2.4mm/m at 100°C temperature difference.
Thermal Conductivity at 25°C (W/m.K)	5.50

Fasteners (Nutserts, Rivets, Clecos)

Nutserts

M6 Threaded Inserts (Nutserts) were inserted in many of the components. Nutserts are designed to provide load bearing threads in thin sheet materials. This meant a light gauge aluminium material could be used for the components but still having a robust fastener assembly for part remove.

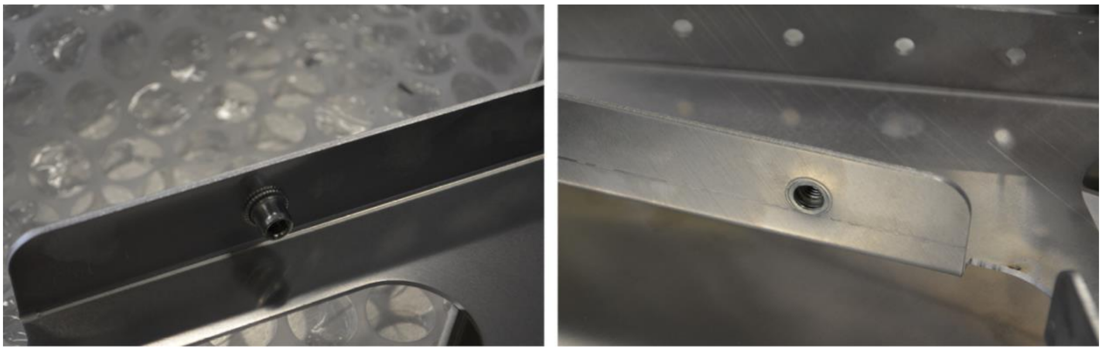


Figure 77. Nutserts installed in a 2mm aluminium component.

Rivets

For the implement unit (and also for the battery box assembly) 5mm Dome head rivets on a 30mm spacing we used. In total, approximately 700 rivets were used to assemble the implement unit.

Generally when specifying a rivet for light aircraft applications, the minimum rivet diameter is equal to the thickness of the thickest sheet to be riveted. And the maximum rivet diameter is three times the thickness of the thickest sheet to be riveted.

The rivet pitch (spacing) depends upon several factors, principally the thickness of the sheet, the diameter of the rivet, and the manner in which the sheet will be stressed. For aircraft construction spacing is seldom less than four times the diameter or more than eight times the diameter. In the case of this prototype a 5mm diameter rivet on a 6 times diameter spacing (30mm) was used.

Figure 78. Dome head rivets using in the Implement Unit assembly.

Clecos

A Cleco is constructed from brass and steel and houses a spring loaded mechanism. Essentially Clecos allow you to hold two pieces of sheet metal together in proper alignment for drilling or riveting. Specially design pliers are used to compress the spring loaded mechanism prior to the Cleco being inserted into the holes to join the materials together.

3/16” Clecos were used extensively during the assembly of the Implement Unit. These enabled us to temporarily assemble the components and ensure that all the holes were in alignment prior to final riveting.

Figure 79. Clecos being used on the Implement Unit assembly.

Nuts and Bolts

A standard set of nuts and bolts were selected for the vehicle to reduce the potential for conflicts during assembly/disassembly. Hex head (Allen Key) stainless steel fasteners were used throughout. Stainless steel, an alloy of low carbon steel and chromium was chosen for its corrosion resistance and appearance. Its low carbon content makes the fasteners slightly stronger than grade 2 steel fasteners but weaker than hardened steel fasteners. Stainless steel can be prone to galling (adhesion between sliding surfaces), so as a precautionary measure a small amount of white lithium grease was applied to the fasteners during assembly.

Table 22. Fasteners used in the vehicle assembly

Component / Connection	Fastener Type	Fastener Size
Implement /Side Chassis	Socket head cap screw	M8
Caster Unit	Socket head cap screw	M8
Swingarm/Mounting Cage	Socket head cap screw	M8
Motor/Gearbox	Socket head cap screw	M8
Gearbox /Wheel	Socket head cap screw	M8
Wheel Halves	Socket head cap screw	M6
Battery Box	Socket head cap screw	M6
Implement Unit	Button Head Cap screws	M6
Covers	Button Head Cap screws	M6
Caster Bearing Covers	Button Head Cap screws	M4

Nyloc nuts were used throughout the vehicle during the final assembly of components. A Nyloc is made of a standard nut with Nylon washer inserted into the top. The washer has an internal diameter smaller than the major diameter of the fastener. These nuts reduce the possibility of the fasteners coming loose by applying a compressive force against the fastener.