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Report No. H030

Further Development and Field Testing of the Robotic Tree-to-Tree Felling Machine

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EXECUTIVE SUMMARY

As part of the FFR harvesting programme, teleoperation of tree felling machinery for steep country harvesting is under development. Part of this project is to design a novel forest locomotion machine for tree felling. The challenge is to develop a machine that can move over steep, difficult and sensitive terrain without causing damage to the terrain and can fell trees safely and cost-effectively.

The concept of the Robotic Tree-to-Tree Felling Machine (dubbed the "Stick Insect") whereby the machine uses standing trees as a means of locomotion has been developed to overcome the issues of steep terrain, soil damage and complex operating environments by remaining above the ground, overcoming the complexities of ground surface travel.

Earlier FFR reports have described the concept development and early design of the Robotic Tree Felling Machine (Parker and Milliken 2013, Parker *et al*. 2015). Until March 2016 the Stick Insect could operate only by way of a laptop computer and a tethered power supply. In addition, the control interface was not suitable for field operation, with limited motor control and reliance on a laptop computer.

This report details the further development of the Robotic Tree-to-Tree Felling Machine to the stage where it is remote controlled and ready for field testing. To enable field demonstration, the power supply and control system have been modified to operate outside the laboratory environment with the addition of an on-board battery and a wireless hand-held controller. Other modifications have been made to the mechanical structure of the machine so that it can be trialled in the forest environment.

INTRODUCTION

The primary goals of the Future Forests Research (FFR) Steep Land Harvesting Programme are to reduce harvesting costs and improve safety in the workplace, and make steep country harvesting operations more desirable as an employment option (Raymond 2010).

FFR has set a vision “no worker on the slope, no hand on the chainsaw”— in other words, removing manual workers from hazards in steep slope operations, by increasing mechanisation and introducing remote controlled and teleoperated felling and extraction (Amishev & Evanson 2010). One of the FFR programme goals is to “Develop alternative tree felling systems with the aim of eliminating manual chainsaw felling. This will require a machine capable of carrying a felling and/or delimbing head that can be operated remotely on steep terrain and hence have the lowest environmental footprint and zero hazard risk to the operator."

In the past, harvesting workers used only an axe or chainsaw to fell a tree. This felling system of manual worker and axe (or chainsaw) weighed generally less than 100 kg. Modern harvesting machines, although faster and with ability to bunch felled trees to improve payload, often weigh in excess of 30 tonnes. Mechanised harvesting on steep slopes can therefore create soil impacts and environmental hazards in downstream waterways, particularly due to compaction of soil (from heavy machinery), and soil erosion (due to traction and ground skidding) affecting future soil productivity, and debris slips from loosened soil and exposure to rainfall runoff (Adams *et al.* 2003; Baker 2014; Fahey & Coker 1989; Ghafferin *et al.* 2012). Reduction of sediment runoff into waterways is a primary concern for forest management when harvesting steeper terrain.

Researchers have found that the forest is a difficult environment that provides a unique challenge to robotic progress in requiring operation in such an unstructured and uncontrolled environment (Milne *et al*. 2013). Other researchers have noted the more complex in-field decision-making required in comparison to agricultural practices. Operating paths are never straight or flat, and there is a high level of vegetation and logging residue, and major variability in terms of soil strength (Ringdahl 2011).

The concept and design of the Robotic Tree-to-Tree Felling Machine has been described in earlier FFR reports (Parker and Milliken, 2013, Parker *et al.* 2015). It has been developed to overcome the issues of steep terrain, soil damage and complex operating environments by traversing across the terrain from tree-to-tree above ground level, eliminating the difficulties of travelling on the surface of the terrain.

Figure 1: Conceptual drawing of the Tree-to-Tree machine working over broken terrain.

OBJECTIVE

The objective of this report is to describe the further development of the scale working model of a "tree to tree" locomotion machine to the extent that it is operated by remote control and can be demonstrated in the forest. In a laboratory situation the machine has had a prototype chainsaw fitted and LiDAR guidance to find the next tree. These additions introduced considerable extra weight and complexity and have, at this stage, not been adapted to work outside the laboratory.

PROTOTYPE DEVELOPMENT HISTORY

The development of the Tree-to-Tree robot from concept of using tree stems for support of a tree-to-tree locomotion device was first conceived at Scion in 2002. In subsequent years the concept was refined and government and forest industry funding was acquired to advance development (Table 1).

Table 1: Chronology of the development of the Tree-to-Tree Robot

Date	Description
2010	• FFR Primary Growth Partnership Steep Land Harvesting programme commenced with the vision "No hand on the saw, no worker on the slope", including a programme to introduce teleoperation and robotics to steep country tree felling.
2011	• Richard Parker demonstrated a Scion-developed servo powered small scale tree-to-tree concept device to University of Canterbury Mechatronics Programme (Prof XiaoQi Chen) for inclusion in the research programme.
2012	• PhD student Bart Milne commenced work on Task A: Teleoperation for Steep Country Harvesting, including haptic feedback and semi-autonomy. • Post-graduate Research Assistant Andre Geldenhuis constructed a working arm prototype of the tree-to-tree robot.
2013	• Fourth year student project "Biped Felling Machine" (Wareing, Gilbert, Paulin, Bayley) built "alpha prototype" Tree-to-Tree Robot. • UC PhD student Chris Meaclem worked on computer control and path planning of Tree-to-Tree Robot. • UC Summer Scholar Kadin Wood investigated tree cutting mechanisms for the Tree-to-Tree Robot.
2014	• Tree-to-Tree Robot was awarded the Ray Meyer IPENZ Award. • Chris Meaclem continued work to improve control of the Tree-to-Tree Robot. • Fourth year student project developed a working chainsaw to fit onto the Tree-to-Tree Robot. • UC Summer Scholar Alasdair Soja investigated scale-up issues for the Tree-to-Tree Robot.
2015	• Chris Meaclem developed a LiDAR sensor linked to the control system of the Tree-to-Tree Robot. • Fourth year student project "Lightweight Tree Felling Robot" (Hong Fan, Mason & Greene) built a strengthened Tree-to-Tree Robot with greater dexterity. • University of Canterbury Mechatronics team – Professor XiaoQi Chen, Bart Milne and Chris Meaclem awarded Forest Owners Association Award for Innovation that enhances sector value.
2016	• Tim Lamborn engaged to write software to control the robot by remote control and on-board power source. Testing undertaken in forest environment.

The Tree-to-Tree Robot was based on a concept animation created by Scion in 2006 (Figure 2).

Figure 2: Early computer animation demonstrating the tree-to-tree locomotion concept (Source: Living Design Ltd, 2006).

After the initial concept was developed, a working scale model was built to demonstrate the concept (Parker and Milliken, 2013). During 2012, post-graduate Research Assistant Andre Geldenhuis constructed a working arm (Figure 3).

Figure 3: Working arm prototype.

In March 2013 the detailed design and construction of a larger scale working prototype (dubbed "alpha prototype") tree-to-tree locomotion device was offered as a final year project for University of Canterbury Engineering students.

This larger scale working prototype was designed and constructed at the University of Canterbury by four final year University of Canterbury engineering students[1]. It was planned that once constructed, the alpha prototype model would be trialled and used to guide the development of a full-sized machine.

The design of the alpha prototype was reported by Parker and Milliken (2013). This prototype weighed 50 kg, had grippers at the end of each arm and could demonstrate movement between simulated trees (fence posts) in the laboratory (Figure 4). The prototype enabled the detailed mechanical and electronic analysis of the device moving controllably from tree to tree taking into account strength of materials, weight, gripper configuration and degrees of freedom of movement. This tree-to-tree prototype used a conventional design for the gripper, which resulted in heavy grippers at the end of each arm, and was dubbed the “Stick Insect” robot.

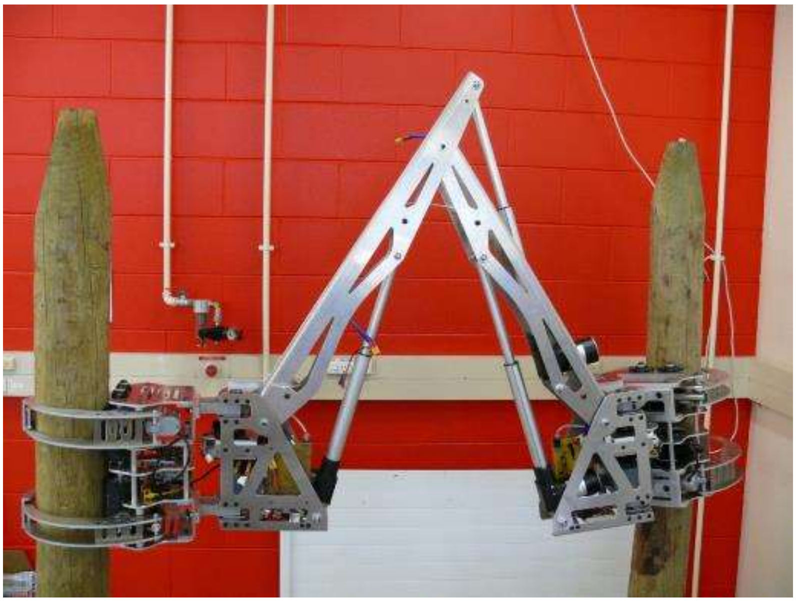

Figure 4: Alpha prototype ‘Stick Insect’ demonstrating movement between fixed stems in the laboratory.

University of Canterbury graduate student Chris Meaclem analysed data from a Scion forest survey to undertake path planning analysis and determine required dimensions of the full scale robot. This work indicated that the grippers of the robot would have to be able to open to at least 600 mm to be able to grasp all the trees in the forest and that a robot with an 8.0-m reach would be able to reach 98% of trees in the forest.

Chris Meaclem continued work on improving the design and control of the machine and developed a range of key measurements to be made in refinement for the detailed design of the device. These included joint displacement and velocity, machine and tool head coordinates, and accounting for the forces and actions required through kinematics and control theory. To ensure manoeuvrability in a forest environment, feedback controls and sensors were needed that could determine and correct for centre of mass and gravity, traverse time, and stability envelopes (Meaclem *et al*. 2015a).

[1] The machine and development team won the Institute of Professional Engineers New Zealand Ray Meyer Medal for Excellence in Student Design for 2014. http://www.3news.co.nz/technology/students-hope-robot-will-make-forestry-safer-2014032217#axzz3qDrvvAz9

METHOD

Development of the Stick Insect for In-Forest Demonstration

At the conclusion of the PhD research programme the Stick Insect needed to be animated so it could be controlled with a simple hand controller. While in the laboratory it was being controlled with a computer interface (Meaclem, 2016; Parker *et al*., 2015 FFR Report) which did not provide sufficient control to show the full range of movement of which the robot was capable. The robot was also tethered to a power supply so could not operate in the forest. Tim Lamborn, a recent graduate of the University of Canterbury Mechatronics Programme, was employed on contract to develop the Stick Insect to a stage where it was suitable for forest demonstration. This further development included remote control using a wireless controller and on-board power supply.

FURTHER DEVELOPMENT OF THE Stick Insect

The following work stages were undertaken to get the Stick Insect ready for in-forest demonstration:

1. Familiarisation with Robot

The first two weeks were primarily spent getting familiar with the robot environment, design and code.

Access to resources:

- Access to the Lab.
- Access to University of Canterbury IT services.
- Collecting documentation on the robot.
- Access to the “Git server” which serves as revision control for the Robot Operating System (ROS) code which runs the robot.

Sorting out networking issues.

- Understanding the networking behaviour of ROS between the robot computer and the desktop computer.
- Getting the robot operating as expected.
- Dealing with issues such as the university network randomly reassigning the robot’s address. This required a physical connection to re-determine the address.

Getting familiar with the robot’s quirks.

- Bugs preventing it from starting up.
- Bugs causing unexpected movement.
- It is still unknown why many of these problems occur. Chris Meaclem confirmed that some of these problems existed when he was working on it.

Setting up the lab.

- Cleaning up the robot cage, and sorting the parts provided.
- Organising the installation of the artificial trees.
- Mounting the robot on the trees.

Preparing for the introduction of a controller.

- Researching the ROS implementation.
- Understanding the existing joystick ROS nodes.

The ROS motor driver node was designed to run only a single actuator at a time. This was heavily modified to generate a throttle control channel for each actuator, enabling simultaneous control of multiple actuators.

Figure 5: The robot mounted in the laboratory and operational with tethered power supply.

2. Getting the controller operational

The controller used was a Playstation3 (PS3) controller, a wireless hand controller commonly used in the control of industrial and military robots. It allows the operator to walk around the robot while operating, and eliminates the need for a wired connection.

Some electronics were purchased to provide a controller directly to the robot computer:

- A PS3 controller.
- The Targus Bluetooth 4.0 adaptor to enable the robot to pair with the PS3 controller.

The PS3 controller was chosen because:

- of its convenient small easily portable form;
- it is intuitive and user friendly;
- it provides many high accuracy inputs and pressure sensitive buttons, and
- Bluetooth is easy to integrate into the existing on-board Ubuntu computer.

A simple solution for successfully pairing with the PS3 controller, and registering it as an input device was needed. An application called QtSixA from http://qtsixa.sourceforge.net/ solved this problem.

Getting the joystick control ROS node operational involved:

- moving the joystick control node off the desktop and onto the robot computer;
- solving more bugs and compilation issues;
- mapping joystick controls to the various robot actuators; and
- solving various bugs causing some actuators to not generate a throttle control channel.

Testing of the robot and controller was largely successful, but the grippers still needed to be selected using the Graphical User Interface (GUI) on the desktop machine before they could be moved.

3. Making the PS3 controller fully capable

The active gripper needed to be selectable from the PS3 controller.

- Looked for the code responsible for selecting and signaling which gripper may move
- Modified the joystick control node to also allow changing the active gripper.
- Mapped gripper selection to PS3 controller buttons.

Damage control

- During a demonstration of the robot being controlled via the controller, smoke was seen emitted from the robot.
- Accessing these boxes requires unplugging many sensors and removing part of the robot frame.
- This problem was isolated to one of the gripper electronics boxes, where an unused power cable with melted casing had shorted to something. Fortunately no damage was caused to surrounding electronics.
- The offending cable, and other redundant cables were removed.
- The robot was tested, and it operated normally.

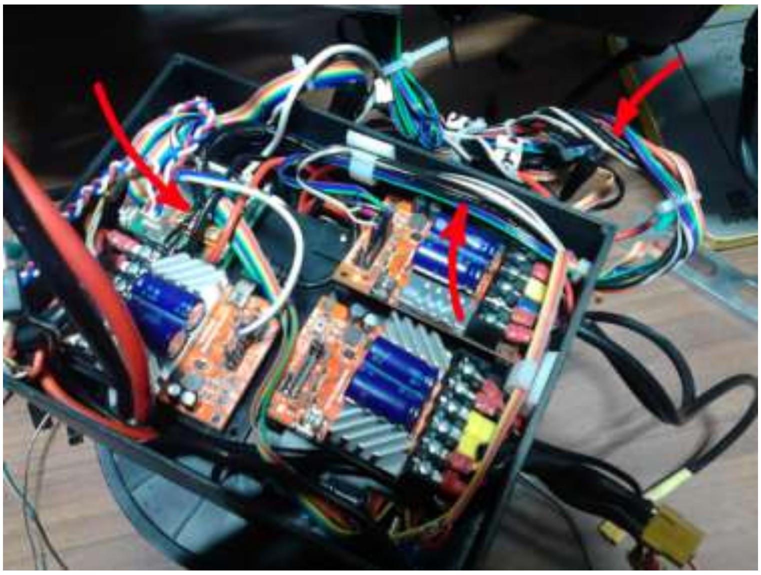

Figure 6: The electronics on the robot in a box, showing melted wires at several locations.

The horizontal wrist rotation problem (part 1):
The horizontal motion of the wrists was very difficult for the operator to keep smooth. The first problem identified was that the free wrist (the one not attached to a tree) was too sensitive to the throttle, because it has less mass to move compared to the fixed wrist.
This was alleviated by scaling down the throttle on the wrist associated with the active grippers.

Eliminating the desktop computer
Up until this stage the desktop computer was essential to the operation of the robot. It was eliminated from the system by:

- disabling the debugging nodes usually run on the desktop;
- launching ROS directly on the robot; and
- specifying that all remaining ROS nodes are launched locally on the robot.

4. Controller implemented for simplifying wrist control

Started remote – relay design.
The need for an isolated remote power cut-off system was identified, and preliminary design on this was started. The remote power cut-off is absolutely critical for safe operation when powering the robot with a battery.

The horizontal wrist rotation problem (part 2):
It feels more natural to the operator when the throttle correlates strongly to the resulting actuator speed. This is the case for all of the linear actuators. However, the horizontal motion of the wrist behaves extremely differently.

- The force required to move the arms increases as the arm extends.
- The force is also dependent on the arms angle from the horizon – this is often the result of getting a crooked grip on the tree.
- The arm has high momentum, so even in an optimal position it requires significant throttle manipulation from the operator to accelerate and decelerate the arm.

This means that the robot arms may behave both sluggishly and jerkily, requiring significant operator effort to compensate.

A Proportional Integral Derivative (PID) controller (a generic control system for goal seeking) was required to set the motor throttle, based on the feedback from the appropriate rotary encoders.

The first attempt was to repurpose a PID module already present in the code by:

- studying the PID node;
- modifying the controller to use my existing throttle input and output systems; and
- retuning the PID controller.

The existing PID controller proved to be prohibitively time consuming to modify, and it was decided instead to build a purpose-built PID node, which involved:

- writing generic PID controller code;
- making a new ROS node which estimated the wrist angular velocity from the encoder readings, then fed it and the target velocity into a PID controller;
- integrating this node with the existing throttle control systems;
- debugging the node; and
- tuning the PID controller to ensure it is as smooth and fast as possible.

Tim was unable to remove a high degree jitter from the PID controller. Paul Milliken suggested that the problem was likely due to the derivative component of PID being sensitive to noisy inputs, as the mechanical system is intrinsically highly dampened. That is, it is resistant to motion, and will slow to a halt on its own. The derivative term could be significantly reduced without becoming unstable. The wrist motion now behaved smoothly as expected.

The PID controller will attempt to remain stationary when the throttle is at zero. This means that if the joint is pushed by a person, the joint will push back. This behaviour is undesirable, and therefore the controller is shut down while the joysticks are at a near-zero position. This can also be used to halt the controller should something cause the PID controller to become unstable, such as faulty encoder.

Motor examination
The 2013 Final Year student project technical report suggested that the power being delivered to the wrist motors was being intentionally limited. The motor voltage, current and stall resistance were all measured, showing that full power was being delivered.

5. Replacing Damaged Linear Actuator

The robot was scheduled to be displayed at the MPI Expo, and had to be detached from its artificial tree. During this process one of the grippers would not detach. It was eventually detached by disassembling the faulty claw.

Inspection revealed that the linear actuator responsible for moving the gripper had failed. It is not known why the actuator failed. Inspection seemed to suggest the actuator's motor was damaged due to being driven for too long while stalled. This could have been caused by some prior stress. A replacement actuator and spare was ordered from the original manufacturer, Firgelli Automations, immediately.

To prevent this from re-occurring, the procedure is that the grippers are not to be driven for longer than a few seconds if they stall. A more fool-proof solution should be investigated in the future.

6. Developing Remote Power Cut-off

Installing the new actuator.
Previously observed was that some of the pins used to connect the grippers to the linear actuators have been bent (Fig 7).

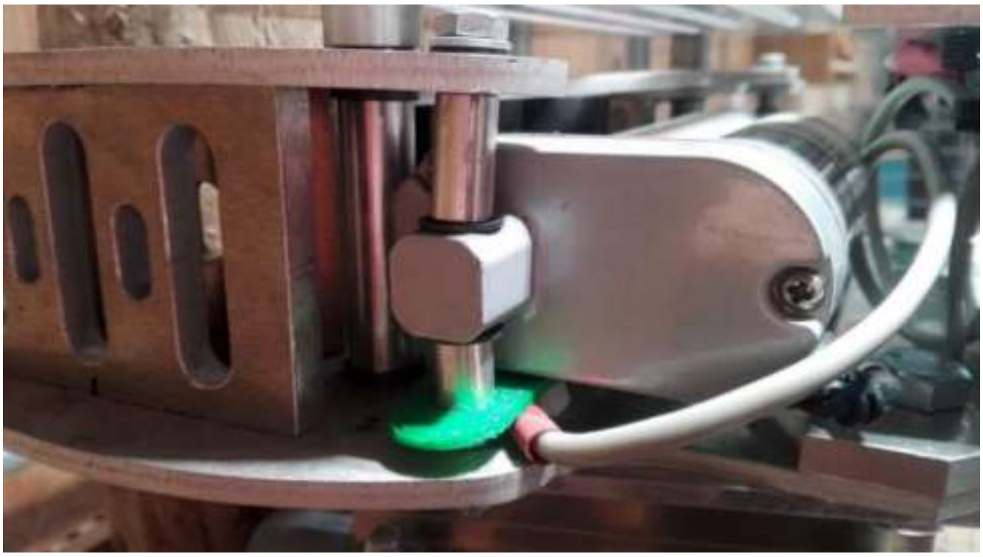

Figure 7: One of the pins which connects the linear actuator can be seen to have visibly bent.

The pin attaching the faulty linear actuator could not be removed, and had to be cut with a hacksaw to replace the linear actuator. Once a new actuator and pin was installed, the gripper was functional again.

The relay and remote modules development

The robot had been operating the actuators from an external power supply, but it was deemed necessary to move to using only the on-board power supply. The external power supply was favoured because it could be cut at any time from a distance. This was important because:

- there are known bugs which may cause the robot to move unexpectedly;
- unknown bugs may be present which cause further unexpected behavior;
- approaching the robot to shut it down should it move unexpectedly is not recommended; and
- an electrical short could cause a fire if power cannot be quickly cut.

Therefore a remote controlled Solid State Relay (SSR), an electrical switch suitable for high current applications, which was fully isolated from the existing control system, was desirable. A relay module and a matching remote module were designed. The relay would be permanently mounted to the robot, and would enable the power to the robot's microcontrollers, and motor drivers when the remote module connects and requests it. The relay would default to the "off" state when no connection could be made to the remote.

The remote was designed with a lithium battery and an in-built USB micro battery charger, and features a prominent red covered switch for arming the relay. The remote and relay on the robot have matching status LEDs, which should inform the user of their status at a glance.

The design of these included:

- simple concept and operation design;
- selection and research and purchase of components;
- schematic and Printed Circuit Board (PCB) design;
- board assembly;
- programming of the microcontrollers;
- testing; and
- final assembly and enclosing.

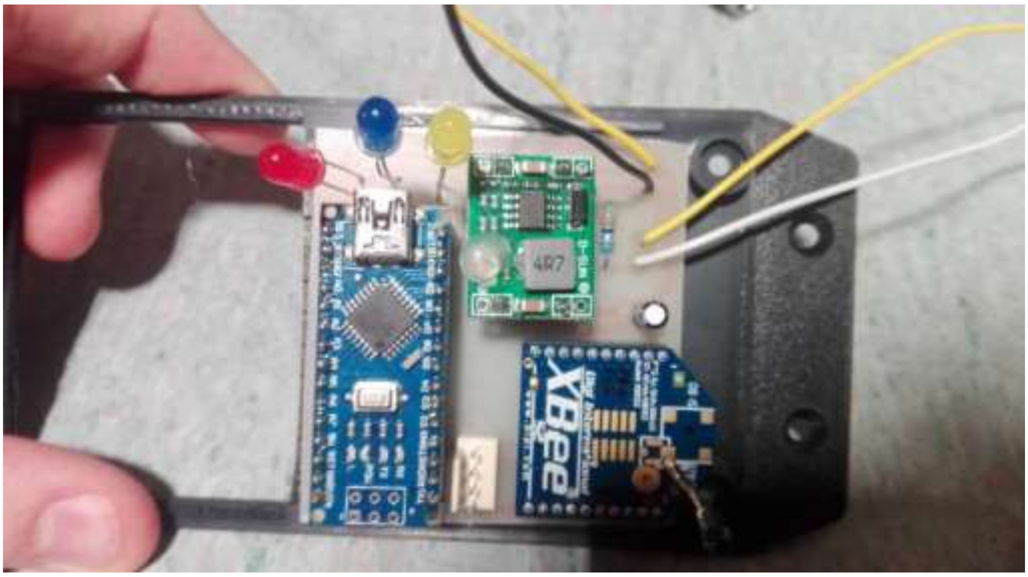

Figure 8: In progress photo of the relay module construction.

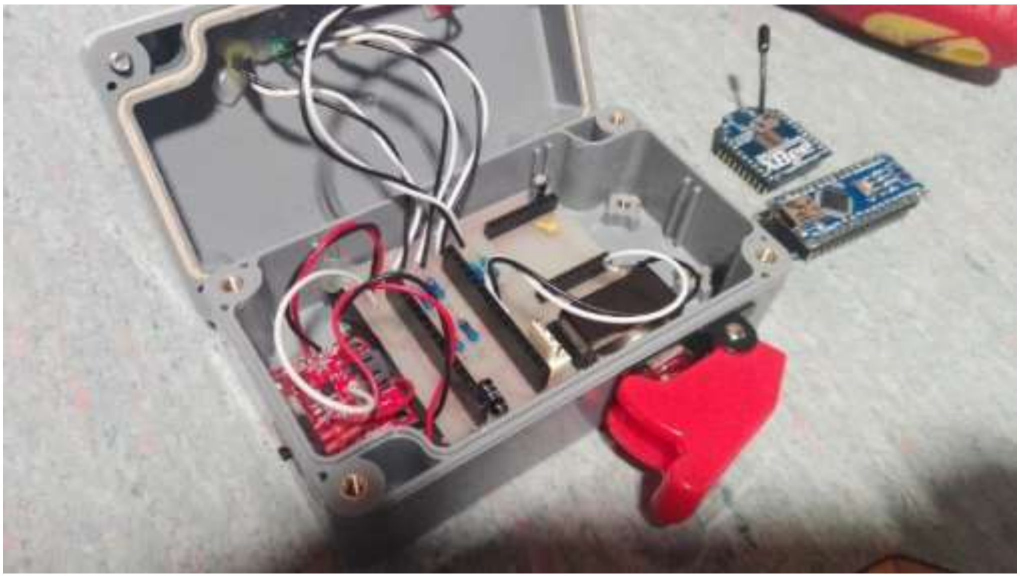

Figure 9: In progress photo of the remote module.

A problem recognised during testing is that the XBee radio transceivers with which the remote and relay communicated were not highly reliable, and would occasionally lose connection for half a second. This is problematic because power loss requires the robot to go through a time consuming start-up procedure. To resolve this, the relay was patched such that when it lost connection, it would hold its last known state for three seconds before disarming. The relay module is bolted to the robot frame, such that the SSR can use the aluminium frame as a heat sink. Once all fully mounted, the relay operated as desired.

Figure 10: The relay module mounted to the Robot (left) and the remote ready to be armed (right).

LAUNCHING ROBOT OPERATING SYSTEM

Launching the Robot Operating System (ROS) automatically was expected to be a trivial task, but ended up taking a very long time due to a few small, difficult to find, bugs. A combination of Python and Bash scripts were written to be launched when the robot's computer was powered up. These scripts would wait for the motor drivers to be powered up and registered as devices. It would then allow the pairing of the PS3 controller and launch ROS.

This is now working, but with the following limitations:

- once power is enabled, it may take several minutes for all the motor drivers to be recognised. It is unknown why this takes so long; and
- if power is lost during operation, the robot will not recover: It must be shut down and rebooted;

Since the start up procedure has been standardised, start up errors have not been observed. It is however too soon to confirm that the process is "error free".

IN-FOREST TESTING

Test Sites

Test areas were investigated in McLeans Island Forest (Environment Canterbury) and Bottle Lake Forest (Rayonier / Christchurch City Council), where suitable sized trees could be located, but the trees have to be no more than 2 m apart. It proved impossible to find suitable trees close enough together, so a location at Bottle Lake was selected, and fence posts were used to fill the gaps between trees (Figure 11).

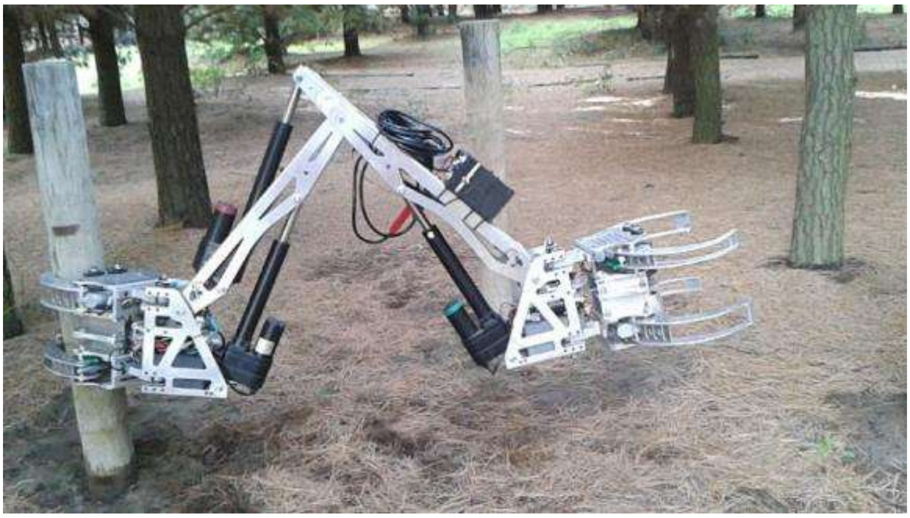

Figure 11: Demonstrating movement between fixed stems in a forest environment.

The machine requires tree stems between 8 and 18 cm in diameter for the grippers to attach securely.

Tree Grip

Fig 12: Gripper supporting the weight of the Stick Insect while attached to a stem greater than 18 cm diameter, indicating a twist of the gripper.

Although experience has shown that the gripper design can hold onto tree stems of greater diameter (Figure 12), the grip is not secure and the body of the robot does not resist lateral forces very well. The gripper often has difficulty maintaining its twist. As the robot moves its mass to either side, the grip's twist will often significantly change.

Having a large grip twist will:

- make getting a good grip on the next tree much harder;
- reduce effective gripping range; and
- when the twist is large, this may damage both the grippers and the tree.

This problem occurs because:

- It is difficult to mate tightly to the tree. In many cases this is due to other problems such as:
    - The intrinsic problem of the robot not being able to control the frame twist: That is, the ultimate difference between the twist of the two grippers.

- The wrist motors often struggle.

• The strength of the grippers is insufficient to pull the claw and tree together, which may overcome a poor mating.

• The gripper rollers do not resist twisting. This could be significantly improved by replacing it with a toothed, studded, or rubber-treaded plate.

Figure 13: Poor grip on oversized stems often results in some damage to the surface of the bark – not full thickness.

Locomotion

The robot was able to move between trees as long as the trees were close enough together and of small enough diameter. It was found that the gripper did not have enough power to grip the tree really tightly so that when the other gripper released the first gripper slipped from the horizontal on the stem (Figure 14). This put the whole frame on an angle so that the motors were working against gravity when traversing the frame. With careful control of the motors movement was possible, but this did slow traversing time.

Figure 14: Angled grip on tree complicates traversing because the robot is at an angle.

The angle between trees was also important, as the geometry of the robot limited grasping trees beyond about 85° to either side (Figure 15). In other words the robot would not be able to traverse along a fence line from post to post.

Figure 15: The design of the robot limits traverses to approximately 170° between trees (not quite a straight line).

Main findings from in-forest trials to date

Table 2: In-field testing results

Feature	Comments
Wireless control	The PlayStation controller is an excellent control interface which allows the movement of up to four robot actuators at once. It also allows the operator to move around the robot to better see where the grippers are located. It will allow for rapid operator uptake and learning.
On board battery	It's large and safe. It is positioned for rapid replacement once drained. It could benefit from a quick release system.
Portability	The robot weighs 70 kg and can be folded into a compact footprint so it can be loaded into the back of a twin cab utility vehicle. Two people are required to carry it to the first tree. We need to develop a carry frame/trolley and launch frame so it is easy and safe to set up.
Emergency brake remote control (held by assistant operator)	This is a remote control unit fitted with a sprung "missile switch". If tripped, the battery circuit is disconnected from the robot and the robot stops. This was accidently tripped twice during operations and worked well. The robot stopped immediately.
Gripper design	The grippers are currently suited to a tree of up to 13 cm in diameter, at a guess. Using the robot on trees larger than 13cm diameter, and at maximum leverage angles to the fixed point, causes minor deformation to the structural integrity of the grippers, which is a concern. It may be possible to further develop the gripper design for improved stability – ideally a more functional self-centring guide top and bottom of grippers at the base (near the current rollers) or a sleeve at the back of and opposite position to the grippers, as a hand cups around in a horizontal "come here motion". Bark damage, although of minor concern to concept development, will impede industry uptake for uses other than harvesting, but may be reduced with rubber treads The 180-degree operational range falls just short of practical requirements and needs to be increased
Frame design	Works well, but due to wear of joints is becoming very flexible
Wrist motors	The wrists have difficulty moving the entire weight of the robot when the gripper is not level. The inertia of the robot is reduced when it retracts, so this can reduce the force needed to turn. However, this significantly increases the time cost of moving. Change the gearing of the wrist motors significantly. They are definitely torque limited and reduce the gripping force.

INDUSTRY DEMONSTRATION

On 27 September 2016 the tree-to-tree robot was demonstrated to about 30 forest industry stakeholders and MPI representatives at Bottle Lake Forest in Christchurch. A demonstration area was created among small pruned trees. The trees had been thinned and were too far apart for the robot to reach so fence posts were used as "surrogate trees" to allow the robot to traverse (Figure 16). To reduce complexity, the robot was demonstrated purely as a locomotion platform with no felling head attached, weighed 70 kg and had a reach of 2.5 m.

Figure 16: Robot demonstration with fence posts as surrogate trees.

The PGP Harvesting Programme was introduced and an overview given of the robotic tree-to-tree felling machine project by Keith Raymond (Programme Manager, FFR). Richard Parker and Tim Lamborn (Scion) gave a summary of the background to the Stick Insect concept and project to build the prototype. Tim explained the recent work done to mobilise the Stick Insect (wireless controller, multiple motors synchronised, on-board power, safety cut-out). The robot was then demonstrated and a technical discussion followed on features of the machine such as weight, reach, size of gripper, battery charge etc., and issues with the current prototype such as non-vertical trees, line of sight range, damage to trees and other limitations. After lunch a further demonstration took place and there was discussion regarding the future of the project ("Where to next?") with feedback from industry representatives on benefits, potential markets, demand for machine, cost etc. Notes of this discussion are presented in Appendix 1.

The main conclusions from the demonstration and discussions were:

- IP needs to be documented and ownership assigned to ensure FFR and Scion are comfortable.
- Applications:
    - Clear felling – long term goal but probably a step too far for the next developments. The possibility of a radically different approach did not alarm the Forest Owners.
    - Thinning and pruning – broad consensus on this as the next goal subject to a proper review of the technical and commercial barriers. Lack of skilled staff an issue. Most don't prune now as not enough staff but would prefer to prune. Matariki, Ernslaw One (Douglas fir – thick undergrowth) and City Forests all strong supporters of this approach.

- Inventory tool – some discussion but didn't sound like a good enough value added operation
- Other points to note:
    - Is there an advantage in light weight?
    - General agreement we need to get a commercial partner (manufacturer) on board with the project.
- Further development of the robotic tree-to-tree felling machine to be included in the new PGP funding proposal on forestry automation and robotics.

Overall the field demonstration was a success. FFR's view was that Richard Parker and Tim Lamborn engaged the participants well and the group participated very well in the discussion. Everyone was very supportive and positive about the future of the project. It was good to get a clear consensus on going forward towards building a thinning-sized prototype. Feedback after the demo (from City Forests, MPI, NZFOA and Russell Dale) has been very positive.

STATIC DISPLAY AT PGP EXPO

FFR provided a static display at the Food & Fibre Future Conference and PGP Expo held at the TSB Bank Arena in Wellington on Tuesday 1 November 2016. The display of the robot attracted considerable attention and helped promote the PGP-funded Steepland Harvesting programme. A special travel crate was built to freight the robot to Wellington, which was used as a display stand (Fig 17).

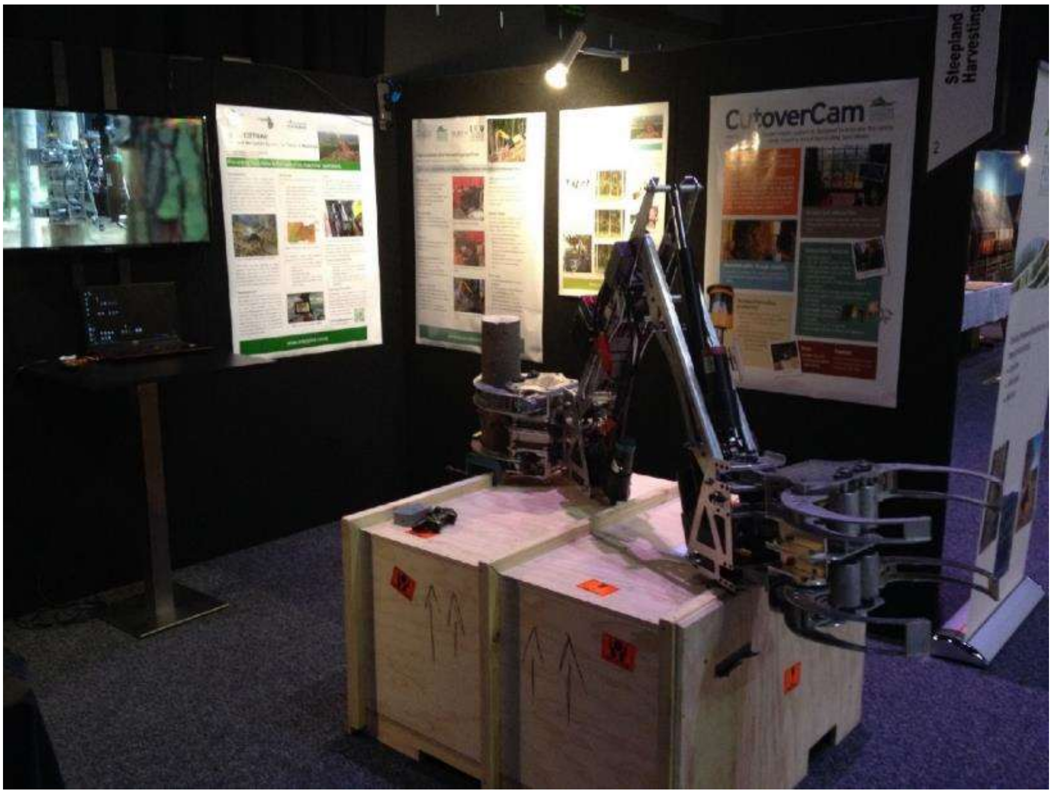

Figure 17: Robot static display on the FFR stand at the MPI PGP Expo in Wellington

CONCLUSION

This report has summarised the development to date of the Robotic Tree-to-Tree Felling Machine (the Stick Insect) following on from the earlier report detailing the design of the prototype.

The Stick Insect has been demonstrated to move between trees and posts under its own power under the control of an operator standing nearby. The robot is quite under-powered and its movements are slow because care has to be taken in establishing a firm, and if possible, horizontal grip on the tree. The concept of tree-to-tree movement is sound and this machine shows that it is possible. Further technical development is required to address the requirements of in-forest operations on trees greater than 2 m apart and of diameters in excess of 18 cm. The best orientation of the gripper with the tree is essential and requires the gripper structure to move about three axes. Currently the grippers can only yaw (left and right movement), pitch (up and down movement) but cannot roll (rotating movement). The ability to rotate the gripper would ensure a solid attachment to the tree.

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APPENDIX 1: Notes from Field Demonstration

Introduction

These are the notes from the field demonstration of the Stick Insect held at Bottle Lake Forest Park, Christchurch on Tuesday 27 September 2016. Richard Parker introduced the general features of the machine: reach 2.5m, weight 70kg, no weight optimisation, no felling head at this stage. Tim Lamborn detailed the work done: coding software, installing battery power, using PlayStation hand controller, building an isolating switch (emergency stop). Machine has sensor-based feedback to control movement. Previous version had a wrist to control head twist (roll). Tim has undertaken extensive testing to extend the machine's use and capability (sometimes testing to destruction). Trouble gripping trees that are not straight, also slicing through bark of tree, so possibly need to modify gripper.

Questions:

Q: Have you thought about electric chainsaw?

A: A saw was designed by the UC Final Year students, with a wide curve to prevent chain-throw.

Q: Any decision on electric versus gasoline-powered?

A: At this stage we have designed for battery power.

Q: How much potential to you think the machine has?

A: Need to solve the current identified problems. The motors are under-specified.

Q: What needs to be done to automate the operation?

A: Need to develop LiDAR to recognise trees. Machine needs to understand a large area of forest to do path planning. Semi-automation is more possible (with teleoperation) rather than full automation, e.g. moving towards next tree etc.

Q: What about trees with branches all the way from the ground?

A: *Needs more power with stronger gripper to crush them. (Note: This would also reduce the bark damage issue on crop trees).*

Q: Can you bring the weight down?

A: Possibly use new materials (composites, carbon fibre, titanium etc.)

Q: Why so focussed on being light weight? Possibly better to build a big one with serious power?

A: Concept was to be equivalent to a man with a chainsaw. Light weight to cause no damage to tree or log.

Q: Other machine applications?

A: Possibly a robot to do shovel logging, or put logs on cables (feeding grapple carriage).

Q: What about the mechanics of tree? Tree weight, pulling trees over (uprooting trees)?

A: Have done some work on radiata pine (Note: the maximum resistant moment of the tree depends on tree age and DBH. The maximum mass of the robot to hold and cut a 25cm DBH tree is about 750kg. To hold and cut a 30cm DBH tree is about 1300kg.)

Q: At what stage do you hand over to a commercial partner?

A: There is no patent on the concept. Possible patentable information is design, software for control system, circuitry etc., more like a Trade Secret.

Q: Is the vision still for a clearfell machine with 8m reach and 600mm grippers?

A: The weight of the machine will limit the size of the machine. May have to look at the marine industry (yacht masts etc.) or aviation (gliders) to get lightweight but strong.

Q: What about the issue of trees falling on the machine.

A: Maybe the path to design is step-wise to a thinning machine cutting smaller trees that will not damage the machine.

(Note: At this point Tim talked about introducing twist in the frame. Possibly in the redesign, ability of parts of the arm to twist - possibly like an elbow – to introduce flexibility in the arms. Also need to redesign the grippers.)

Q: What about push-pull force?

A: Have got some data on actuating forces.

Q: What about the time to fell – is it much different to manual felling?

A: Generally it takes a lot longer to position the gripper on the tree. But we are optimistic that a lot of these functions can be automated.

(Note: At this stage Richard mentioned the Robotics conference in Montreal where he met engineers involved in the development of the Canada Arm for the International Space Station. There were possibilities to collaborate on engineering design).

Discussion:

Guy Bonner (City Forests): The next goal should be as a thinning machine. Waste thinning is hazardous and as an industry we are struggling to get skills. We recognise the challenges involved in development but this is a worthwhile next step. If you want a forestry company to test it out or as a demonstration City Forests are keen to be involved.

Peter Weir (Ernslaw One): Ernslaw One is 2,000ha into a 12,000ha Douglas fir thinning programme. Trees are about 25-30cm DBH sitting at 1600spha on rolling country. There is no undergrowth, because of the tight stocking, but it is also very dark under the canopy (affecting cameras, sensors etc.).

Paul Nicholls (Rayonier Matariki Forests): We need a more accurate control system, and to be able to solve the roll/yaw issue with trees that are not upright or straight.

Phil Taylor (Blakely Pacific): FFR has done a great job of proof of concept. Now we need to analyse the technical and commercial barriers to realising the vision. Until this is done it is too early to decide whether to go for clearfell or thinning machine.

David Rhodes (NZFOA): Is there a trade-off between protecting IP through a patent and finding commercial partners? The goal should be to get it out into commercialisation as soon as possible not to protect the IP. It definitely will help to address the labour issues.

John Schrider (Forme Group): The clearfell machine could be a step too far at this stage – in terms of size, power requirements, cost and development time.

Peter Weir (Ernslaw One): What about the comment earlier about pre-bunching machine? If it only fells it may not be useful unless wood is bunched?

Rob Miller (MPI): Ask Richard about the potential for a bunching machine? May be possible to hold one tree and pull the felled trees together?

Geoff Manners (CFK): The learnings as the project has gone along are important. There may be other things that come out of this project, such as LiDAR for tree recognition etc.

John Schrider (Forme Group): Need to think carefully about the size/weight/power issues.

Keith Raymond (FFR): A thinning machine thinning from 800-900 stems per ha down to 400sph may be possible to move down two rows of trees only holding onto the thin trees not the crop trees. May only need a reach of 5.0m which is a lot smaller machine than one with 8.0m reach.

Andy Wiltshire (Pinoli Ltd): For a thinning machine, if only holding onto the cull trees, you may need a machine that is as big as a clearfell machine, depending on the silvicultural thinning prescription (if thinning to 250-300spha).

Phil Taylor (Blakely Pacific): Needs to be considered as part of an integrated silviculture/genetics solution. Improved genetics will mean less variation between trees, so some kind of mechanised thinning may be possible. Also need to consider what other spinoff benefits there may be from the project (unintended consequences), such as the saw, which will push the boundaries of other developments.

Peter Weir (Ernslaw One): Also need to look at the forest estate planning, as there is a bulge in the thinning at the moment for the next 5 years but later on there will be none, as a consequence of very little new planting in the 2000's decade.

Paul Nicholls (Rayonier Matariki Forests): Labour is the issue. Better genetics may improve tree size, straightness, shape, but also be aware that some regimes are "plant at final crop stocking" (i.e. no thinning). Not all sites but quite a lot in Matariki estate.

Guy Bonner (City Forests): Part of the ultimate goal of FFR was to reduce costs, so must remember that this development must be cost-competitive with manual waste thinning costs. If it is successful it could be a good springboard into other applications such as pruning or clearfelling.

Richard Parker (Scion): It may not be faster or more productive, but it will have the capability to work longer hours without supervision.

Peter Weir (Ernslaw One): Want it to move in bulk, quickly. Also want it to be cheap, and safer.

Paul Nicholls (Rayonier Matariki Forests): Also has application as a resource inventory measuring tool. If it has more sensors (what type to be determined), and more automated. Could work in periods of semi-darkness or all night.

Phil Taylor (Blakely Pacific): Progress is a function of resources. To what extent has lack of resources slowed the project down? Or put another way, how much faster could it have gone with more resources? It is essential that we find commercial partners for additional resources.

Geoff Todd (Viclink): But it is still too early for a commercial partner. Too risky at this stage.

Phil Taylor (Blakely Pacific): Need more information gathering. Must build on Richard's vision and commitment. If there is sufficient evidence to break down the technical and commercial barriers to building a functional commercial machine, we should do it.

Geoff Manners (CFK): Additional resources could be sourced using more students, to open up the possibilities, apply fresh minds to the problems, if it is too early for a commercial partner.

(Note: At this point Keith Raymond had to draw the discussion to a close in the interests of time).

Summary Notes from Geoff Todd (FFR Commercialisation Team):

1) Possible IP that needs to be documented and ownership assigned
    - Autonomous control software with LiDAR
    - Navigation methods
    - Engineering design and sub-assembly designs
    - Control system – code
    - Sensor based feedback
    - Gripper design
    - Movement methods

   This IP will continue to be developed and invented so there should really be a plan to capture and protect it.

2) There may be an IP issue. Richard said the SCION patent person was looking into it and the University may feel it has some rights. I know FFR thinks it owns it all. It would be good to document the understanding.

3) Applications
    - Clear felling – long term goal but probably a step too far for the next developments. The possibility of a radically different approach did not alarm the Forest Owners.
    - Thinning and pruning – broad consensus on this as the next goal subject to a proper review of the technical and commercial barriers. Lack of skilled staff an issue. Most don't prune now as not enough staff but would prefer to prune. Matariki, Ernslaw One (Douglas fir – thick undergrowth) and City Forests all strong supporters of this approach.
    - Inventory tool – some discussion but didn't sound like a good enough value added operation

4) Other points to note:
    - Is there advantage in light weight?
    - General agreement we need to get a proper manufacturer on board

Conclusion

The field demonstration of the Stick Insect on 27 September was a success with about 30 industry stakeholders attending. Richard and Tim engaged the participants well and the group participated very well in the discussion. Everyone was very supportive and positive about the future of the project. It was good to get a clear consensus on going forward towards building a thinning-sized prototype. Feedback after the demo (from City Forests, MPI, NZFOA and Russell Dale) has been very positive.