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Design of a Prototype Autonomous Forestry Extraction Machine

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EXECUTIVE SUMMARY

The purpose of this project was to design and build a prototype autonomous forestry extraction vehicle and demonstrate the feasibility of integrating an autonomous control system on a forestry forwarder.

Forestry in Australasia is a multi-billion-dollar industry and provides opportunities for autonomous vehicles with the potential to improve efficiency, productivity and worker safety and health. The use of autonomous vehicles to support industry processes is not a new concept. For over 10 years they have been successfully used in the mining industry carrying ore from the mining site to the processing area. The process of transporting material from an extraction site to a sorting and distribution area following a consistent route is common throughout many industries, including forestry. Log extraction from the tree felling area to a loading site and returning for another load is a typically repetitive task and has been identified as well suited for early adoption of autonomous vehicles.

Technology integration and semi-automation in forestry equipment is becoming commonplace (such as integration of hydraulics, cameras and remote control in a motorised grapple carriage for cable logging). This project focussed on opportunities to develop equipment with autonomous control; that is without direct control of a human operator.

Introducing autonomous forwarders has the potential to improve safety and worker health, extend working hours and providing all year round wood supply, increasing annual production and reducing operating costs in the forest industry. In addition, less experienced operators can help manage autonomous forwarders providing a solution to the present shortage of skilled machine operators.

As a first step to achieving these goals, a small prototype wheeled vehicle was built to provide a platform for testing the electrical componentry necessary to achieve autonomous functionality. Construction of the prototype began by modifying a low cost wheeled trolley to serve as a mobile platform and installing a chain drive system. This provided drive and differential skid steering functionality. The integrated sensor system included GPS for guidance and LiDAR for obstacle detection. The GPS unit provided location and compass direction, which gave the prototype a heading and approximate distance from a predefined waypoint. The electrical system was designed to include an electrical board to mount a microcontroller to interface with the obstacle detection sensors. A primary scope change removed the requirement for the prototype to self-navigate around detected obstacles. Instead, the prototype would simply stop movement and provide live video feedback using of an optical camera. A remote operator would then move around the prototype obstacle and subsequently then continue its autonomous travel.

The present functionality of the prototype includes remote control operation of the motors, and basic collision avoidance. GPS guidance is provided by inputting a path through waypoints and wireless camera feedback to a smart phone screen has been achieved. While further testing and refinement would be required to consider the project a success, overall the project has demonstrated that basic autonomous movement of extraction machines such as forwarders can be readily achieved with relatively low-cost existing technology.

ACKNOWLEDGEMENTS

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INTRODUCTION

Finding ways to increase productivity and improve worker health and safety is an important focus for the New Zealand forest industry. The use of autonomous vehicles in harvesting operations provides an attractive option to enable the New Zealand forest industry to address the growing annual harvest volumes, improve productivity and continue their focus on improving worker health and safety.

A forwarder is a vehicle that carries whole tree stems or processed logs from the harvesting areas to a landing where processing and loading takes place. A typical operation comprises loading, using a self-loading crane, of either processed logs that are cut-to-length in the forest, or whole stems. The forwarder then transports its load through the forest to a landing area or a roadside site, unloads then returns to the harvest area to continue the next cycle. A forwarder has a large load capacity (up to 20 tonnes) which is well distributed because of its multiple axles and as a consequence has a lower environmental impact compared to another ground-based extraction machine (such as a grapple skidder, which drags its load along the ground). The forwarder has an optimal extraction distance ranging from 200-600 metres (Strandgard *et al.,* 2017) as measured from the point where the first log is loaded on to the forwarder, to where the logs are unloaded at the landing.

A forwarder typically travels through the forest over different types of terrain ranging from flat, to rough ground, but is typically limited to slopes of less than 30% (17 degrees). For example as a guide (where manufacturer’s limits are not given), subject to weather and ground conditions, wheeled machines should not operate on slopes that exceed 30% (Berkett & Visser 2012). Current regulations in the province of British Columbia, Canada, restrict the use of ground-based logging equipment to slopes not exceeding 40%. The slope is not the only limiting factor, however, and fully mechanised ground-based systems are often limited by other terrain factors, such as soil strength and/or ground roughness (Amishev *et al.* 2009).

Driving over rough terrain can cause whole-body vibration to the operator, a common health problem. Whole body vibration is a direct result of sudden jolts, rapid changes in vehicle speed, and abrupt stops (Waters *et al.,* 2007). This leads potentially to severe problems such as muscle fatigue and may result in short and long-term side effects (Tiemessen *et al.,* 2007). The effects of whole-body vibration combined with long working hours spent operating, can cause long-term fatigue that affects the operator’s performance, increasing risks to their health and productivity.

Implementation of autonomous vehicles has been successful in other industries such as mining and agriculture. For example in Australia, Rio Tinto, BHP Billiton and Fortescue Metals Group have all incorporated self-driving vehicles in their operations, using unmanned trucks to haul ore (Brown, 2018). Improving productivity and reducing the costs of harvesting is a common goal of harvest managers. Autonomous vehicles can do the same work as a skilled driver, with the added benefits of reducing human error and inefficiencies (Hamada & Saito, 2018).

Autonomous vehicles in forestry are in development for other operations. For example the Swedish trucking startup, Einride, is currently developing an autonomous logging truck capable of carrying 16 tonnes of logs up to 200 km (Lambert, 2018). This development is expected to be completed by 2020 as they ensure that the truck can safely perform in a large variety of driving scenarios.

There are several environmental, social and economic benefits from using autonomous machinery. These are:

Environmental benefits

With the vehicle traversing the forest constantly it can monitor the forestry tracks, altering its track to preserve the soil density in well-used areas., can relay information from monitoring points throughout the forest providing accurate information on soil conditions, tree health and growth rates, and helping to optimise the harvesting operation itself.

Social benefits

One of the biggest challenges to full-scale roll-out of autonomous vehicles is public mistrust of such vehicles. These concerns are safety to the general community and concern about job security. As dangerous jobs are replaced with autonomous vehicles, new and safer job roles are created such as in developing, marketing, maintaining, installing and monitoring these vehicles and the systems they need. If autonomous machines become more common, it is expected that people will begin to change their views with the advantages outweighing the disadvantages. However, managing public concerns is recognised as a critical step for future success in that it affects regulations for autonomous equipment operations (Christensen, 2016).

Economic benefits

Economic benefits arise from increased productivity and efficiency. Without operators forwarders could run uninterrupted throughout an entire shift, until refuelling or maintenance was required. Machines equipped with GPS receivers could traverse a path within one-half meter accuracy even in a forestry environment. Multiple forwarders can travel in close proximity to each other, increasing extraction productivity.

PROJECT GOAL

The goal of this project was to design and build a prototype of an autonomous forestry extraction machine, capable of navigating autonomously along a set route and thereby demonstrate the feasibility of such a system for use in a forestry forwarder.

Specifically, the aim was to develop a prototype system capable of:

- Traveling along a series of pre-defined skid trails using GPS
- Identifying major obstacles that prevent forward motion
- Provide live video feedback for remote operator override and
- Evaluate whether a navigation control system with appropriate navigation algorithms could be smoothly transitioned into an existing forwarder.

DESIGN PROCESS

An initial project outline was developed, including project milestones defining when each stage would be completed. At the beginning of the project, potential risks were identified which could hinder project development.

Risks included:

(1) The learning curves associated with use of unfamiliar electrical componentry and their integration into the system. This risk was minimised by delegating tasks to members most specialised to perform those tasks. As the project utilised unfamiliar componentry, some significant learning curves were experienced, negatively impacting overall progress. Minor problems throughout the project compounded causing completion of the milestones to be delayed by approximately two weeks.

(2) Exceeding the budget, caused by components failed during tests, and a $500 extension to the initial $5000 budget was needed to facilitate purchasing replacement components.

The design, build and testing processes areas detailed in Figure 1. Delays in the testing phase arose due to component failure. Because of this, testing the GPS integrated with the LiDAR sensors could not be accomplished within the timeframe.

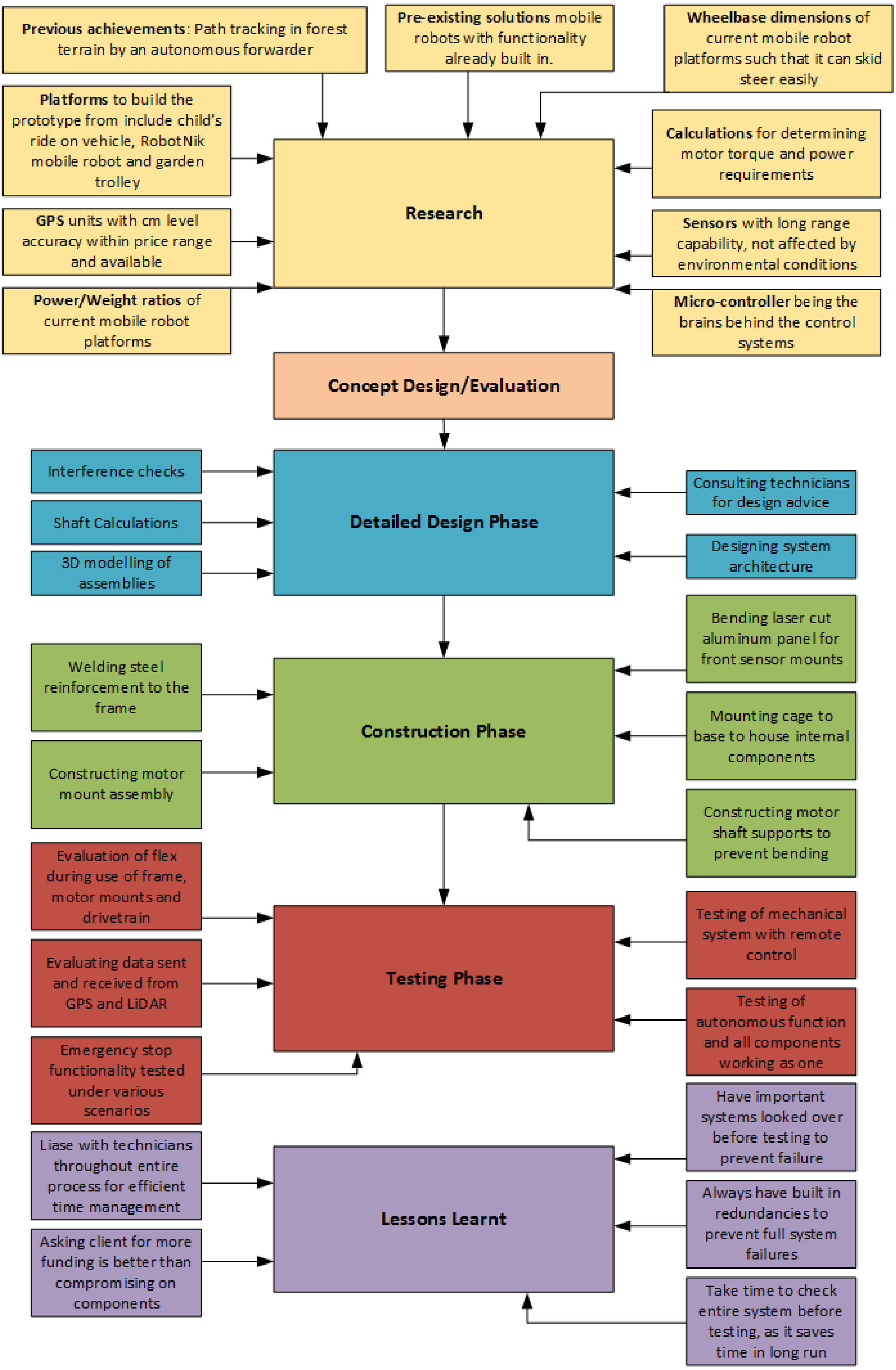


Figure 1: Overview of the project

Requirements and Specifications

The following describes requirements considered in the design phase, which were used to evaluate the viability of a solution:

Environmental Interactions

R1.1 The vehicle must identify potential obstacles and notify a remote operator.

R1.2 The vehicle shall use GPS as a means of navigation but must be adaptive to an intermittent signal. The vehicle shall continue its heading, avoiding obstacles as necessary until GPS communication is restored.

R1.3 The vehicle must be capable of traversing terrain of slopes of 20 degrees.

R1.4 The vehicle must be capable of navigating a 1.6m wide track (scaled down from an 8m wide forestry track)

Physical limitations

R2.1 The vehicle must fit on available transporter (scaled to 1/5 of full size loader: Length must not exceed 2.3 m and width must not exceed 1.0 m.

R2.2 The vehicle should operate at user defined speeds.

R2.3 The vehicle chassis must be inherently safe; contain no sharp edges or surfaces that could easily cause harm to a person.

R2.5 The vehicle must take a pre-programed GPS route and follow it with reasonable accuracy; Reasonable accuracy is defined as a maximum of 1.0m

R2.6 The vehicle should identify hazards and notify an operator if the hazard is deemed "not real". Should wait for operator's instruction before continuing.

R2.7 The vehicle must have emergency stop buttons located around the machine.

R2.8 The vehicle shall operate on a 24V system.

Specifications

The following specifications were considered in the design process but were not necessarily incorporated into the final design.

S1.1 The vehicle shall be of two sections that actuate in the centre.

S1.2 The vehicle shall use sensors capable of working at a maximum speed of 35 km/hr. Sensors working was defined as operating at or above 80% of the time.

S1.3 The vehicle should identify small obstacles and attempt to safely navigate around them.

S1.4 The vehicle must identify changes in ground level such as drops and take precautions to avoid these. Rapid changes in ground levels were defined as gradients greater than 50^o from both above and below.

S1.5 The vehicle should be aware of the number of journeys it can travel on a particular path and notify an operator for an updated route when necessary.

S1.6 The vehicle must distinguish a person in a forestry environment.

S1.7 The vehicle must stop (while in autonomous mode) if a person is identified within the operation exclusion area. The operation exclusion area was defined as 15m around the machine.

S1.8 The vehicle must not exceed 10 km/hr when operating within 20m of other machinery.

Early prototype components were built to allow the testing and refinement stage of the build to commence as soon as possible. The final design of these components was left for a later date. For example a remote control was made to control the prototype and only later was full functionality and ergonomics added to it. This meant that the development of the remote control ended up being one of the final developments even though it was originally anticipated that it would be done much earlier.

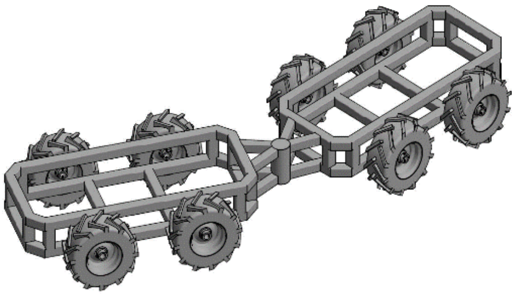
Similarly with the wiring of the prototype. Basic wiring was done to allow testing of components. However, the wiring loom became an adaptive task as parts changed and were added as required. This meant that the wiring loom was not finished until much later than first anticipated.

The largest delays in this project were experienced as the team worked out what was required and learning to use different componentry. Problems with components meant that the testing and developing sections had to be delayed while replacements were ordered and installed. An example of this was in the microcontroller implementation, with an incorrect voltage level fed into the Teensy 3.6 microcontroller resulting in damage.

One of the other major problems was in the original design of the motor mounts. This led to delays in the testing and implementation of the prototype base. When the original design was implemented, it was found that the prototype was unable to turn correctly due to flex in components that needed to remain rigid and could possibly damage the motors and chain. This had to be remedied twice to ensure the rigidity required to skid steer.

Steering

The original concepts included design aspects of existing forwarders. A forwarder is typically an articulated machine that includes a rear trailer unit with the front module being the operator cab and engine. Two concepts were designed: the first based on a current forwarder model with articulation between two trailer units as in Figure 2. Later, it was decided that the autonomous vehicle will not need a cab, so a second design was proposed. A single bunk unit enabled simplification of the design allowing for faster development. The project goal is to demonstrate the autonomous control system and simplifying the design enabled faster progress.



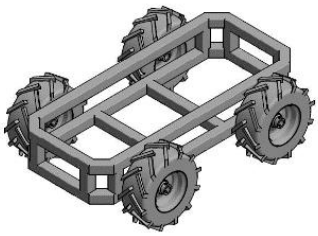


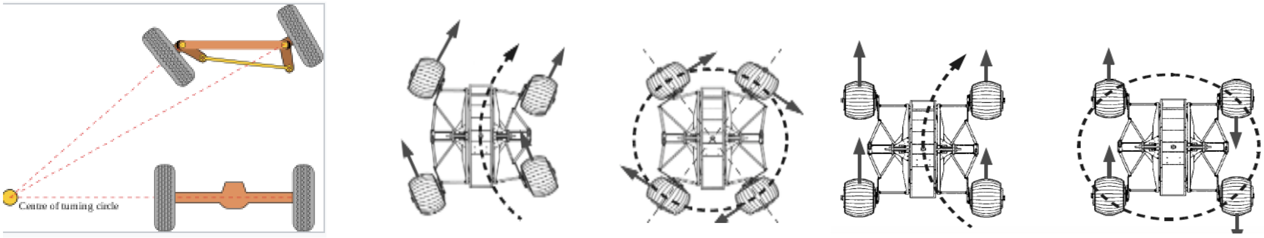
Figure 2: The first concept of a double bunk prototype (left); and the single bunk unit (right)

The development team diverged from existing forwarder design and instead presented an innovative concept that would generate interest in further developing autonomous technology. A second innovative feature desired was implementing a clam bunk grapple mechanism into the forwarder's bolster design (the vertical supporting beams holding up the logs). This would allow logs to be held in a manner similar to a forwarder and also have the ability to grasp multiple stems and drag them behind the vehicle. Clam bunk mechanisms are a log securing mechanism traditionally found on skidders, an example of this mechanism is shown in Figure 3.

Figure 3: Tigercat C640E skidder with a clam bunk mechanism (Tigercat, 2018)

With the project focus on achieving functioning autonomous capability, the clam bunk mechanism was left for possible future development. Instead bolsters, such as those used on forwarders, were selected to cradle the logs.

The skid steering configuration was selected to minimise the number of components required to be manufactured, simplifying development of the prototype following Investigation of three steering and drive configurations: Ackermann, explicit and skid steering configurations are summarised in Figure 4 below.



(a) (b) (c)

Figure 4: a) Ackermann steering geometry (Wikipedia, 2018), b) Explicit steering geometry, c) skid steering geometry (Shamah, 1999)

Navigation

Initially it was desired that a method of adaptive self-navigation would be implemented, where GPS waypoints are updated so that the forwarder could move into the constantly changing harvesting sites. Project Supervisor Prof. XiaoQi Chen has experience with autonomous navigation and advised the development team that this would be very time consuming to implement.

Instead it was suggested that a predetermined route should be created by recording GPS waypoints, then uploading these into the system to be followed whilst avoiding any obstacles. The design included:

- GPS unit using Real Time Kinematic (RTK) positioning technique to enhance GPS accuracy up to 1 centimetre level precision. Equipment includes:
    - Stationary GPS Base Station
    - GPS rover receiver

While this prototype will only follow a predefined route, further development of the navigation system is possible to get the vehicle to automatically update and alter its path. This would ensure the system could follow the ever-changing position of the harvester, where the trees are cut and ready to be loaded.

Another aspect of the initial brief that changed was the hazard identification and analysis system. Ideally the system should be able to identify an object, be it a stump, a person, or another vehicle, and determine the best course of action. This could involve an attempt to go around, to drive over it, or to await instructions from an operator. Instead the design changed such that the prototype sent live video feedback of any detected obstacles and waited for a human operator to issue commands to the prototype machine. The human operator then directed the prototype via remote control to take appropriate action.
The design included:

- LiDAR (Light Detection and Ranging) sensors capable of detecting obstacles up to 50m away, providing a 90º field of view. Sensors were to be used for detecting obstacles such as humans, rocks, tree stumps and other machinery.

PROTOTYPE DESIGN

For the prototype chassis, two options were considered: either purchasing a pre-existing platform 'off the shelf' or custom designing and fabricating the chassis. Research into 'off the shelf' platforms revealed a child's ride-on vehicle as a possible starting block. However, further investigation concluded that these were unsuitable due to their plastic construction. Mobile robot platforms were another option considered. Some platforms already have built-in autonomous capabilities. However, their cost is excessive, with the least expensive option at USD10,000. The final option considered was a metal framed garden trolley, a low-cost alternative that provided a base and wheels that could be used and modified into a more appropriate unit. A 3D model of the envisioned prototype is shown in Figure 5.

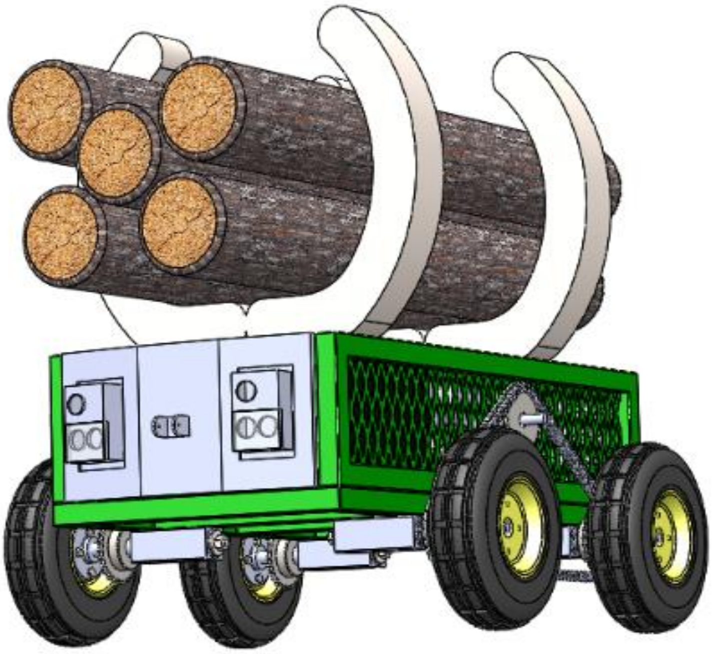


Figure 5. 3D model of autonomous forwarder prototype

The electrical system required a main processing brain to interpret information from the sensors and send commands to the motor driver. Three options were considered.

The first option was an Intel nuc which is the largest and most powerful of the three options, containing an Intel i3 processor and large storage. This would have been able to perform simple computer vision algorithms. However, the nuc would need to use the robot operating system (ROS) which would have required an extensive learning curve that the team did not have time for.

The second option was an Arduino Mega. This processor has a much slower speed of 80 MHz, compared to the 1.9GHz for an Intel nuc. However, this was all the speed necessary to process the information from the radio, GPS and sensors and was a more desirable option due to its smaller size.

Thirdly, a Teensy 3.6 microcontroller. This was selected as the processing unit for this design, due to it being specifically designed to be compact as well as having a sufficient processor speed of

120MHz. It also had a greater number of communications pins, allowing for more leeway if additional sensors were to be added to the design.

At the centre of the electrical system is a motherboard which contains various connectors to interface with electrical hardware and a mount for the teensy microcontroller. Figure 6, displays the layout of the board, labelled are the key features. To protect critical items, such as the GPS, radio, and teensy, from current surges, 250mA fuses were connected in series with their power supplies. This board allows for a tidy and compact method of interfacing the various sensing elements to the main microcontroller, reducing the risk of shorts, tangled cables and damaging components.

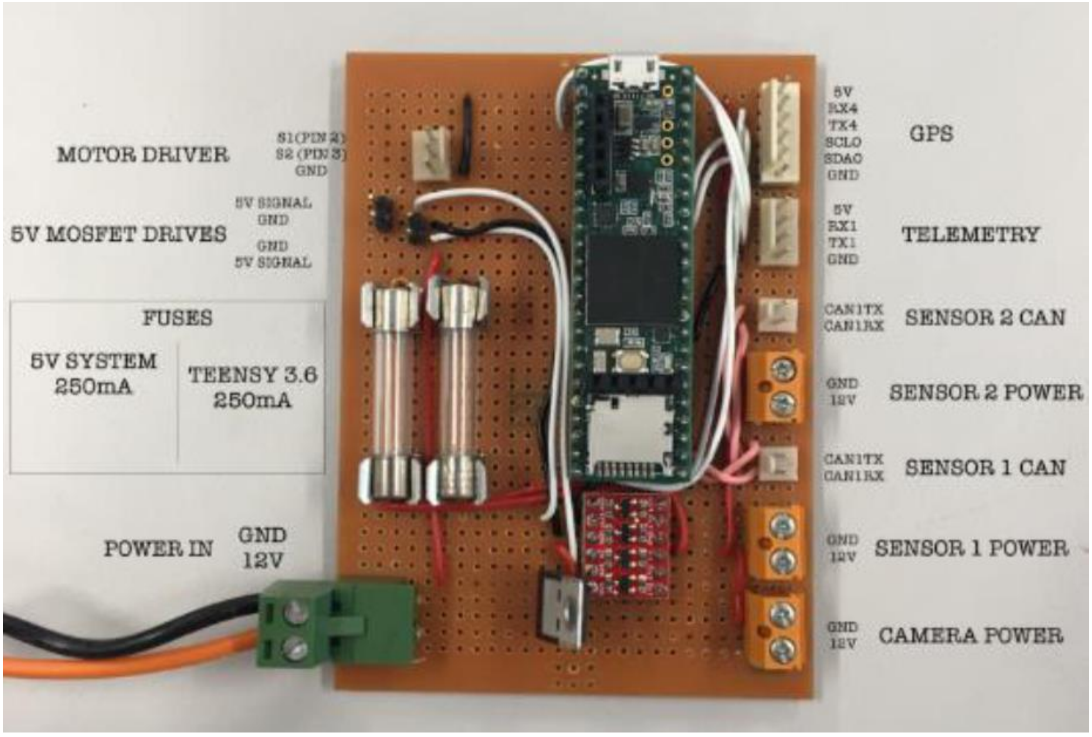


Figure 6: Labelled layout of prototype board containing various connectors and main microcontroller

Prototype Specifications

- Twin 750w DC brushed motors
- 2 x 12v 75 Ah batteries provided on board 24v supply
- RTK GPS unit with centimetre level accuracy
- Twin M16 solid state LiDAR sensors provide a 90o field of view of obstacles
- 3 x Emergency stops
- 1080p camera provided live stream video feedback to screen via radio
- Teensy 3.6 microcontroller served as brain of electrical system, receiving data and sending commands to the motors
- 3D printed remote control

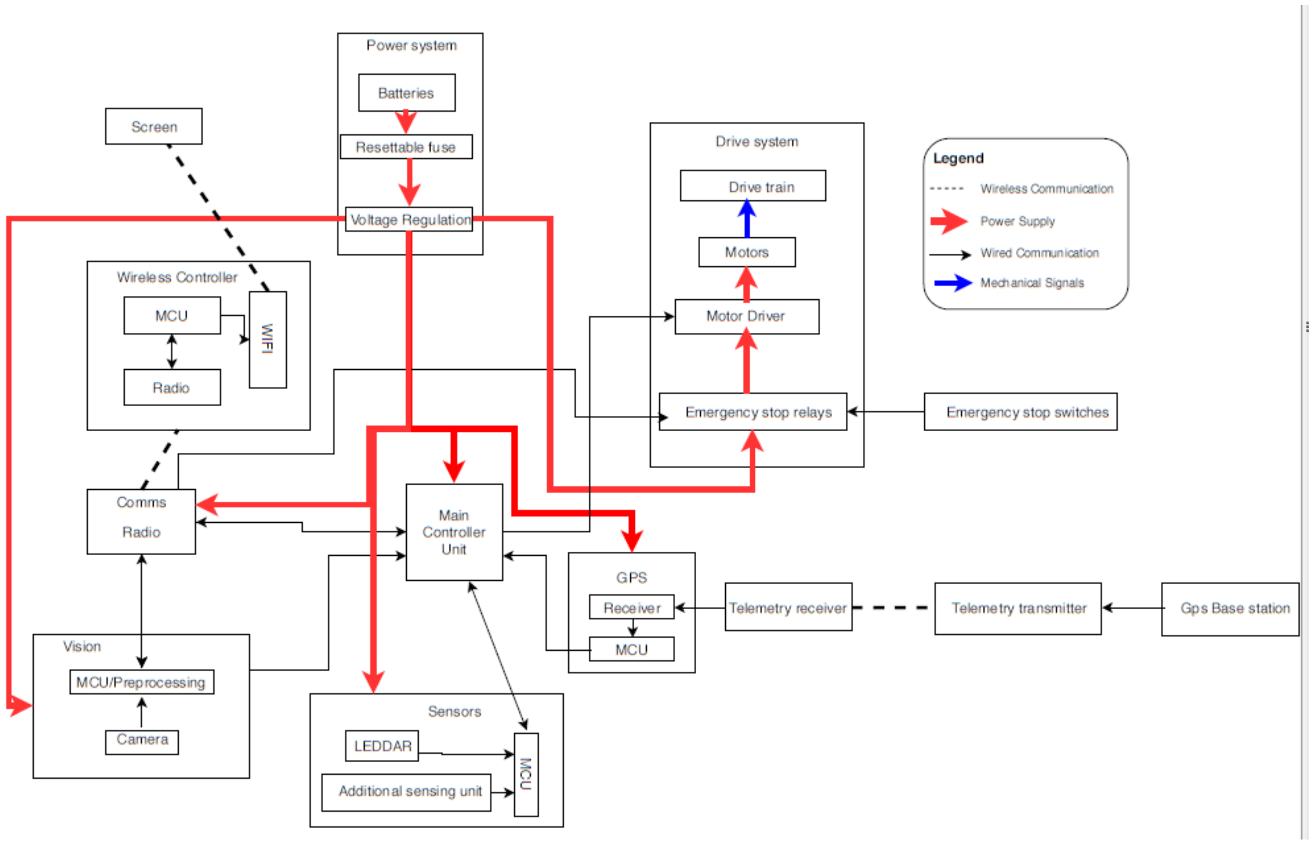


Figure 7: Control system specifications

PROTOTYPE BUILD

The original scope set out requirements for the final design. This list of requirements was referred to throughout the design process in order to determine if the system was a viable solution. The final prototype was designed to meet most of the requirements. These included:

- R1.3 During testing the vehicle was exposed to various gradients exceeding 10 degrees and showed no sign of difficulty in ascending and descending the terrain.
- R1.4 In testing, the vehicle was able to navigate down a gravel path approximately 1.2m in width, without leaving the track.
- R2.1 The size of the vehicle was approximately 1.06m long by 0.8m wide by 0.75m high. This fitted within the given constraints. The vehicle was approximately 100kg, well within the limit of 250kg.
- R2.2 Both the drive train gearing ratio, and the user defined maximum speed were selected to ensure the vehicle was not able to exceed 20km/h.
- R2.3 The mechanical chassis was built from a garden trolley rated for 100kg. The chassis was then reinforced with rigid steel angle section, welded around the perimeter of the chassis base. The strengthened frame was heavy enough to cause injury to a person if it were to roll into them. To mitigate this risk, corners were chamfered, and sharp edges filed smooth. The batteries were fastened to the base to prevent them rolling over, and large power switches added to isolate the electrical circuit.
- R2.4 The batteries had a capacity of 75Ah, which was approximately 2 hours of operation.
- R2.5 In testing, the prototype followed GPS way points to an accuracy of approximately 0.5m, half that of the 1.0m target.

R2.6 In testing the vehicle stopped at an identified hazard. However, notification of the operator has not been implemented into the feedback system.

R2.7 The final prototype contained three emergency stop buttons: one on the rear, and two on the side panels. These were tested rigorously while the robot was operational and had a 100% success rate

R2.8 The prototype operated with a 24V power supply provided by twin 12V SLA batteries mimicking the 24V power supply used by John Deere forwarders.

S1.6 Throughout the sensor selection and testing phases this requirement was considered. However due to limitations in time and experience, was deemed too difficult to implement and was not imperative to developing the initial stages of the autonomous system.

A photo of the final prototype as built is shown in Figure 8. The GPS unit is on the front left bolster, and right below the bolster is one of the emergency stop buttons. The video camera linked to the remote control in is the front middle of the chassis, and on either side are the LEDAR units. All the computer control systems are embedded in the chassis, as are the battery and electric winches that drive the unit.

Figure 8: Final prototype build.

The rest of the requirements and specifications were either hard to quantify success or were eliminated during scope changes. Example of the standard evaluation process for componentry used in the project can be seen in Figure 9.

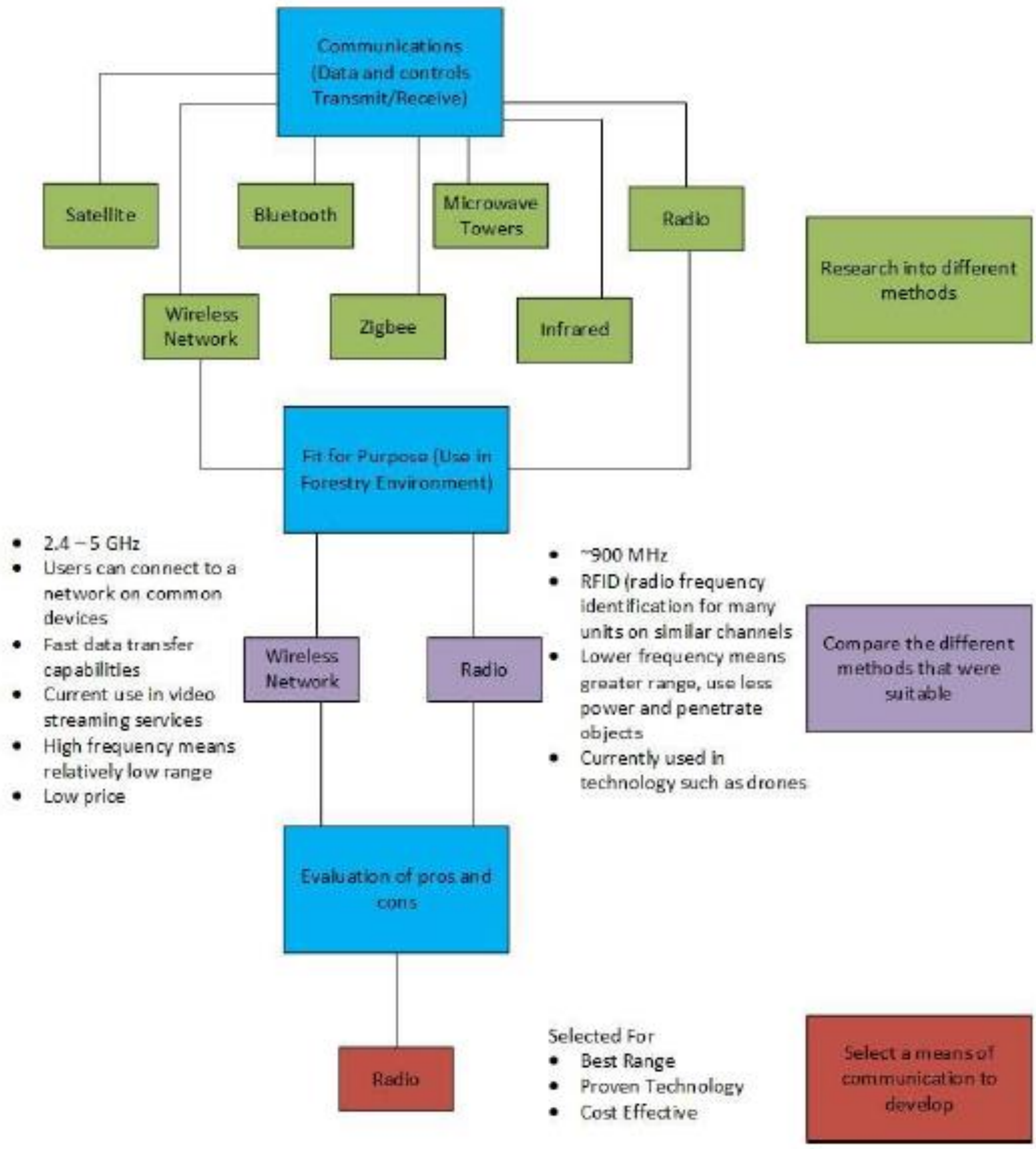


Figure 9: Example Standard Evaluation Process

DISCUSSION

The final prototype can be controlled by an operator from a remote location, and is capable of stopping in front of an obstacle detected by the LiDAR sensors. Although an important aspect for an autonomous vehicle was GPS waypoint navigation, this has not been achieved. Failure of the rover GPS module at the end of the build, meant that testing could not be completed on time. However, after discussing the issue with an electrical technician, the prompt replacement of components meant that the issue was resolved. At this stage the full electrical system was operational and at a stage where the prototype can be tested for GPS path navigation. The team was willing to continue testing and developing this aspect.

This project only focused on determining the feasibility of implementing an autonomous forwarder in the forestry industry. To get to a stage where autonomous machines are operating throughout the Australasian forestry sector, several key stages need to be achieved: completion of the scale model autonomous forestry forwarder; integration with the control system of existing commercial forwarders; and partnership with a forwarder manufacturer.

Completion of the scale model autonomous forestry forwarder

The first step was developing a prototype to test the components necessary for demonstrating a scale model of an autonomous machine could (1) follow a planned route, (2) identify major obstacles and (3) provide live feedback. These objectives were achieved to a limited extent.

The wheeled platform for the autonomous forwarder was mostly finished, it could move when given the correct inputs and was able to be driven powered by its battery pack for at least a couple of hours. The autonomous system components were installed and tested, but in order to have the full system working autonomously would require further development of the wiring and coding.

The feedback system for the project was initiated, with a remote control capable of controlling the machine and of broadcasting a network for video streaming. This remote control still required further development for mounting a screen to broadcast live video stream and development of other feedbacks such as sensor data, battery voltages, current speed and current GPS data for troubleshooting and accurate system monitoring.

Integration with existing forwarder control system

Once the current system has been fully developed and the autonomous functionality proven, manufacturers of forestry machinery will need to be contacted for information on how the current electric over hydraulic system functions. This information would include receiving plans for wiring diagrams, plug types, signal inputs and voltage levels. With this information the system could be transferred over to mimic the signals of the current user controls of forwarders. With this plug-in system functional, work with manufacturers would be required in order to fully implement this technology into new forwarders.

Partnership with a commercial forwarder manufacturer

To integrate the developed system into a forwarder, this would require a willing industry manufacturing partner. The sensors would need to be mounted on custom mounts in order to get the widest viewing angle and there would need to be a safe area where testing of the navigation system and hardware can be carried out. With these factors, the system could be debugged, enhanced and finalised.

Demonstration of this working system potentially could increase interest in the automation of the forestry industry and help clarify concerns over safety. Feedback from the market could be used to further develop parts of the system. By installing data recorders for clients that are interested in using the system, data of current forwarders could then be compared to that of the autonomous forwarder, and the comparisons between the two systems could be quantified. This data would also help in further development and fine tuning of the system before it is ready for the market.

NEXT STEPS

If project development was to be continued in the future, several recommendations have been made to ensure this project could continue without interruption or unwanted component failures. Concerns to be addressed for project handover/further project development include:

1. Sealing the tapered roller bearings from the environment. The bearings are currently exposed to environmental debris. Remedies include installing covers to seal the bearing housings from dust, dirt and water entering and damaging the bearings. Further, the bearing housings lack a grease nipple to lubricate the bearings, instead grease has to be manually smeared into the tapered roller bearings. This is recommended to be performed every 10 hours of operation.

2. The components within the system are rated at voltages varying from 5 to 24 volts and achieving these voltages within one system proved more challenging than originally expected. With the base being predominantly metal, it is easily earthed, and isolating components became a necessity. Due to the spikes in voltage as the motors change their power demand, damage could be caused to delicate electronics. The best way to combat this would be by using a capacitor bank to even out the flow of electricity entering the control system. Once the capacitor bank had cleaned the voltage, simple voltage converters could be used with protection circuitry to keep control systems operating optimally. This would also mean that the entire system is run off a single source and allow for the simplification of charging.

3. The LiDAR sensors at the front of the vehicle are the forward most component of the design and in the event of a front-on crash, have the potential to take the brunt of the impact, likely damaging them. Sensors like these are expensive and the risk of damage could otherwise be diminished by installing sensor guards or a bumper. Encasing the unit in a rigid plastic shell would prevent damage to vital components. However, the light emission and receiving lens of the LIDAR should not be covered as this would prevent sensors detecting obstacles. Such covers can be purchased from the LIDAR website or 3D printed.

4. Further, a crash bumper attached to the front panel could behave as an emergency stop; upon impacting an object it would bring the vehicle to a halt. The bumper would be designed with redundancy built in, such that it can deform elastically absorbing the vehicle's kinetic energy, protecting the sensors and camera from damage.

5. Although initially proposed in the scope, the remote control did not have a remote emergency stop feature. Developing a remote emergency stop acts as a failsafe to eliminate the need for operators to physically interact with the prototype. Attempts made to install a rudimentary version of this feature on the prototype led to damage to the GPS unit. A remote emergency stop could be successfully implemented with careful analysis of the circuit diagram to isolate voltage levels.

6. The original design of the motor mount system for tensioning the chains, failed to provide a support for the free-end of the motor shaft. The prototype demonstrated the difficulty in performing a skid steering manoeuvre on surfaces where there is large friction between wheels and the ground. In an attempt by the motors to rotate the wheels, the drive chain remained fixed as the wheels failed to rotate, causing the drive sprocket on the motor shaft to ‘ride’ along the chain. As a result, the unsupported motor shaft bent under the applied chain tension load. Furthermore, the face plate onto which the motors were mounted twisted. This was remedied by fabricating and mounting a 3-membered shaft support, providing support in both vertical and lateral directions, preventing the motor shaft undergoing bending. The support is not adjustable, it instead locks the motor into a rigid position eliminating the chain tensioning functionality of the original design.

   The process for re-tensioning the chain involves removing the fixed supports, adjusting chain tension through the adjustable tie rod and supports reinstalled into their new position by drilling and tapping new holes along the base. The chain does not need to be overly tight, with deflection at the centre of the span recommended to be between 10-20mm.

7. The radio transmitter/receivers proved temperamental, with the radios frequently losing connection between each other, especially when the prototype was loaded with The loss of connection between radio transmitters is not due to limitations on range. The full extent of the reason for the fault is currently unknown and would require investigation. Further considerations would see relocating the radio receivers to better positions or replacing the units.

8. The wheel shafts have been designed such that they are able to support a 50 kg payload of logs, satisfying considerations of stress overload and fatigue failure of the wheel shafts. Despite built in safety factors incorporated into shaft calculations, overloading the prototype could cause shaft failure, therefore it is advised that this prototype be used for demonstration purposes only and should not be ridden on or sat on by users.

9. The prototype is heavy due to its steel construction and twin 20 kg SLA batteries powering the electric motors, the prototype is expected to weigh approximately 100 kg unloaded. The tyres used are of soft rubber and provide a large amount of grip so that when skid steering on surfaces with high friction, the prototype struggles to turn. It is recommended, that skid steering is performed on smooth surfaces only, such as concrete or tiles and should not be used on high friction surfaces such as carpet. The best way to remedy this would be to change the drivetrain gearing, to increase torque delivery to the wheels. The prototype was initially devised to travel at speeds close to 15 km/h, but testing has seldom gone beyond 7.5 km/h speed due to safety concerns. Tripling the gear ratio, restricts the prototype to a maximum speed of 5 km/h and will triple the delivered torque to the motors. This will significantly improve the steering capabilities whilst still allowing for a good range of speeds for testing.

10. Finally, incorporating the prototype with static electricity protection for all electrical components would prevent the risk of static shock destroying electrical components. This is especially significant for the Teensy 3.6 microcontroller as they are sensitive to voltage and current inputs.

IPENZ Code of Ethical Conduct Clause 1 states *“You must, in the course of your engineering activities, take reasonable steps to safeguard the health and safety of people”* (NZ, 2018). Identified from the developed prototype are a series of potential threats that could compromise the health and safety of people. Early testing identified system faults so that they could be eliminated in future versions of the prototype. Firstly, there is the risk of the prototype running away due to system faults, it has been noted on some instances that the remote can sometimes freeze and send an aberrant command to the motor controller. This causes the prototype to unexpectedly drive with sudden and rapid motion in a random direction. This threat is mitigated by incorporating Emergency stops located on the rear and side panels of the vehicle, these allow for the prototype to be quickly shut down by users. In addition to this a pull-stop mounted on the rear of the vehicle allows operators to quickly ‘yank’ the pull cord disabling the vehicle preventing it from running away. It is hoped however; further testing of failure methods would eliminate the need for using the safety cord to fulfil complete autonomous function.

Another threat to health and safety of people was the potential for limbs getting caught in the external drive chain system. At present the sprockets do not have any guards to enclose them and prevent crushing. This is a serious health and safety issue as hands and fingers can easily get caught in the drive chain and pulled through the sharp sprockets. To mitigate this threat, chain guards and sprocket covers will need to be manufactured before this prototype can be demonstrated to prevent the potential for limbs getting caught and injury occurring.

Finally, the deep cycle batteries although sealed have the potential for emitting flammable gas while charging. To mitigate this threat, batteries are to be charged in areas with adequate ventilation and not in areas with exposed flames or sparks.

Recommendations

- In order to test in accurate forestry environments, attempts to waterproof some key components is recommended. Failure to take appropriate measures to waterproof could result in corrosion, electrical shorts and unwanted wear on components such as the unsealed bearings.

- The biggest limiting factor to the control system in its current form is processing power. By transitioning to Robotic Operating System (ROS), more computational power and advanced algorithms could be implemented, therefore increasing the prototypes ability to adaptively navigate its surroundings. By using ROS, the prototype would have the ability to monitor more internal functions during normal operations, and log data as it travels.

- Currently the emergency stop system is limited to only being on-board the prototype, so to stop the unit requires that the user be within reach of the unit. But if they are monitoring it or driving it using the remote this is not always possible. A suggestion would be to incorporate an emergency stop switch into the remote that kills the motors if the remote cuts off or if a button on the remote is pushed. This will prevent any unwanted runaways.

- While testing the unit, components have proven to be unreliable and should be evaluated to see if it is a wiring, quality or positioning issue. The radio transmitter/receivers are a good example of this. The radios often disconnected and would struggle to reconnect, making testing with the remote difficult as a lot of time was spent cycling the power to reconnect the units.

CONCLUSION

The aim of this project was to demonstrate the feasibility of integrating an autonomous control system on a forestry forwarder.

A small-wheeled vehicle was designed and built to test an autonomous navigation system in an environment simulating flat forest terrain. The drive train was tested and used to move the system forwards and backwards and to change its heading using the skid-steer capability. The key components for autonomous navigation were installed and tested. These components worked as expected with data obtained during the testing process, such as the GPS position and heading relative to magnetic north. This allowed the testing of the prototype’s ability to travel to a set position and wait for further instructions. The LiDAR sensors provided data on obstructions faced by the prototype. With this data the unit could travel through areas safely while stopping when it detected an obstacle directly in front of it.

The prototype and the concept of autonomous extraction was presented at multiple events, and the concepts included into the Forest Engineering teaching curriculum. This began the process of raising awareness for the deployment of autonomous systems in the forestry industry and set the foundation of further development. This can include further development of the prototype with more advanced capability, but also highlights the possibility of integrating simple autonomous control into a forwarder.

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APPENDIX: COSTING

The main difference between the expected cost and the actual cost of the project came in the design and research stages. With a scope in mind the development stage of the project began. However, in fleshing out the intricacies of both mechanical and electrical systems, extra costs were incurred. These were due to limitations in the 'off the shelf' items purchased for the project. Items such as the motors and motor drivers added cost to the project due to the fact that in detailed calculations, it was determined that larger motors would be required than previously anticipated. With larger motors required, a higher rated motor driver was also required in order to power them. A similar scenario occurred in both the wiring of the motors and the structural strengthening of the prototype base.

Cost item	Description	# of units	Unit Cost	Shipping Cost	Estimated Cost	Actual Cost
Garden Trolley	Saxon Garden Cart modified for use as chassis	1	89.00	0.00	89.00	99.98
Leddar (solid state Lidar)	Leddar tech platform evaluation kit (Light Emitting Diode Detection and Ranging)	2	407.79	30.00	845.58	937.26
Ultrasonic Sensor	Waterproof ultrasonic sensors.	4	21.85	20.00	107.40	0.00
Motor	48V 500W	2	88.00	120.00	296.00	502.85
Drive Belt/Gears	Drive belts/gears connecting motors to wheels	2	45.00	10.00	100.00	736.78
GPS unit	EMLID Mapping Kit (changed to Drotek unit)	1	1492.78	20.00	1512.78	1100.00
Batteries	12V 100Ahr gel	2	399.00	0.00	798.00	598.00
Emergency stop	30V 3A - may need to run with relay	4	1.70	0.00	6.80	10.52
Stop relay	24v 20A relay for emergency stop	1	9.54	0.00	9.54	56.90
Controller buttons	Remote control buttons	7	0.49	0.00	3.43	3.43
Controller joysticks	Remote control joysticks	2	7.64	0.00	15.28	15.28
Intel nuc	Processor boards	1	228	0.00	228.00	0.00
Transmitter/Receiver	Transmits the video signal for hazard identification by the user	1	230.00	0.00	230.00	174.47
Additional hardware	Fasteners, Hubs, Drive shafts, Spray Paint	1	200.00	0.00	200.00	0.00
Camera	For giving a signal of any potential hazards	2	40.00	20.00	100.00	0.00
REQUESTED TOTAL BUDGET FROM PROPOSAL			$4541.81			$4235.47

Additional Componentry						
Cost item	Description	# of units	Unit Cost	Shipping Cost	Total Cost	Actual cost
Micro controller	Teensy 3.6	2	57.00	10.00	134.00	134.00
Motor driver	Saber tooth 2x60	1	285.00	45.00	330.00	330.00
Laser cut material	Autobend cut Alum face plate, steel motor mounts	1	155.40	0.00	155.40	155.40
Material cost		1	80.86	0.00	80.86	80.86
GST/Import tax		1	223.00	0.00	223.00	223.00
Telemetry kit	For GPS RTK and Remote control	2	44.52	0.00	89.04	89.04
Battery isolation switch		1	22.00	0.00	22.00	22.00
Signal converter	RS485 to TTL	2	20.00	5.00	45.00	45.00
Chain Tensioner		2	16.00	0.00	32.00	32.00
Arduino nano	Remote control	1	17.00	0.00	17.00	17.00
Misc. components	Fasteners, paint, lubricants	-	62.14	0.00	62.14	62.14
Total Additional costs			$1190.44			
Total Project Costs			$5425.911			