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Demonstrating the use of ground robotics for data gathering and analysis to assist farming decisions

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Abstract

The primary objective of this project was to demonstrate the application of mobile ground robotics for collecting high spatial and spectral resolution data of pasture and animal state on-farm. To achieve this, SwagBot, a prototype robotic vehicle developed by the Australian Centre for Field Robotics, was adapted for the target applications of weed management, pasture survey and livestock monitoring. Field trials on commercial livestock farms in Southern and Central NSW were used to validate the technology and to collect data for development of software algorithms. Key technical milestones included the demonstration of autonomous path planning and obstacle avoidance, and the demonstration of a fully autonomous weed spot spraying capability for serrated tussock. An assessment of technology readiness levels leads to the recommendation that the auto weed spraying technology is ready for commercial development now, with automated pasture surveying soon after. Livestock herding/leading was successfully demonstrated and a small amount of applied research will validate the technology. Longer term research would focus on livestock monitoring for welfare measurements.

Executive summary

There is growing interest in the need to provide timely information on pasture and animal state to livestock producers to support on-farm decision-making. The primary objective of this project was to demonstrate the application of mobile ground robotics for collecting high spatial and spectral resolution data of pasture and animal state on-farm. To achieve this, SwagBot, a prototype robotic vehicle developed by the Australian Centre for Field Robotics, was adapted and developed.

Extensive industry consultation was carried out prior and during the project to identify key areas within the production cycle where intelligent mobile robotics could support farmer decision making. These areas were identified as weed management, pasture survey and livestock monitoring.

An approach to autonomous driving on farm was demonstrated, making use of digital farm mapping, mission planning software and robotic perception technology for real-time obstacle detection and dynamic routing. An end-to-end solution for autonomous weed detection and spraying was demonstrated. The technical approach includes a computer vision system for real-time weed detection; a visual-servo control system to manoeuvre the vehicle into position; and a robotic spot spay system for chemical application.

Proof of concept pasture survey and livestock tracking applications were also demonstrated. In addition, the project showed interoperability with other emerging farm technology: data collected by SwagBot was used in combination with aerial data from a drone, and the mission planning system integrated with FarmMap4D, a commercial farm mapping tool.

Field trials on commercial livestock farms were used to validate the technology and to collect data for development of software algorithms. The locations of field trials were Chatswood, Nevertire and Arthursleigh, Marulan, both in NSW. The team also visited Central Queensland University’s livestock research facility to collect a dataset for development of livestock tracking software.

An assessment of technology readiness levels leads to the recommendation that the auto weed spraying technology is ready for commercial development now, with automated pasture surveying soon after. Livestock herding/leading was successfully demonstrated and a small amount of applied research will validate the technology. Longer term research would focus on livestock monitoring for welfare measurements.

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1 Background

The ACFR has been conducting research and development of robotics for outdoor environments for over 20 years for industry partners including BAE Systems, Rio Tinto, Qantas and Patrick Stevedores. The benefits of applying robotics and automation in these environments include reduced labour costs, improved worker safety, increased speed and efficiency and improved decision-making.

The ACFR has been applying field robotics technology to the environment and agriculture for 15 years. Examples include robotic platforms for the vegetable and tree crop industry including large scale commercial and small-holder farmers, and drones for weed mapping, including previous research conducted by the ACFR for MLA for mapping woody weeds on remote properties in Northern Australia [1][2]. One of the recommendations from that MLA work was to develop a robotic ground vehicle to provide an autonomous weed control capability on the ground.

Another pre-cursor to this project is the University of Sydney's Farmbot for the People project that used philanthropic funds to develop low-cost ground robotics for Australian farmers, aimed at both the row crop (horticulture and grains) and livestock industries. The SwagBot platform was developed using these funds. SwagBot is a lightweight autonomous electric vehicle designed for rugged terrain and with capacity for onboard sensing and computing.

There is growing interest in the need to provide timely information on pasture and animal state to livestock producers to support on-farm decision-making. As the cost of robotic and sensing technology decreases there are increasing capabilities available to farm managers. Key underpinning technologies for SwagBot include batteries and electric motors; sensors for navigation and autonomous driving such as GPS and 3D LIDAR; and intelligent software, in particular Machine Learning algorithms, for data processing. These technologies are improving rapidly in terms of price-performance, making robotic agriculture feasible and worth exploring. The vision for SwagBot is to have it routinely operating on livestock farms, collecting data to support effective management decisions and automating labour-intensive tasks, such as weed spraying.

2 Project objectives

The primary objective of this project was to demonstrate the application of mobile ground robotics for collecting high spatial and spectral resolution data of pasture and animal state on-farm. To achieve this, the SwagBot prototype was adapted and developed, enabling the technology demonstrations described in this report.

Important capabilities to be demonstrated included the ability to operate safely with minimal operator supervision, and a prototype user interface. In addition, the project aimed to demonstrate applications within three areas of extensive livestock production. Two previous workshops with beef producers, agriculture researchers and veterinary researchers had identified these areas within the production cycle where intelligent mobile sensing systems (on robots) could support farmers decision making. The key findings where producers need decision support were identified as:

- Pasture availability and quality: the use of sensors and perception algorithms to estimate the amount of pasture available in a paddock and the application of classification algorithms to determine pasture quality.
- Weed management: the use of classification algorithms to identify and map weed species and the application of novel mechanisms for precision weeding.
- Animal properties and behaviours: the use of sensors and algorithms to sense key animal performance indicators such as live weight and to understand the relationship between animal behaviour and animal performance indicators.

The data and software systems would also be developed to integrate with aerial imagery and multi-spectral data captured by a drone, and with the FarmMap4D mapping tool, to demonstrate interoperability with other emerging farm technologies.

3 Methodology

3.1 Industry consultation

Ongoing analysis of industry needs is important to ensure a technology solution meets industry requirements. The program included consultation with industry to explore potential use cases. The outcomes of this consultation can inform the focus of future investment in R&D.

The industry consultation took the form of:

- Detailed discussions with property owners and managers during the SwagBot field trials at Chatswood, Nevertire and Arthursleigh, Marulan.
- Customer interviews with c.60 industry representatives conducted during the Growlab startup accelerator program from September-November 2017. The program was developed by Cicada Innovations in partnership with MLA. The objective was to explore market opportunities for commercialisation.
- Producer workshops hosted by Central West Farming Systems at Condobolin in June 2017, by Central West Local Land Services at Chatswood, Nevertire in October 2017 and by the University of Sydney in May 2018.
- Attendance at the Sydney Royal Easter Show and Beef Australia 2018, in Rockhampton, where informal discussion with producers took place.

3.2 System integration

A first prototype SwagBot platform had been developed prior to the start of this project using philanthropic funds. Several hardware and software upgrades were made during this project to enable successful completion of project objectives by adapting the platform to specific applications relevant to the grazing livestock industry. These changes to the platform increased its robustness, integrated new sensing capabilities and upgraded onboard computing.

In addition, the project investigated interoperability with other emerging farm technology: how data from SwagBot can be used in combination with aerial data from drones, as well as integration with a commercial farm mapping tool, FarmMap4D. The SwagBot platform and drone used during the project are shown in Fig. 1, and a summary of the platform specifications are shown in Table 1.

(a)

(b)

Fig. 1. (a) SwagBot (b) 3DR Solo multirotor drone with Parrot Sequoia multispectral camera

Table 1. SwagBot performance specifications

Parameter	Performance	Notes
Drive	Electric motor	
Steering mode	Omni-directional	
Endurance	4-6 hours	Depending on terrain, speed and payload.
Range	60 km	Single charge, assuming 10 km/h and flat terrain
Max speed	20 km/h	
Payload capacity	100 kg	
Sensors	RGB machine vision cameras 3D stereo camera VIS-NIR hyperspectral camera LWIR thermal camera 3D scanning LIDAR	Used to conduct obstacle detection and environment mapping/localisation/tracking.

3.3 Technology demonstration

Field testing was conducted at commercial properties in Southern and Central NSW and at the Central Queensland University's livestock research facility at Rockhampton, QLD.

Field trials were used to validate the technology and to collect data for development of software algorithms. The locations of field trials were Chatswood, Nevertire and Arthursleigh, Marulan, both in NSW. The team also visited Central Queensland University's livestock research facility to collect a dataset for development of livestock tracking software.

The field trials focused on four key capabilities:

- Platform autonomy: demonstrating the capability for SwagBot to complete tasks on the farm safely, with minimal operator interaction or supervision.
- Weed management: demonstrating the capability for SwagBot to automatically map weed locations and the automated spot spraying of those weeds.
- Pasture survey: demonstrating the capability for SwagBot to map pasture quantity (biomass) and quality metrics for a paddock by driving transects and collecting sensor data.
- Livestock tracking: demonstrating the capability for SwagBot to detect and track livestock, enabling future applications in health, welfare and production monitoring and animal interaction (herding or leading).

4 Results

4.1 Autonomous operation

Overview

This section describes the approach to autonomous driving. A digital farm map is required for safe autonomous operation of SwagBot on farm. The SwagBot mission planning software is able to generate safe routes between waypoints using this pre-defined map. In addition, a 3D LIDAR sensor, robotic perception and dynamic path planning algorithms implemented onboard SwagBot are used for real-time obstacle detection and dynamic routing.

Global path planning and farm map interface

One of the objectives of this project was to demonstrate interoperability with FarmMap4D, a commercial spin-out from the NRM Spatial Hub program, as a mapping tool to support SwagBot missions. Farm infrastructure data including paddock boundaries was uploaded for both the Chatswood and Arthursleigh properties. Hazards/obstacles were defined using the FarmMap4D polygon tool and these data were successfully integrated with the SwagBot mission planning software.

Fig. 2 shows an example use of FarmMap4D for SwagBot mission planning at Chatswood, Nevertire. FarmMap4D also provides visualisation of satellite and aerial mapping data from various sources, including Landsat fractional cover. In future a more comprehensive user interface would be developed for vehicle command and control tasks including mission planning, data visualisation, live telemetry feed etc.

Obstacle avoidance and dynamic path planning

In addition to the global path planning approach that uses a pre-defined map, a local path planning and obstacle avoidance approach was demonstrated, enabling safe operation in unknown or dynamic environments including around moving objects (farm vehicles, animals etc.).

The approach was successfully tested and demonstrated during field trials at Arthursleigh, see Fig. 3, which was a key technical milestone.

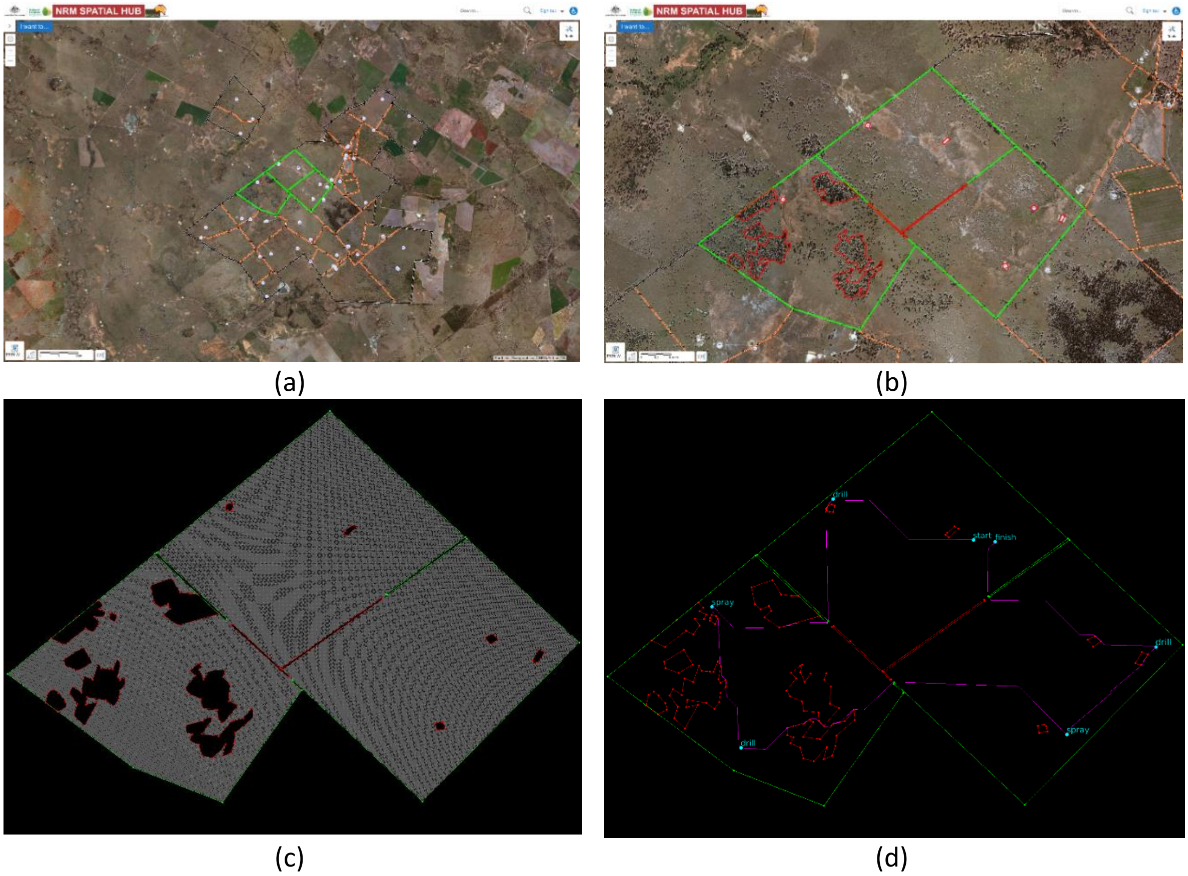


Fig. 2. (a) Figure showing the Chatswood property boundary (black lines), internal paddock boundaries (orange lines) and water points (white circles) in FarmMap4D. (b) SwagBot permissive areas (green lines) and restrictive areas (red lines) defined in FarmMap4D. (c) Mesh used by the autonomous path planning algorithm. (d) SwagBot mission plan showing route (magenta dashed line) and waypoints (cyan circles).

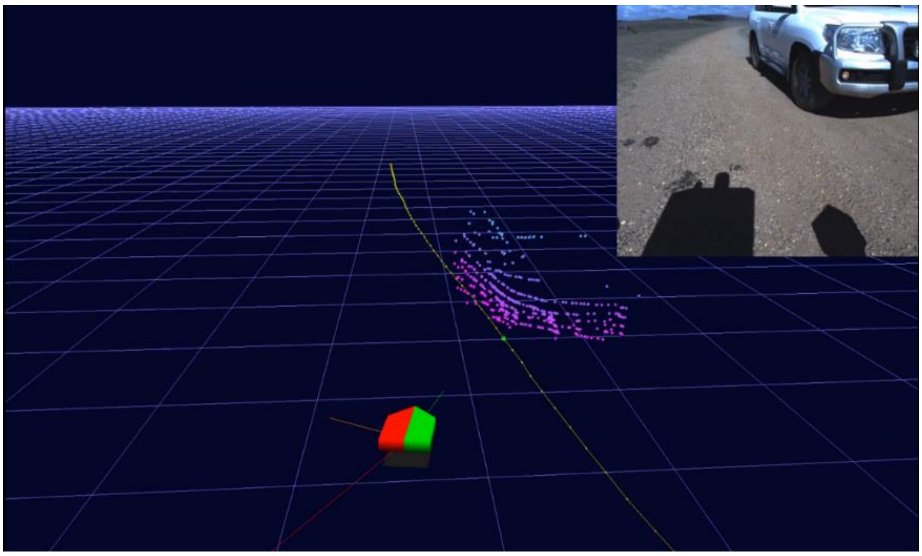


Fig. 3. SwagBot obstacle avoidance and local path planning on a farm track at Arthursleigh Farm. The main view is a visualisation of the robot planner and detections of the obstacle (Toyota Landcruiser) from the scanning LIDAR. The inset shows an image from forward-looking camera.

4.2 Weed management

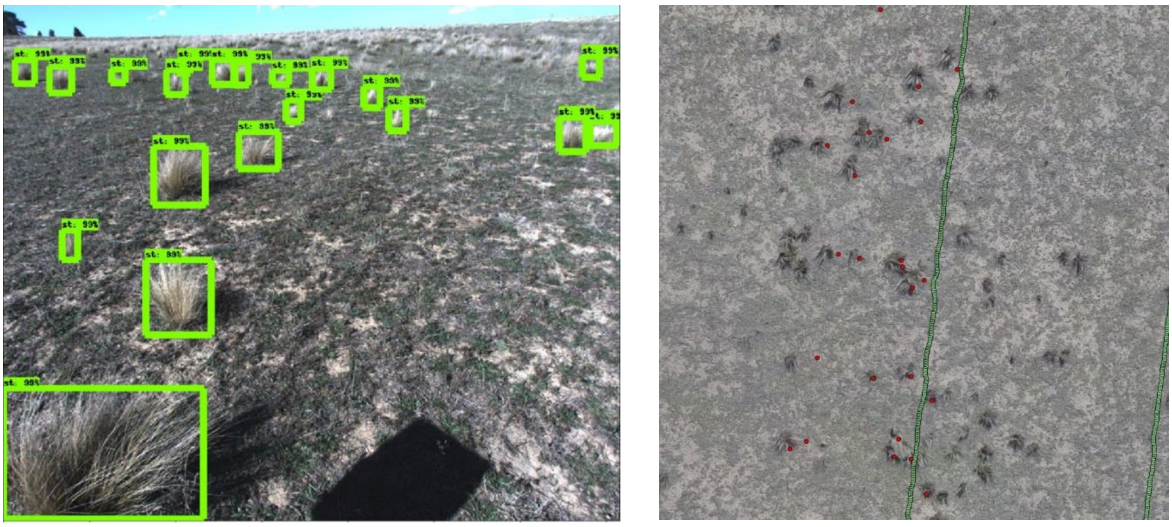
Overview

This section describes the approach for autonomous weed management. The technical approach includes a computer vision system for real-time weed detection; a visual-servo control system to manoeuvre the vehicle into position; and a robotic spot spay system for chemical application.

Detection and mapping

Automated weed detection in aerial imagery from drones has already been proven [1][2]. The objective in this project was to evaluate more recent machine learning frameworks and to prove the concept of fully automated weed detection and spraying from a ground platform. This is seen as a harder problem than from aerial imagery due to the potential for many different scales, viewpoints, lighting and occlusion when imaging weed species on the ground, compared to from the air where these parameters are relatively consistent for a single flight.

Despite these challenges, a computer vision model was able to detect serrated tussock, with a sample frame shown in Fig. 4 (a). The data processing operated in real-time onboard SwagBot. The model was also trained to detect African boxthorn and further vegetation classes can be added. Weed locations were mapped and georegistration accuracy verified by overlaying locations on aerial imagery captured by drone, Fig. 4 (b).



(a) (b)

Fig. 4. (a) The output of automated serrated tussock detection software showing green bounding box detections and confidence levels. Data was collected at Arthursleigh using SwagBot's forward facing camera. (b) A sample region showing high-resolution (1cm per pixel) aerial orthomosaic (data collected using 3DR Solo drone), SwagBot track (green) and weeds detected by SwagBot (red). The georeferenced weed locations correspond well with the aerial imagery, with only a small offset observed.

Automated spraying

Two concepts for weed treatment are outlined below, with both requiring the same core visual servoing and spraying component.

The first concept is that the paddock to be treated is mapped using a drone survey, weeds are detected in the imagery and a path is planned to visit all of the weed locations. This path is uploaded to SwagBot which drives to each location in the paddock in sequence, detects the weed using the downward looking camera and uses visual servoing to place the weed underneath the spray arm for spot spraying.

The second concept does not require the drone survey. A generic survey path for the paddock is built and SwagBot drives along this path. Weeds are detected opportunistically and georeferenced using the forward looking cameras, see Fig. 4 (a). When a weed is detected, SwagBot drives over the weed and uses visual servoing to spray it, as in the previous example.

Fully autonomous weed spraying is a promising application of agricultural robotics and all aspects of an on-the-ground weed detection and treatment approach have now been demonstrated. We believe that this is a world-first demonstration of this application for livestock farms.

Further development is required to increase robustness of the approach to different lighting conditions, and also to develop models that can identify multiple weed species. A potential area for future development is the method of herbicide application. This may include foliar spray and basal bark application, as well as application of pellets, depending on the weed species.

(a) (b)

Fig. 5. (a) A sample detection frame from the downwards-looking camera with the spray target position marked by a red cross, the spray coverage area marked by a red oval and the weed detections by green bounding boxes.
(b) SwagBot spraying a serrated tussock plant at Arthursleigh.

4.3 Pasture survey

Overview

Objective measurement of both pasture quantity and quality were identified as potential target applications for SwagBot. Quantitative estimation of pasture biomass underpins a range of applications including feed allocation, soil fertility, pasture yield mapping, and feed prediction [7]. However, visual assessments of feed quantity are subjective, with objective measurements rarely taken due to labour constraints. Pasture quality information is also valuable to producers because it gives them information on animal nutrient intake and production.

Integration of a soil moisture sensor with SwagBot was added to the project scope after positive feedback from producers about this capability. Soil moisture is the principal limiting resource for pasture growth and forecasting growth requires information about soil moisture retention.

Pasture quantity

Pasture height was measured using a 3D stereo camera mounted on SwagBot. Paddock surveys were completed by driving transects, with data on pasture height collected and used to produce maps showing the variation in pasture height across the paddock. Pasture biomass can be estimated by measuring the physical properties of the pasture (height) and combining with information about pasture species, time of year, latitude or geographic location, and also potentially weather, rainfall or soil moisture data. However this requires a calibrated pasture growth model, which was beyond the scope of this work. An example pasture height map is shown in Fig. 6.

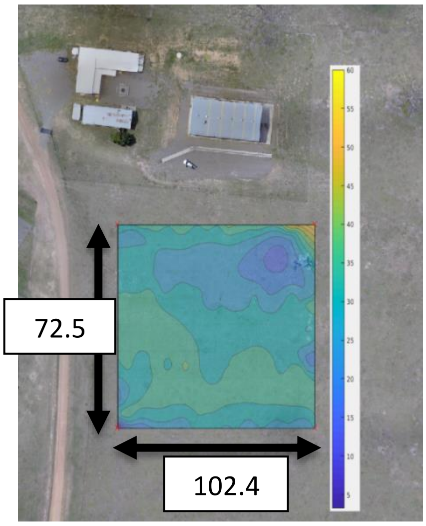


Fig. 6. Pasture height map for a paddock at Arthursleigh. With appropriate calibration, this could be converted into biomass (kg DM / ha).

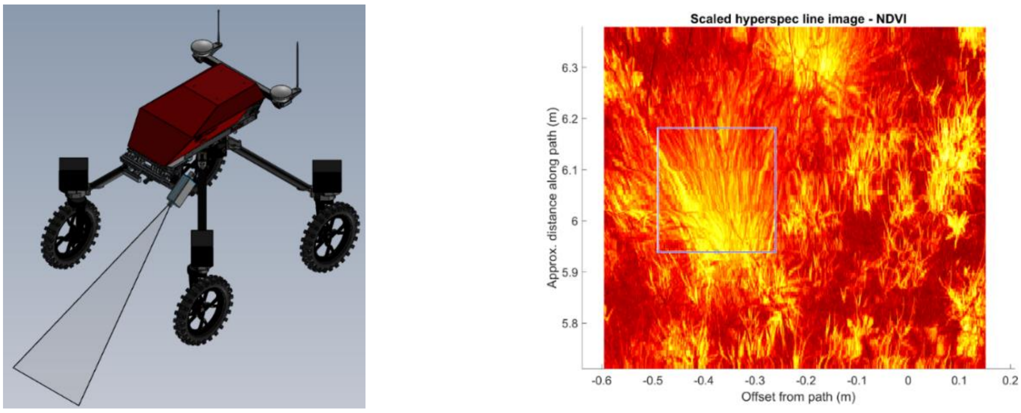
Pasture quality

The most useful metrics are reported to be digestibility and crude protein. Various researchers have shown hyperspectral imaging to be useful in estimating pasture quality metrics. In this project we demonstrated the use of SwagBot for collection and processing of hyperspectral data of pasture. The hyperspectral camera mechanical integration is shown in Fig. 7 (a).

The calculation of vegetation indices from the spectral data was demonstrated and an example NDVI image is shown in Fig. 7 (b). The georeferencing of this data was verified by comparing with multispectral data gathered via aerial survey of the same region by drone. Additionally, we analysed the spectral response for different pasture and weed species. Examples are shown in Fig. 8 (a) and (b), for two different vegetation types encountered in the survey. This type of analysis could be further developed for characterising species mix and pasture quality at paddock scale.

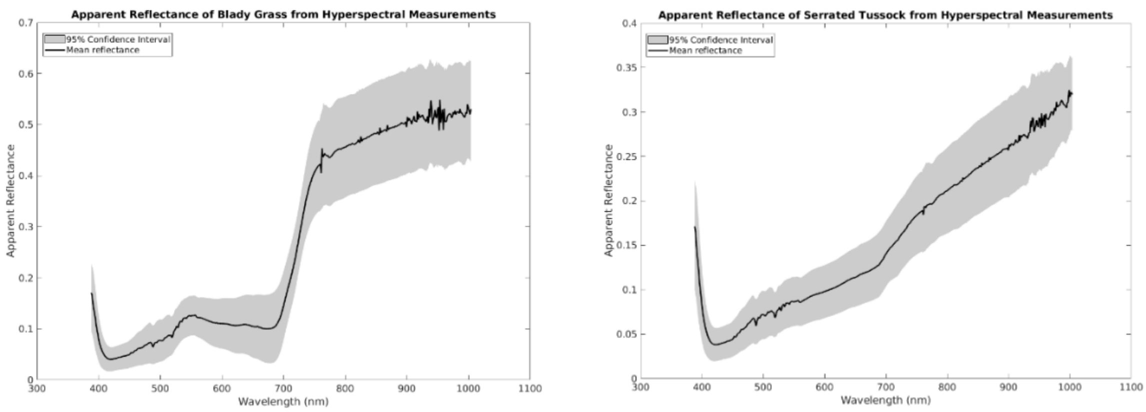
Soil moisture sensing

A Steven's HydraProbe sensor was selected for integration with SwagBot. The Steven's HydraProbe is a single level soil moisture sensor which may be used as an insertion probe or buried in the soil at a fixed depth. The sensor measures soil moisture, soil temperature and electrical conductivity. The sensor was integrated with SwagBot's linear actuator, which is a modular universal tool that combines a drill for soil testing and spray unit for herbicide application. Sample data points were collected for a demonstration of soil mapping. The current capability is limited by the depth that the probe can be inserted into the ground.



(a) (b)

Fig. 7. (a) SwagBot with position of Resonon Pika XC2 line scan hyperspectral sensor including the sensor instantaneous field of view projected to the ground plane. (b) Scaled NDVI image generated from SwagBot hyperspectral measurements.



(a) (b)

Fig. 8. Reflectance spectra of (a) blady grass and (b) serrated tussock computed from 10 samples along the region imaged by SwagBot, showing distinct spectral responses that can be used in identification of different species.

4.4 Livestock tracking

Overview

The livestock detection and tracking system implemented on SwagBot is to support a range of potential applications including animal location monitoring, health and welfare monitoring, livestock growth and production monitoring and autonomous stock movement. Detection and tracking of livestock is performed using a combination of a 2D colour camera and a 3D LIDAR with overlapping fields of view (FOV), see Fig. 9.

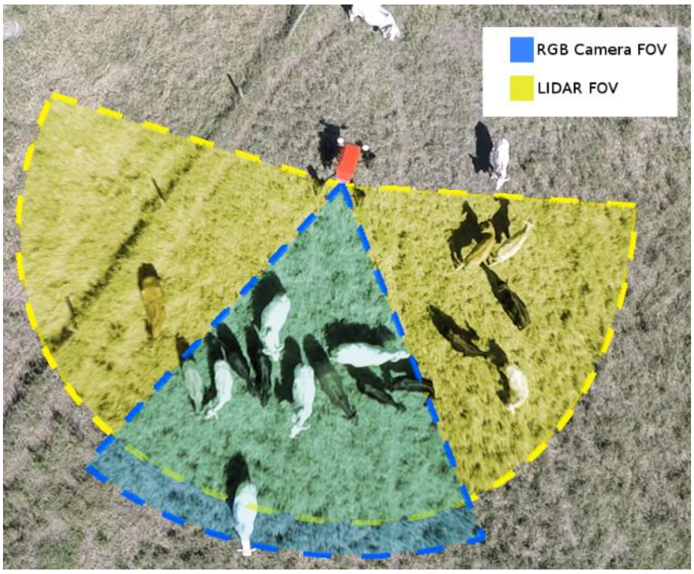
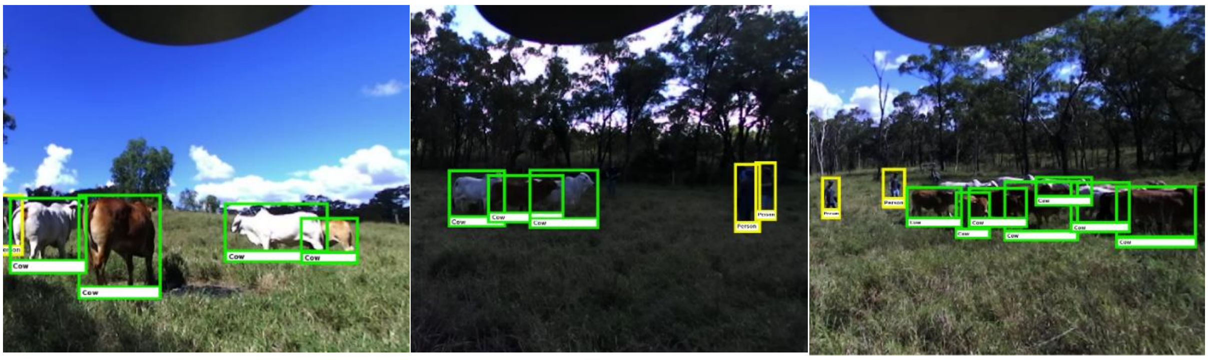


Fig. 9. Colour (RGB) camera and LIDAR sensor fields of view

Livestock detection

The detection system runs offline on a frame-by-frame basis, where the output from each frame, a series of 2D bounding boxes, is then combined with the inter-frame output of the 3D tracking system. Fig. 10 below demonstrates the system running on a data set in Rockhampton taken on 10th May 2018, in which the detection method was tested on two classes: people and cattle.



(a) (b) (c)

Fig. 10. (a), (b) and (c) 2D detections of known object classes (people and cattle) with bounding box segmentation showing successful detection even when there is variation in object pose, scale, lighting conditions and occlusion

Livestock tracking

Tracking is performed on a 3D point cloud generated by a scanning LIDAR. The output of this tracking system is the geo-referenced tracks of detected livestock and other known classes, in real-time.

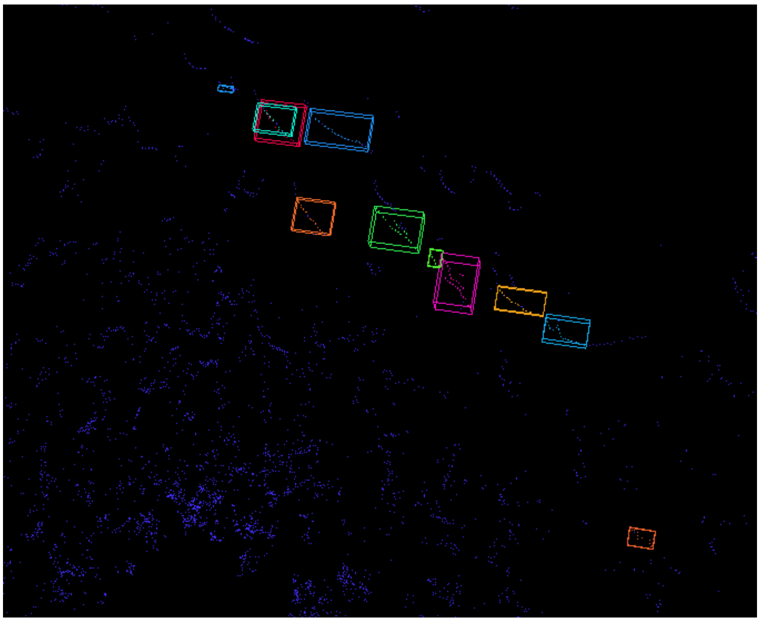


Fig. 11. Clustering of the 3D point cloud into 'unknown' objects. These can then be identified as cattle using the 2D detections.

Next Steps

Association of livestock detections between sightings would enable tracking of animal movement over an extended period of time and comparison of visual features from a single animal across a period of time. These visual features may provide information on animal health, disease, calving, growth and body condition. The capability to achieve this in the paddock would reduce the need to muster cattle and reduce stress leading to a positive effect on production.

4.5 Industry consultation

Producer consultation during field trials

Detailed consultation with producers was carried out during the field trials at Chatswood and Arthursleigh to gain insight into the particular challenges, outlined below, on both properties which make them useful facilities for testing SwagBot.

Chatswood is an 8,000ha cattle station in Central West NSW with c.1,000 breeding Angus beef cattle. They have problems with African boxthorn weed and galvanised burr. The seeds of boxthorn are spread by birds, with the plants often located under trees. This makes access to shade difficult for cattle and reduces the amount of feed available. Spot spraying is used for weed control and paddocks have also been cleared using mechanical removal and burning, however regrowth is an issue. An autonomous mobile platform that could spot spray young weed stems (using the basal bark technique) and monitor for outbreaks would be very helpful on this property.

Other tasks that have the potential to be automated include monitoring cattle, fences and water points; moving cattle between paddocks; and estimating feed. At the owner's other property in the Hunter Valley there is a problem with wild dogs taking calves.

Arthursleigh Farm, located in the Southern Highlands NSW, covers c.6,000ha with 15,000 sheep and 1,000 cattle. Arthursleigh has a particular problem with serrated tussock, a highly invasive weed that reduces pasture productivity. The farm is moving to a more intensive regime of boom spraying followed by sowing annual pastures in an attempt to suppress the weed and reduce its seed bank. After several cycles each paddock will be re-sown with perennial pasture species. This strategy is being rolled out progressively across the property. Autonomous weeding would be beneficial in this environment to help protect the investment in improving pastures.

Another labour-intensive task is taking pasture measurements (e.g. with a pasture ruler or rising plate meter), with visual assessment from the track or gateway increasingly used instead to save time. The visual approach is not representative of a whole paddock so an autonomous platform would improve accuracy and coverage of pasture measurement.

Customer interviews during the Growlab AgTech startup accelerator program

Interviews were designed to test a series of hypotheses about the market, with the objective being to develop an understanding of the SwagBot value proposition: how a product/service can meet the needs of potential customers. 58 customer interviews were conducted by phone and in person. Several potential customer types were represented with a bias towards producers and commercial livestock operations, as shown in Fig. 12 below.

Initial interviews were aimed at finding out the most pressing challenges faced by livestock farmers, with the hypothesis that weed control would be the most challenging issue. Although some farmers raised this as an issue, it did not come up as frequently as expected, as shown in Fig. 13. Pasture monitoring and feedbase assessment were cited as most challenging.

Fig. 12. Customer types interviewed as part of Growlab

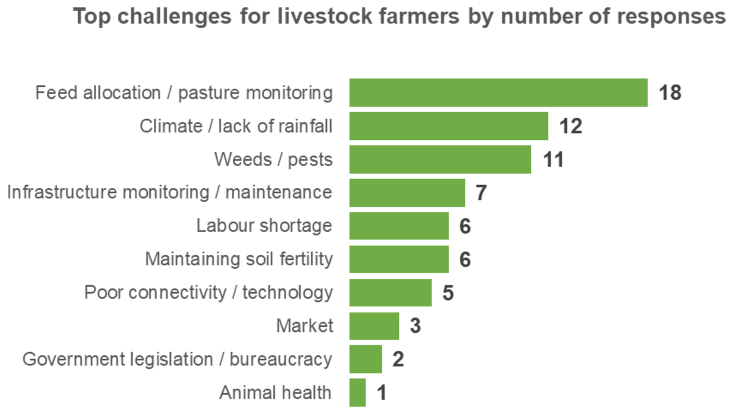


Fig. 13. Results of customer interviews for the top challenges facing livestock farmers

Table 2. Summary of customer discovery hypotheses and outcomes based on 58 customer interviews

Hypothesis / assumption	Valid Y/N	Learning	Outcome
Farmers are used to financing expensive farm equipment so will be willing to purchase the SwagBot platform	N	Farmers don't want to purchase more capital equipment, with associated operation and maintenance costs. They would prefer to pay for the data as a service, or potentially retrofit to existing platforms "The value is in the data, equipment will be obsolete in 3-5 years" "Enough platforms on the farm, make use of existing platforms"	Offer SwagBot as a service solution, as well as to develop 'bolt-on' technologies for other farm vehicles.

Most livestock farmers would benefit from data provided by SwagBot	N	Only an estimated 5% of livestock farmers are currently equipped with the infrastructure for digital agriculture, although generational change and improved connectivity will be a factor in increasing uptake of digital technologies. Many farmers make decisions by gut feel and intuition. A common response was they wouldn't use the data if they had it. "No-one is doing feed budgeting properly" "50% of irrigating farmers don't measure their water usage" (dairy example)	The initial target customer segment should be the top 5% most profitable producers.
Sales/distribution should be direct to farmers	N	Agronomists and farm consultants provide valued advice, have established clients and provide greater reach as a distribution channel. "Hard to get them [farmers] to open an email."	Focus on agricultural service providers as a distribution channel or consultants.
Weed control is one of the most important challenges for livestock farmers	-	Some farmers rated it highly challenging, however climate and feed allocation rated higher (see survey results) Weeding (like many tasks) is seasonal, can only be carried out when plants are actively growing.	Consider pasture monitoring (as an input to feed budgeting/allocation) in addition to weed spraying.
Knowing how much feed is available is important for livestock farmers	Y	Accurate assessment of feedbase is important for decisions on stocking rates and stock rotations, however it's currently mostly done by visual assessment which is time consuming and subjective. An accurate assessment opens up several management interventions. However this has been a "20yr problem that hasn't yet been solved". (Biomass is seen as a "holy grail" or "silver bullet" for livestock farmers.)	Value proposition for SwagBot is timely, automated and accurate pasture assessment
Current methods of biomass assessment have limitations	-	Ground-based methods are either time-consuming or subjective. Most farmers use visual assessment. Although expensive, aerial mapping is seen as more practical than ground-based for larger properties. Satellite (Pastures from Space) is accurate enough in southern areas, estimates within 200 kgDM/ha, but suffers from cloud cover. Satellite resolution is adequate for paddock-level assessment	Understand how SwagBot can complent other technologies

Spatial mapping (within-paddock variation) of pasture and soil data is important	-	Only important for the top producers. Most require paddock-level information for tactical management decisions. "Precision Agriculture/variable rate will move from cropping into pasture" "More pasture work recently, a growing trend, but still only 5% of work" (precision ag consultant) "High value land is likely to be cropped - if worth soil testing"	Minimum Viable Product would be paddock level estimates. Later sub-paddock spatial mapping data can be generated.
Pasture monitoring is a weekly task during the growing season	Y	It depends on the application (decision). Can be tactical (stock rotation) or strategic (decision on stocking rate over winter based on available feed, or positioning of new infrastructure to gradually improve pasture over time). Supporting this was the commonly cited problem with satellite data being low frequency (2-3 weeks out of date) often due to cloud cover	SwagBot pasture measurement would need to be provided weekly. Potential to combine ground and aerial/satellite data at different frequencies.

Discussion

The main means to pasture management platform is the farmer's own visual assessment of their pasture (the status quo), and there are a range of technologies for a digital solution to pasture measurement. These include technologies such as aerial/satellite remote sensing. However it's likely that a single approach will not fit all segments and there is room for complementary technologies.

It is useful to consider the advantages of SwagBot compared to alternatives, namely the ability to interact with the environment and take direct measurements e.g. soil moisture, and also that it will be fully autonomous, unlike drones which may not routinely be operated autonomously or beyond visual line of sight under current regulations. Furthermore, the potential for SwagBot to interact with cattle continuously and measure cattle performance as well as other features on farm is also a unique element. Finally, the cost of a ground autonomous platform will decrease in a similar way to how drones have over the last decade.

5 Discussion

5.1 Technology maturity assessment

This program has demonstrated four key technologies that are each at different stages of maturity. These include the core robotic platform, including technology for long-term autonomous operation on farm, and three key applications:

- Pasture survey
- Weed management
- Livestock tracking

The current status of each technology and potential future developments are described below. The maturity of each technology is described in terms of Technology Readiness Levels (TRL) where:

- TRL 7-9 means the technology is mature – ready for commercialisation
- TRL 4-6 is an intermediate stage – further applied R&D is required
- TRL 1-3 is early stage – fundamental research is required to validate the technology

SwagBot robotic platform: TRL 7-9

The SwagBot platform is a rugged lightweight electric vehicle that can safely drive between pre-defined GPS waypoints while detecting and avoiding obstacles. Further work is required to develop the robustness of the approach to moving objects. In future a full 24/7, all-weather, all-terrain capability would be developed.

Weed management: TRL 7-9

Automatic weed detection and mapping have been demonstrated and validated for accuracy. Detection of two weed species, serrated tussock and African boxthorn, was demonstrated. In addition, fully autonomous weed spraying was demonstrated for serrated tussock, thought to be a world first demonstration of this capability.

The computer vision-based weed detection technology is relatively mature, and the major development for an operational system would be solving engineering problems such as autonomous herbicide resupply and developing a concept of operations for effective weed spot spraying. E.g. mapping areas that have been sprayed and revisiting them to check for any plants that were missed.

Pasture survey: TRL 4-6

Pasture height measurement and multispectral technology for measuring pasture NDVI is relatively mature and has been demonstrated during the course of the program. The main issue to resolve, which requires further applied research, is calibrating pasture height and NDVI to provide accurate biomass estimates.

Pasture quality measurement (energy content, digestibility, protein and nutrient content) using hyperspectral sensing is less mature and requires further fundamental research.

Livestock tracking: TRL 1-3

The use of SwagBot for livestock monitoring is at an early stage of research and development. The first stage in this process has been demonstrated, which is the detection and tracking of animals using onboard sensors (scanning LIDAR and colour camera). It is a relatively straightforward extension to georeference and map animal locations in farm mapping or other GIS tools.

6 Conclusions/recommendations

6.1 Overview

The project demonstrated integration of pasture sensing (quantity and quality) and weed detection capabilities, development of autonomous path planning and integration with the FarmMap4D mapping system. The project has also demonstrated autonomous weed spraying and a high degree of platform autonomy, including obstacle detection and avoidance. Further, a livestock tracking capability has been developed that can underpin future assessment of livestock health and welfare in the paddock.

The demonstration of real-time obstacle detection/avoidance and path-planning was a key technical milestone for safe autonomous operation of SwagBot on farm. In the case of weed management, the project went beyond the original scope of weed mapping and was able to demonstrate a proof-of-concept autonomous weed spraying application for serrated tussock at Arthursleigh.

6.2 Recommendations

It is recommended that there is further applied research, including potential collaboration with researchers with domain expertise in the areas of pasture survey and livestock management. In future, SwagBot could improve grazing management by providing objective estimates of pasture quantity and quality, while animal location and behaviour can provide useful information about their production status, health and welfare. Further engagement with industry will be important to guarantee solutions meet industry requirements from both a performance and cost perspective. Autonomous weed management is assessed as ready to transfer out of the university research setting.

7 Key messages

- Robotic agriculture has the potential to generate multiple benefits including: labour savings, reduced input costs, increased worker safety and improved decision-making.
- The price-performance of key enabling technologies means that mobile ground robots on livestock farms is feasible.
- The SwagBot platform is a prototype autonomous ground robot developed by the ACFR. This project has demonstrated applications for SwagBot including autonomous pasture survey, weed spot spraying and livestock monitoring, through field testing on commercial farms.
- Full exploitation of this technology requires additional sensing capabilities to be developed, also identification of additional use cases for robotics through further consultation with industry.

8 Bibliography

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