Design Report- An Autonomous Mowing Robot

Introduction

This report will discuss the design of an autonomous mowing robot that has to operate in a typical Vineyard within New Zealand. This environment differs from others due to its dense rows, exposure to shifting climate changes, and varying light conditions. The robot should be capable of navigating fully autonomously with minimal human oversight. Furthermore, the robot should be able to operate on flat ground and some areas that have a 20-degree slope, regarding the day and night time. The autonomous mowing robot should have the ability to sense the environment and to choose safe and efficient paths to reach a destination, which is typically a specific zone requiring mowing as designated by human operators or management systems. This means the robot should be able to avoid obstacles and maximise its speed while remaining resilient to inaccuracies or noise from sensors and actuators [1]. In this report, physical requirements, sensing, localisation and path planning of the robot will be discussed. It will also be considered for the robot to be designed in a cost-effective way considering being realistic enough to enable multiple systems to be built for the various vineyards.

Size and locomotion

Considering that the vineyard rows are typically spaced between 1.5m to 2.5m, the autonomous mowing robot will be designed with dimensions of approximately 0.8m in width and 1.2m in length. This compact size not only facilitates comfortable navigation through the rows but also enables the robot to efficiently cover the same area multiple times if needed, ensuring thorough mowing without risking damage to the vines. The robot will be designed with water-resistant materials so that it can operate under unpredictable weather conditions. The robot will be equipped with four individually controlled tracks, each featuring treads designed for optimal traction. This design not only improves its performance on loose soil and in wet conditions but also confers multidirectional capabilities on the robot, significantly enhancing its ability to navigate tight spaces and efficiently reposition itself. This is particularly crucial given the varied terrain of vineyards. Additionally, the robot is designed to handle a range of terrains, including flat surfaces and slopes, with the capability to operate on inclines of up to 20 degrees.

For the robot to navigate up the slope and in wet conditions. the robot wheels will have treads. Furthermore, since the vines are spaced tight and there is limited space at some row ends, an articulated steering mechanism will be implemented which allows sharp turns. Additionally, an efficient mowing mechanism is integrated into the robot's design.

Sensing system

Due to the agricultural expansive nature and fluctuating light conditions, the autonomous robot must be specifically designed to be robust and adaptive, ensuring reliable operation in these demanding farm conditions. Feature identification in agricultural environments can be a tough task due to their vast and open nature with extreme variations in light[2], depending on the time of the day, weather conditions, or seasonal changes.
LiDAR sensors, which are accurate to within centimetre ranges and are resilient to light variations, are preferred over cameras, as highlighted in [6]. LiDAR sensors, such as the Velodyne 16 laser puck which has an accuracy of up to 3 cm, offer precise measurements with some basic data processing.

While LiDAR data can be sparse, making detailed object recognition challenging in some contexts, its ability to detect elevation changes and uniform patterns makes it particularly effective for identifying the critical points required to discern crop rows [2]. The consistent and linear arrangement of crop rows contrasted against the soil or space between them, allows for efficient differentiation even with sparser point clouds.
In [3], a robot uses LiDAR sensors to identify crops and navigate autonomously in the field, ensuring the crops remain unharmed. [3] highlights the limitations of traditional camera systems and classic sensors in agricultural applications. In this context, LiDAR-based methods are presented as an alternative that, while potentially having a higher initial cost, can offer long-term advantages such as reduced maintenance or improved reliability, especially given their minimal susceptibility to external lighting conditions.

In reference [4], the study analyses plant detection and mapping for agricultural robots which are similar to our project case. The robot described in [4] employs 3D LiDAR sensors emphasising the advantages of 3D LiDAR sensors over 2D LiDAR sensors.
The research points out that although robots that operate in indoor environments mostly rely on 2D sensors for map creation, self-positioning, and obstacle avoidance, they do not work well in outdoor conditions. The reason why 2D LiDAR falls short in the outdoor environment is due to several different conditions of the outdoor environment such as not flat ground and differing weather conditions. Despite these challenges, the decision to utilise 2D LiDAR sensors was made after careful consideration of the specific requirements and constraints of the project. While 3D LiDAR sensors offer advanced features compared to 2D LiDAR sensors, their cost makes them less feasible for our project where systems should be built for many different vineyards. As a result, 2D LiDAR sensors are used for our autonomous moving robots. 2D LiDAR sensors can provide a 360-degree view around the robot so that it can detect vines, rows, and other obstacles with the advantages mentioned above. Hence, for the autonomous mowing robot, a 2D LiDAR sensor is placed on the top-middle part of the robot.

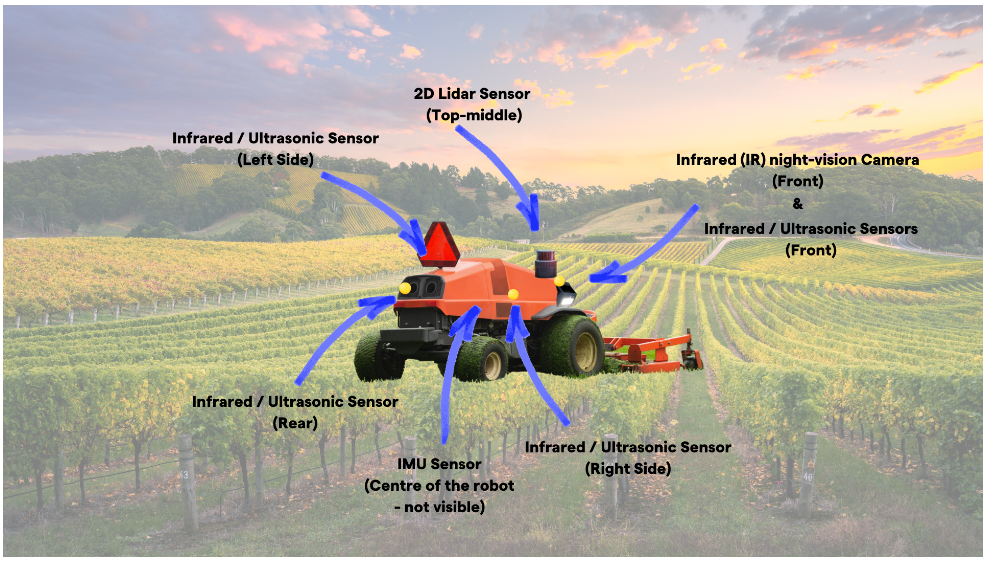

Fig. 1. Placement of different sensors
(The robot photo is just used to describe the placement of the sensors)

Reference [5] examines the application of 2D LiDAR sensors on both constructed and unconstructed roads. This research is similar to our project where vineyard rows are well-defined, constructed roads, and irregularities like slopes or gaps between vines represent the unconstructed roads. [5] highlights the limitations of the 2D LiDAR sensors, particularly under adverse weather and ground conditions like rain and fog. Mowing under extreme conditions may not occur, but mowing on wet ground is possible, given New Zealand's tendency for sudden and unexpected rains.

As limitations are mentioned above, only using a 2D LiDAR sensor is not enough for the mowing robot to navigate fully autonomously in the vineyard for various outdoor conditions. Numerous researchers insist that no singular sensor can wholly depict and adequately capture all relevant features in a real-world environment [6]. This is largely because different sensors have distinct strengths and limitations, and a diverse array of conditions in the real world can challenge a single sensor's capabilities. One possible approach to overcome this problem is to employ sensor fusion, which involves combining data from varied sensor types [6]. Therefore, IMU is used as an additional sensor for the autonomous mowing robot at the robot's centre. Primarily, IMU is employed in devices to measure velocity, orientation, and gravitational force [7]. In our project, it can be used for navigating slopes, providing data on the robot's orientation, and ensuring stability and correct navigation on not flat ground. Another use of the IMU in navigational systems is to assist in the creation of a 3D map [8]. A 3D map offers a comprehensive spatial representation, capturing elevation and depth data which can be crucial for applications like terrain analysis, obstacle detection, and precision agriculture. In [8], the researcher enhanced their robot's accuracy in sloping areas by integrating an IMU. The essential data, including angle and angular velocity, are processed through a simple IMU stabilisation filter. While the IMU drifts over time and is sensitive to vibrations, it provides essential orientation and motion data, crucial for navigation on uneven vineyard terrain.

Furthermore, the camera equipped with infrared (IR) night vision is attached to the front of our robot, allowing it to operate in low-light conditions. This feature ensures continuous operation, even during dusk or dawn hours when natural light might be insufficient. This camera is used with machine learning algorithms primarily for object recognition, which then informs the robot's decision-making process. The infrared/ ultrasonic sensors are also placed at the front, back and sides of the robot for short-range obstacle detection. The purpose of these sensors is to detect unforeseen obstacles such as animals. Infrared sensors and ultrasonic sensors are both widely used to measure distances [9]. While infrared sensors are more cost-effective and offer quicker responses than ultrasonic sensors, ultrasonic sensors provide more reliable obstacle detection and perform better under poor lighting conditions [9].

In the project, a comprehensive sensing approach is employed, integrating infrared sensors, ultrasonic sensors, and LiDAR, all strategically positioned on the front, rear, and sides of the robot. This combination ensures the robot is equipped to handle unexpected obstacles. For effective data interpretation from these multiple sensors, a weighted sensor fusion approach is proposed, where each sensor's input is evaluated based on its reliability and accuracy in given conditions. The system, integrating various sensors, inherently faces challenges like power consumption and environmental vulnerability. However, it is a necessary step for advanced autonomous functionality. The placement of the different sensors is described in Figure 1.

Localisation and navigation

The autonomous mowing robot employs the SLAM (Simultaneous Localisation and Mapping) method for localisation and navigation. Given the dynamic nature of vineyards, where environmental features can change seasonally or due to various farming activities, having a system that can simultaneously map its environment while determining its position is essential. SLAM allows the robot to adapt to changes in the vineyard, ensuring accurate navigation even if the landscape or the placement of obstacles has changed since the last operation. While there are many sensor types such as IMU, camera, GPS, and RGBD sensors, lidar-based SLAM has gained significant popularity [10]. This popularity arises from lidar sensors' high accuracy, strong resistance to interference, and insensitivity to changes in lighting conditions. However, it's recognized that LiDAR can sometimes struggle with sparse objects or surfaces that don't reflect well, such as thin grapevine branches. To counter this, the system will complement LiDAR data with information from the IMU, ensuring a more comprehensive environmental perception. Using 2D LiDAR data and IMU, SLAM algorithms for the autonomous mowing robot become invaluable. They assist the robot in determining its position within the vineyard and facilitate decision-making based on its current and past observations. Consequently, a LiDAR-based SLAM algorithm, supplemented by the IMU, will be utilised for localisation and navigation.

A study [10] explored three distinct LiDAR-based SLAM methods: Cartographer, developed by Google and known for its real-time capabilities and robustness, especially its loop-closing functions; GMapping, which uses Rao-Blackwellized particle filters with each particle having its individual map, known for its efficiency but sometimes needing intricate parameter tuning; and Hector SLAM, which uniquely functions without odometry data, relying purely on LiDAR-inferred movement, ideal for robots devoid of wheel encoders. The study identified Cartographer as having superior accuracy over the other two. While Gmapping resulted in higher map precision, it performed poorly when dealing with large and complex environments. Furthermore, Cartographer has advantages when working in large and complex areas which can be seen as useful for this project that involves large vineyards. Another study [11] evaluated various SLAM techniques, determining that Cartographer is superior in terms of mapping effects, data processing, and sensor prerequisites. Once applied, this algorithm allows the robot to generate a 2D grid map with a precision of 5cm [11]. For our application in the expansive vineyards, a 5cm precision is beneficial, ensuring that the robot navigates efficiently while minimizing any risk of damaging the vines or missing areas during mowing. The Cartographer algorithm is composed of two parts: Local SLAM and Global SLAM. Within the Local SLAM segment, data from odometry and the IMU are employed to estimate the robot's position and this estimation serves as the starting point for Lidar data scanning and matching [11]. After the motion filtering, individual frames of Lidar data are layered to create a submap [11]. For enhanced map accuracy, the robot aligns the IMU's coordinate system with the ROS system tracked by the SLAM algorithm and odometer to release the pose coordinates [11]. Therefore, the autonomous mowing robot will employ the Cartographer SLAM algorithm to ensure the robot performs well under conditions that need mapping in large and complex vineyards with unpredictable external factors.

Path Planning

For instance, vineyard environments may have workers moving about, animals that roam in, or even equipment being shifted. These dynamic elements require a system that can promptly recognise and respond to unforeseen obstacles to ensure safe and efficient operation. Although static maps provide a foundational layout, they cannot account for new or temporal obstacles. In [11], they used a cost map in the planning process since the constructed map is static and does not update obstacles in real time. A cost map consists of three main layers: the Static Map Layer (containing the original map data), the Obstacle Map Layer (showcasing real-time sensor-detected obstacles), and the Inflation Layer (which enlarges obstacles based on a set parameter, ensuring safer robot movement). The path planning of the robot in the greenhouse was divided into two parts: global and local planning. This dual-phase

approach ensured the robot could avoid both static obstacles from the map in the global phase and new or dynamic obstacles in the local phase.
According to [12], search algorithms like A* or Dijkstra are commonly used with the cell decomposition method to find a path. A* in particular, when implemented correctly, consistently yields the most optimal path based on the desired criteria [12]. Given the dynamic and potentially intricate environment of vineyards, selecting an efficient path-planning algorithm becomes essential. Therefore, our autonomous mowing robot employs a cost map for real-time obstacle recognition and the A* algorithm for effective path planning in the vineyard environment, ensuring that no section is left unmowed.

Safety Systems

There are some safety systems that should be considered when designing the autonomous mowing robot. As the robot is designed to be capable of navigating fully autonomously with minimal human oversight, the robot itself should have a safety system to prevent accidents and keep the vineyard undamaged.
Firstly, the robot is equipped with an emergency stop button to stop its operations immediately under risky conditions. While such a button is standard practice for many robots, it's particularly vital for our autonomous mowing robot when faced with unexpected obstacles like wandering animals or misplaced equipment in the vineyard. To continuously monitor its surroundings, the robot employs an array of sensors, including LiDAR and ultrasonic sensors. These sensors offer real-time feedback, enabling the robot to detect deviations from its intended path or imminent obstacles. If the robot behaves unpredictably or detects a potential collision, the integrated safety protocols, including the emergency stop, are activated to halt its operations immediately. The robot should also have a remote control system where humans can operate the robot in unforeseen challenges or to navigate the robot out of risky situations. Furthermore, the robot itself should be alert when the obstacle suddenly approaches the robot’s path or something comes too close.

Conclusion

In conclusion, the design and development of an autonomous mowing robot that has to operate in vineyards are discussed in this report. Due to the nature of agriculture, the autonomous mowing robot will be 0.8m x 1.2m sized, equipped with four individually controlled tracks each featuring treads for optimal traction in various terrains. It will also have an articulated system and an effective mowing system. The robot will be equipped with a 2D LiDAR Sensor positioned at its top-middle centre, an IMU sensor located at the centre, an infrared (IR) night-vision camera at the front, and infrared/ultrasonic sensors positioned at the front, rear and sides.
The robot will utilize the Cartographer SLAM algorithm for navigation and localization, along with a costmap and the A* algorithm for path planning. This setup will ensure obstacle avoidance and complete coverage of the vineyard. The cost estimate considering all sensors and materials, would be around $5000 which makes it suitable to be used in many vineyards. (approx. cost estimate under appendix)

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Appendix

- Tracks and Treads: $1200
- Articulated System: $600
- Mowing System: $900
- 2D LiDAR Sensor: $1500
- IMU Sensor: $300
- Infrared Night-Vision Camera: $500
- Infrared/Ultrasonic Sensors: $500
- Battery System: $400
- Communication System: $200
- Total Estimated Cost: $5000