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Theme: Harvesting

Objective Number: 1.2 Task B
Milestone: 5.8

Report No.: H023

Design of the Tree-to-Tree Robot: Technical and Economic Feasibility Analysis

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Date: 9 July 2015

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INTRODUCTION

The forestry industry is associated with a high risk of injury. The greatest injury rates are associated with the logging operation, in particular felling and skid work. Felling injuries comprise between 20% and 30% of logging injuries annually (Bentley, Parker & Ashby 2004). The greatest risks to workers from felling are being hit by falling trees or other debris.

Manual felling is significantly more dangerous than mechanised felling. To reduce the risks of injury and improve efficiency, the forestry industry has moved toward using large machines to fell trees. The large machines are safer to operate than using a chainsaw, but are expensive to purchase and operate.

Large machines also cause significant disturbance to the soil. The structure of the soil is changed through compaction and churning. The soil disturbance makes it more likely to wash off the hill side. Councils and forest managers do not want this disturbance to occur because it makes the soil less fertile and more prone to run off into rivers. Manual felling does not result in soil compaction or churning but is dangerous for workers on steep slopes.

Significant numbers of *Pinus radiata* trees were planted on steep slopes in the 1980s and 1990s and are reaching the harvesting age of approximately 28 years. The mechanical felling of trees on steep slopes is a major problem for forest managers. It is safer than motor-manual felling but currently few machines exist that can effectively negotiate steep slopes.

The motivation behind the tree climbing robot project is to have a machine that can safely fell trees on steep slopes. The machine will traverse the forest by moving from tree to tree while being remotely operated. Traversing the forest without touching the ground would eliminate soil compaction and churning. Remote operation makes the tree-to-tree robot a safe option for felling trees because there would be no need for a human on the slope while trees are being felled. This tree-to-tree robot (Figure 1) could be the solution that forest managers with large plantations on steep slopes require.

Figure 1: The Tree-to-Tree Robot

OBJECTIVE

The objective of this project is to develop a scale working model of a "tree to tree" locomotion machine which is operated by remote control. Major outcomes of this project will be:

- the gaining of practical knowledge of tree-to-tree locomotion and control
- a model to demonstrate tree-to-tree locomotion
- a model to test control systems
- an understanding of the technical feasibility of a full sized machine
- an understanding of the economic feasibility of a full sized machine.

The development of the tree-to-tree robot is part of the "Innovative Harvesting Solutions" Business Plan prepared for the Primary Growth Partnership in February 2010. That plan identified steep country harvesting as the key bottleneck in achieving greater profitability in forestry. Harvesting costs need to be reduced by 25%; the harvest machinery industry in New Zealand must substantially grow to future-proof the industry; and harvesting jobs must be made safer and more desirable for workers. The vision for this plan is encapsulated in the statement -"no worker on the slope, no hand on the chainsaw". The technical outcomes of the programme are to create novel remote-controlled machines that can work on the harvesting slope, and to develop high speed cable extraction systems.

One of the tasks in Objective 1.2 of the Programme, Teleoperated Felling Machine, was to develop a tree-to-tree robotic felling machine. This report details the stages of development of the tree-to-tree locomotion and felling system from concept design to alpha prototype, and presents the detailed design for the alpha prototype. It also summarises the technical and economic feasibility analysis of the alpha prototype tree-to-tree robot to date (July 2015).

STAGES OF DEVELOPMENT

The original tree-to-tree concept was conceived in the late 1990s by Richard Parker at the Logging Industry Research Organisation. Through support from Scion and the Future Forests Research harvesting programme the concept became a working machine. The technical feasibility of the concept was first assessed through building simple functional physical working models. Technical feasibility has progressed through six stages to date (July 2015) as described below.

Stage 1 – Concept Model

To demonstrate the general concepts of movement Richard Parker at Scion built a balsa wood model with two arms and water-filled syringes and a gripper on the end of each arm. This model demonstrated the basic structure of a tree-to-tree articulated device and secured initial Scion funding which led to the development of the second concept model.

Stage 2 – Second Concept Model

Scion sponsored a radio-controlled multi-servo device with grippers at each end. This device could, under radio control, successfully grasp a model tree (a piece of dowel) with one end, then reach out with the other end and grasp and attach to a second tree, then release from the first tree, thus demonstrating tree-to-tree locomotion. The prototype used a "heel" like a heel boom log loader to reduce the weight of the grippers.

Stage 3 – Early Prototype

At an early stage of the Primary Growth Partnership Steep Land Harvesting Programme, FFR sponsored the construction of a larger prototype, built at the University of Canterbury (UC), which demonstrated the ability to reach out, in a controlled way, and grasp a tree (Figure 2). This prototype also used a heel to reduce gripper weight and complexity. The control of the arm has been summarised in a paper (Milne *et al.*, 2013).

Figure 2: Early prototype of the tree-to-tree device

Stage 4 – Alpha Prototype

FFR then sponsored the construction of a one-quarter scale radio-controlled tree-to-tree prototype, constructed by four final year University of Canterbury engineering students (Figure 3). This device weighed 50 kg, had grippers at the end of each arm, and could demonstrate movement from "tree" (fence post) to tree in the laboratory. The prototype enabled the detailed mechanical and electronic development of the device to move controllably from tree to tree. The students analysed the strength of materials, weight of device, gripper configuration and degrees of freedom of movement. The development and technical details are summarised in a report (Wareing, Gilbert, *et al.* 2013). The machine and development team won the "Ray Meyer Medal for Excellence in Student Design for 2014". This prototype used a conventional design for the gripper, without a heel, which resulted in heavy grippers at the end of each arm. An analysis of a portion of forest comprising 500 trees in the Central North Island has allowed the estimation of the required reach of the robot. A machine with approximately 8.0 metres reach should allow it to traverse 97% of the trees in the forest.

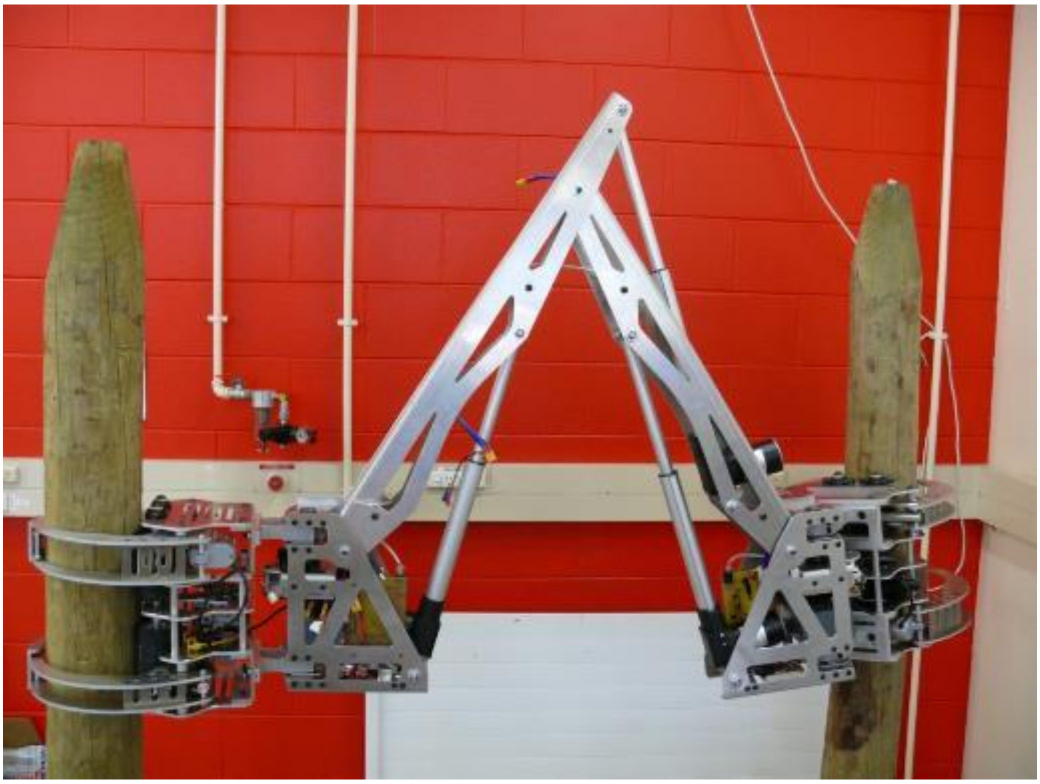

Figure 3 – Alpha prototype 'Stick Insect' tree-to-tree locomotion robot in laboratory

Questions answered by the Alpha prototype were:

- How will the machine traverse the forest efficiently and safely?
- How will the machine adapt to different forest conditions (slope, tree size, tree-to-tree distance)?

Key measurements were:

- Joint displacement and velocity, machine and tool head coordinates
- Centre of mass and gravity, traverse time, stability envelopes
- Forces and actions required through kinematics and control theory.

Stage 5 – Felling Head

Scion and FFR sponsored four final year mechanical engineering students to build a working cutting head for the tree-to-tree machine (March to October 2014). On consultation with Richard Parker (Scion) and Stefanie Gutschmit (University of Canterbury) they developed a chainsaw-based cutting head with a broad bar which was pushed directly into the tree. The saw was powered by a 5kW electric motor and could cut trees of 20 cm diameter. In 2015 the cutting head will be incorporated into the tree-to-tree machine.

Stage 6 – Feasibility Analysis

FFR sponsored a summer student scholarship at UC to undertake an analysis of the issues involved in scaling up the quarter-scale model to a full-sized machine with an 8.0 m reach (November 2014 to February 2015). The Summer Scholar found that using conventional engineering design and scaling up the quarter-scale model will result in a very heavy steel structure. Calculations showed that a steel tree-to-tree machine would weigh approximately five tonnes and would require a large diesel engine and hydraulic power to operate the rams. Such a design would probably not be able to fully support its own weight and remain independent of the ground. The motor unit would most likely have to rest on the ground. The machine would also be expensive to construct and difficult to shift from site to site. Consideration was given to a lighter weight machine rather than pursuing the development of such a heavy machine. A lighter machine could have a much smaller power system – such as a two-stroke petrol engine running either a generator for electric actuators, or a small hydraulic system. Another promising design idea was to create a lightweight composite design strengthened by external steel cables similar to a yacht mast.

Stage 7 – Improved Alpha Prototype

FFR sponsored three UC final year mechanical engineering students to improve some of the operating features of the robot. An investigation of a lightweight structure for the tree-to-tree machine was undertaken (March 2015 to October 2015). The objectives of this student project are to redesign the frame of the machine to make it stiffer, strong but no heavier. A solution to the issue of handling trees that are not vertical will be sought. One gripper will have a rotator added to the wrist to enable the tree-to-tree machine to grasp trees that are not standing exactly vertical (i.e. trees that lean). An improved battery and electrical system will run the actuators and chainsaw. The control system developed by Chris Meaclem will be integrated into the machine, and it will be tested in forest conditions.

DESIGN OF ALPHA PROTOTYPE (ONE QUARTER SCALE MODEL)

Mechanical Design Overview

This design was undertaken by final year Mechanical Engineering students George Wareing, Thomas Gilbert, Scott Paulin and Sean Bayley. Individual parts for the prototype were built during the third term. Most of the parts were fabricated by the team and university workshop technicians. Other items such as the arm sections were made by a local laser-cutting company. Manufacturing drawings were produced for all of the parts before they were manufactured.

The robot was fully assembled by the team at the university. The entire device was fixed together using only mechanical fasteners. This meant that no special tooling or equipment was required to assemble or disassemble the system. The team did not encounter any significant problems during the assembly stage and the total time to assemble the device was approximately 4 weeks.

The final performance specifications of the robot were defined as:

- Mass: 50 kg
- Maximum horizontal reach: 2.2 m
- Minimum horizontal reach: 1.0 m
- Vertical reach: ±0.75 m
- Maximum wrist rotation: ±90°

Design for Assembly

The system was designed so that it was easy to assemble and disassemble. The entire system was assembled with fasteners and there were no special tools required to build the device. Major components such as the gripper units could be unbolted to allow for access to the internal mechanisms and electronics.

Laser-cut Sections

Laser-cut components featured prominently in the robot's design. Using laser-cut parts reduced the cost and time to build the prototype. Laser-cut components have the following benefits:

- They are easy and cost effective to manufacture quickly and accurately.
- It is easy to produce manufacturing drawings for laser-cut parts. All that is required is a DXF file of the shape outline and hole details.
- Complex shaped parts that are functional, ergonomic and aesthetically pleasing can easily be produced without the need to include datum surfaces.

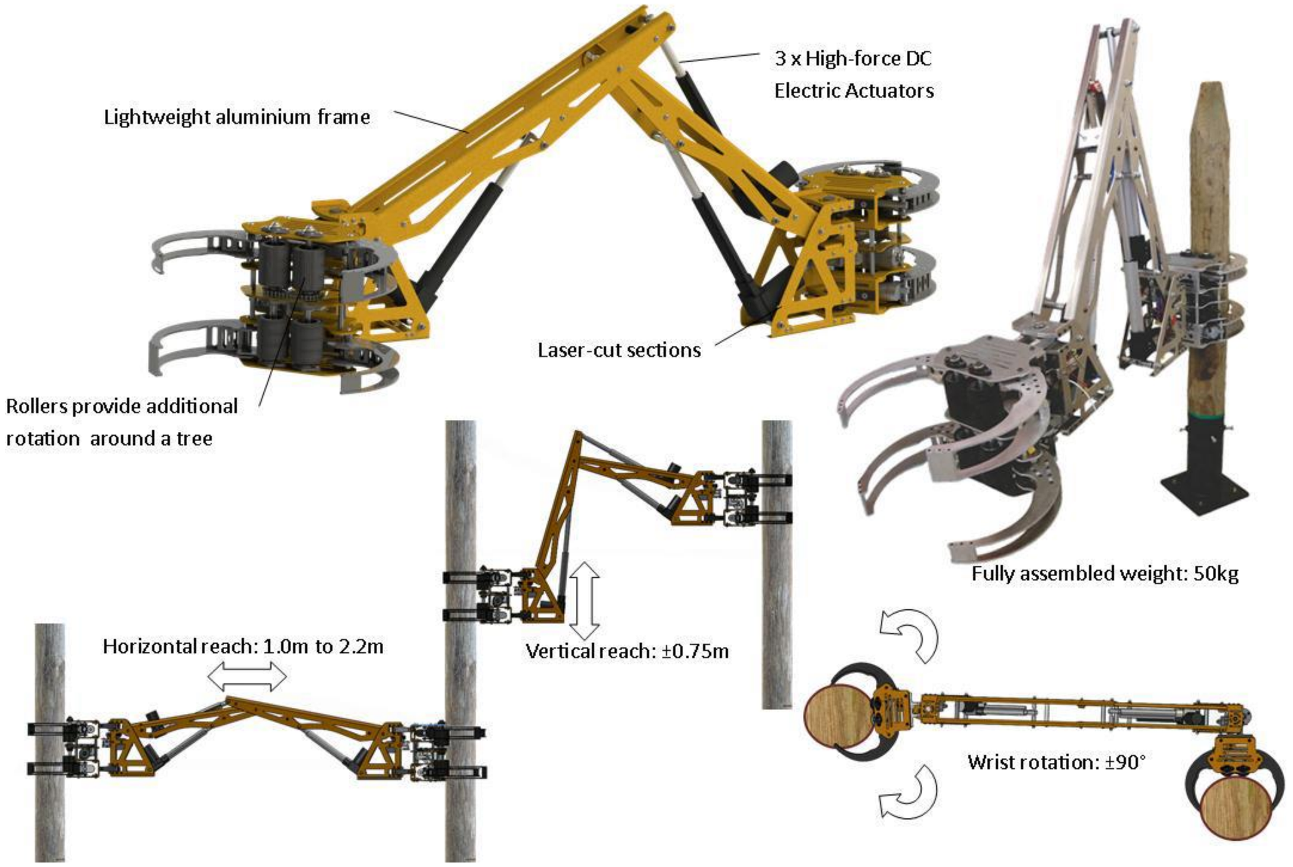

Figure 4: Key features of the prototype included being lightweight with a maximum reach of over 2 m. The wrist allowed the robot to rotate ±90° around a tree.

Modular Design

There were three main mechanical groups in the design; the arm assembly which included the lifting actuators, the wrist assemblies, and the gripper units. This modular design was conceived to make the device versatile and easy to assemble. This type of design meant that individual sub-systems could be replaced, repaired or improved without affecting the operation of the remaining device. Figure 5 shows the main subsystems of the prototype.

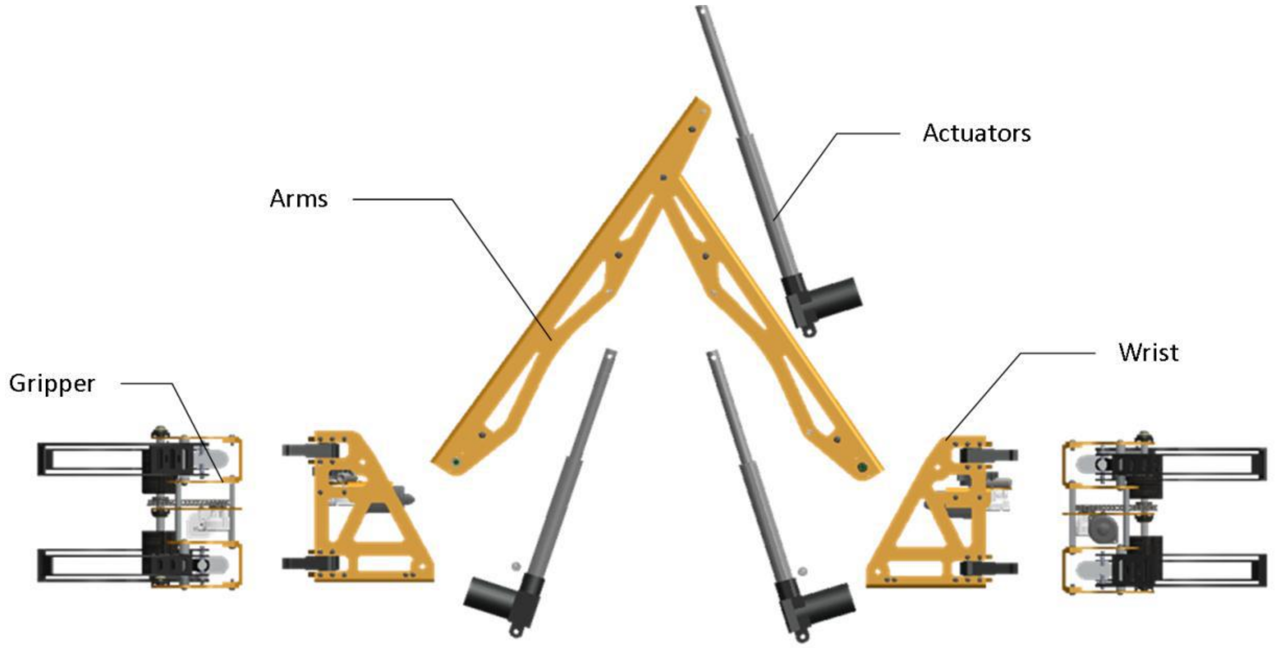

Figure 5: Tree-traversing robot subsystems. The robot's modular design made it easy to assemble and will be important if new attachments for the machine are developed.

Mechanical Design Sub-systems

Arm Assembly

The arm section consisted of two main structural members that pivot at a central point. Each arm was assembled with two 5-mm-thick aluminium sections that were connected using spacers and fasteners. A folded flange was included at the top of each arm to increase the flexural and torsional rigidity of the overall structure. The arms could be raised and lowered by extending or retracting one or more of the three linear actuators that were connected to the device. Figure 6 illustrates how the device was manoeuvred by extending or retracting the linear actuators.

The pivoting joints in the arms were designed to incorporate rotational encoders. These were included so that positional information could be used to provide closed-loop feedback control of the robot. The joints incorporated flanged bearings and shoulder bolts. This meant that the two adjacent arm sections could be clamped tightly together while still permitting them to rotate relative to each other. Purpose-built shoulder bolts were designed for the encoders to be attached to the rotating joint. Brackets were designed and 3D-printed to hold the non-rotating section of the encoder and to fix it to the inside of the arm.

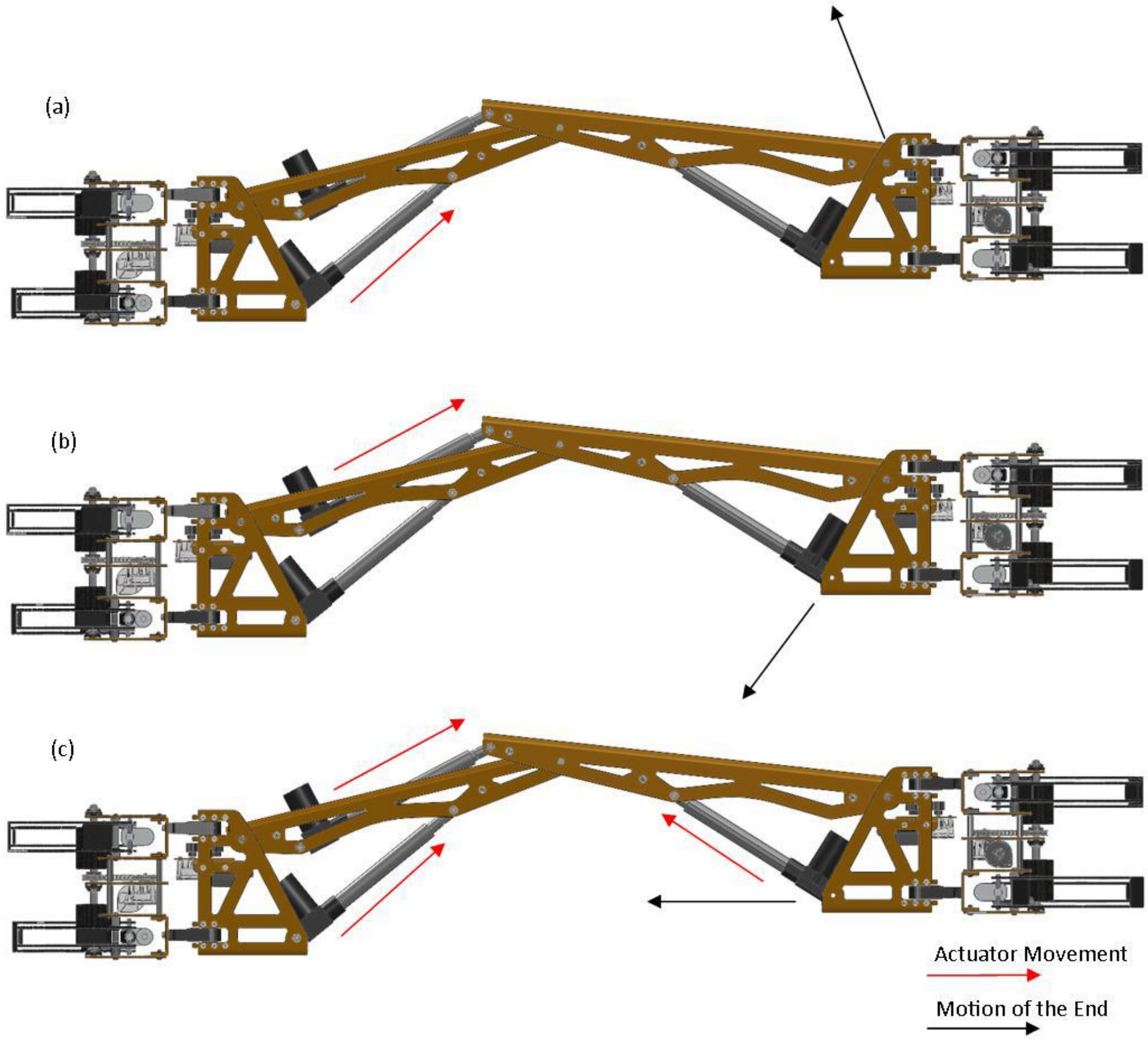

Figure 6 (a) and (b): The arm was raised or lowered by extending any one of the three linear actuators. (c) Vertical or horizontal movement of the end of the device was achieved by operating a combination of the three actuators.

Wrist Assembly

The wrist section allowed the robot to swing ±90° relative to the gripper when it was attached to a tree. Each wrist section was constructed from two 3-mm-thick aluminium plates. An electric gear-motor for rotating the arm was housed between these two sections. This motor was chosen because it had high torque and low speed characteristics. The wrist section attached to the gripper unit at two stems that were clamped to two pins. The lower pin was free to rotate while the upper pin was coupled to the motor via spur gears with a ratio of 2.5:1. These gears were used to reduce the output speed of the motor shaft and increase its torque. The inside of the wrist section provided clearance for the arm actuators during operation, and room for the electronics. A CAD model of the wrist unit is shown in Figure 7.

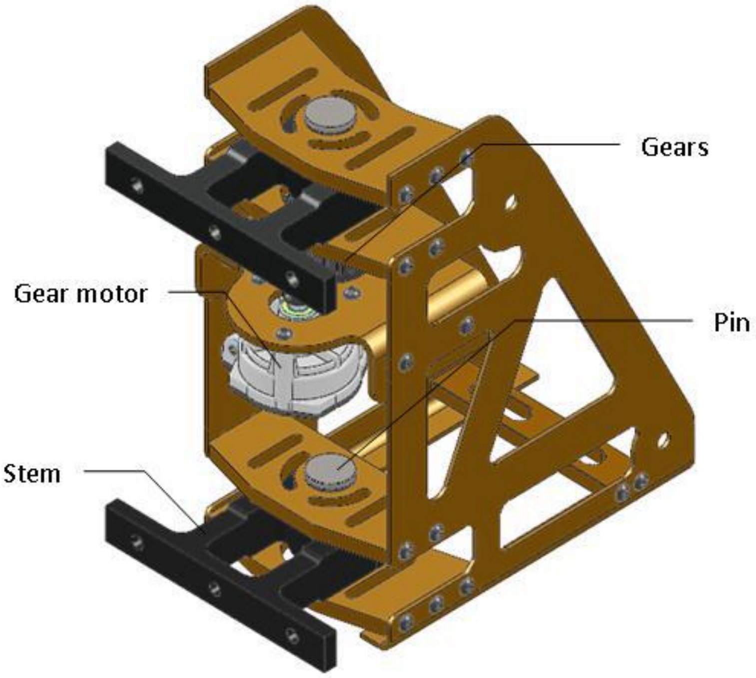

Figure 7: The wrist unit allowed the robot to rotate ±90° relative to the gripper when it was attached to a tree. Rotation was achieved with the gear-motor on the inside of the unit.

Gripper Assembly

The purpose of the gripper unit was to allow the robot to hold onto a tree. Units also needed to be able to release the grip on the tree once the device had grasped a new tree. The unit was constructed from laser-cut aluminium sections and two 90x40 mm channel sections where they bolted on to the stem of the wrist. The gripper unit contained two key functional mechanisms. The first of these mechanisms was the gripper claw system which provided the clamping force required to support the device during operation. The second key mechanism was the roller drive system which was intended to increase the range of motion of the device. Figure 8 shows the main features of the gripper module.

The gripper claw system was designed so that it was strong enough to hold the device fixed to a tree without external support. The final design of the gripper unit included two claws spaced 300 mm apart to help counteract the large moment produced by the weight of the arm at its fixed end. The claws were actuated using linear actuators, and were independently controllable. The geometry of the gripper mechanism was developed using SolidWorks layout sketches. The geometry of the final design allowed the grippers to grasp a tree with a diameter of 50 mm and to open to a width of 435 mm.

The roller mechanism was intended to give the device a full range of motion around a tree. This was an innovative and potentially patentable concept. The rollers were driven by a chain that was connected to an electric gear-motor. The design of the rollers included a rubber outer layer that increased traction when rolling.

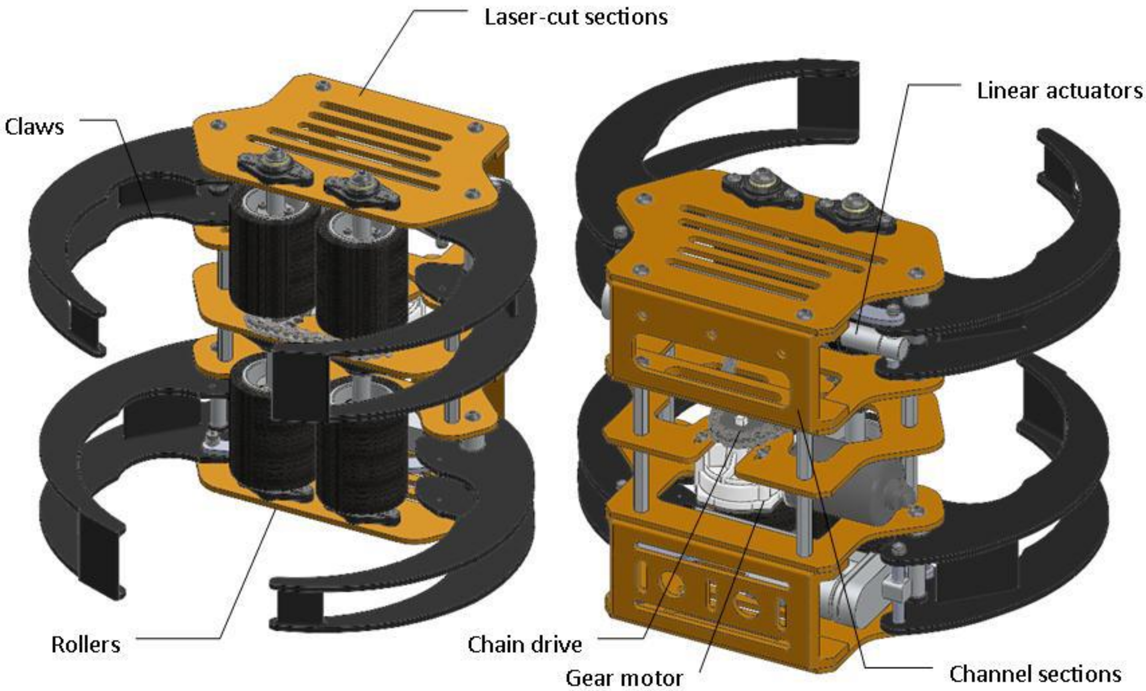

Figure 8: The gripper unit was used to fix the robot to a tree. It was constructed from laser-cut and channel sections. The unit contained two key functional mechanisms, the claw system and rollers.

Electronics Design

Overview of Electronic Design

The system had three microcontrollers that were used to control the robot as shown in Figure 9. Bluetooth was used to communicate high-level commands (such as "open the left gripper") from the host computer to the primary microcontroller. The Primary microcontroller was mounted in the middle of the robot. The secondary microcontrollers were mounted on each of the grippers. High-level commands were then relayed to the secondary microcontroller at the appropriate end of the robot using the Universal Asynchronous Receiver Transmitter (UART) microcontroller peripheral. The secondary microcontrollers translated the high-level commands to control signals which were sent to the motor controllers.

Interface Boards

Printed Circuit Boards (PCB) were designed as interfaces for the microcontrollers on the robot. These boards sat on top of the microcontrollers and interfaced the microcontrollers to each other, the motors, and the encoders using an Ethernet cable. The interface boards had differential line drivers so that the inter-microcontroller communication was performed using differential signals to improve signal integrity. The interface boards resulted in a tidier and more electrically reliable system than would have been achieved with ad-hoc wiring and single-ended signals.

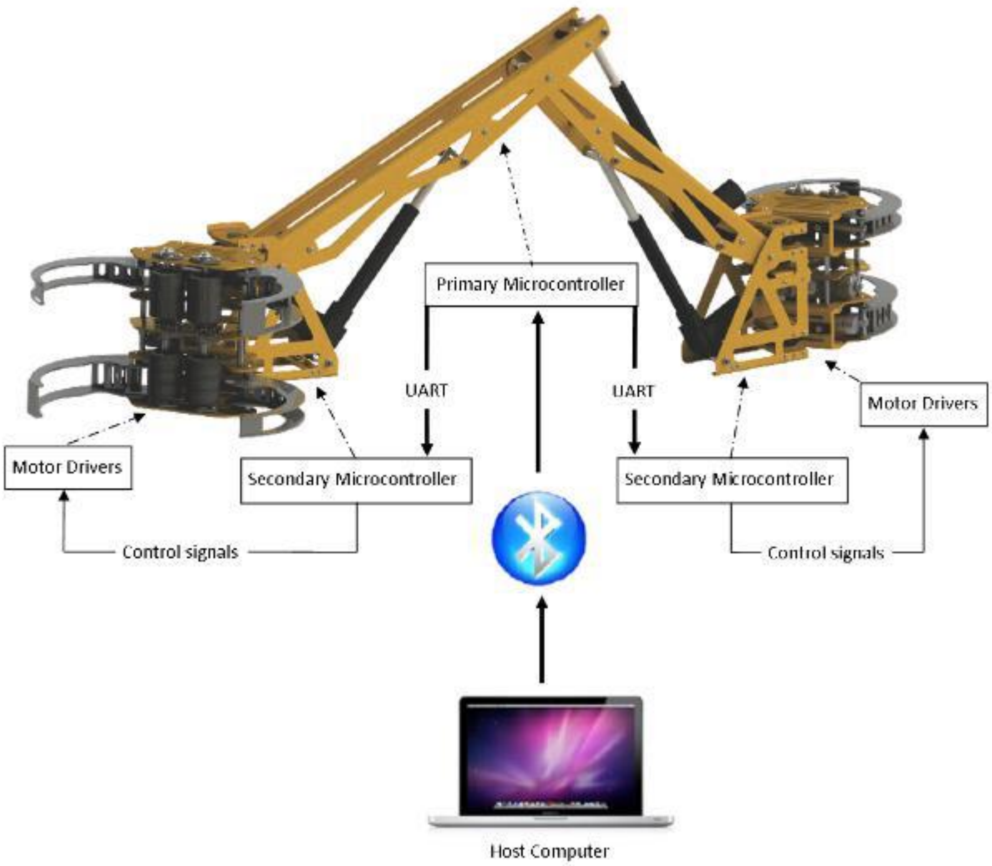

Figure 9: Robot microcontroller layout.

Motors

Motors were selected during the mechanical analysis phase of the project. Linear actuators to control the robot movement and the gripper were required. The wrist and rollers required rotational actuation. Motors with internal worm gears were selected for all of the motors as a safety measure because they would hold their position when power was lost to the robot.

Table 1: Motor specifications for the prototype. The push/pull forces and torques stated are maximums.

Motor	Purpose	Operating voltage (V)	Max Current (A)	Torque (Nm)	Push/Pull Force (N)
AME 226 Series	Wrist and rollers	12	67.4	36.7	-
FA-240-S-12-4	Gripper	12	5	-	900
PA-02-10-400 PA-02-12-400	Robot movement	12	4.5	-	1810

High torque motors were selected for the wrists and rollers as discussed in the Wrist Assembly section of this report. The maximum torque of 36.7 Nm was deemed sufficient to rotate the robot around a tree. The maximum current of 67.4 A was of concern for the battery life of the robot. Overcurrent protection was used to limit the maximum current to the wrist and roller motors.

Linear actuators were required for the robot movement and the grippers. FEA performed during the mechanical analysis phase of the project revealed that high force actuators were required for the robot movement, while the grippers could be actuated with lower force actuators. Table 1 shows the motors purchased for the robot movement and gripper control actuation.

Motor drivers

Motor driver circuits were designed to control the motors on the robot. Three different circuits were designed to control the three different motors. Each motor required bi-directional control. Table 1 shows the operating voltage and maximum current draw of each of the motors used.

The motor drivers for the wrist, rollers, and gripper motors incorporated overcurrent protection. The overcurrent protection extended the battery life of the robot and added functionality to the gripper motors. When grasping a tree, the grippers could be closed until the overcurrent protection stopped power to the grippers to ensure a sufficiently tight grip.

Rotary encoders

Absolute position rotary encoders were fixed on the robot at the positions shown in Figure 10. Using absolute position encoders would mean that the robot would not need to be calibrated at system start up. The encoders are intended to provide angular feedback for the robot's position. Feedback will be important if a closed loop controller is developed in the future.

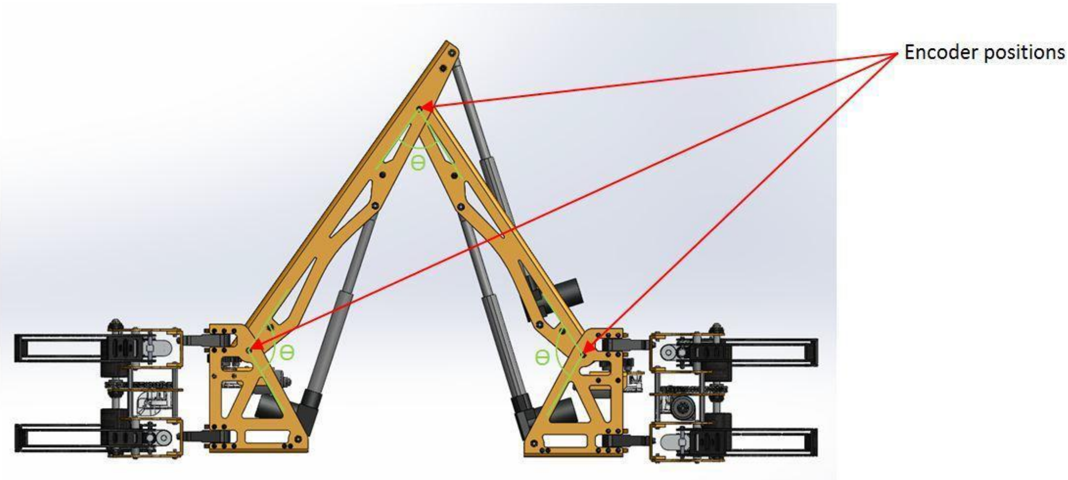

Figure 10: Positioning of encoders on the robot. The encoders will be used to provide angular feedback for the robot's position.

Software Design

Primary microcontroller

The purpose of the primary microcontroller was to provide a central control point for the robot. The primary controller received commands from the host computer and relayed them to the secondary microcontroller located on the appropriate end of the robot.

Secondary microcontroller

The secondary microcontroller translated commands received from the main microcontroller to command signals to control the robot motor drivers. Motor states were stored and checking was performed to ensure a dead-time when the direction of a motor was changed. Changing the motor drive direction without a dead-time would result in a short-circuit across the motor driving Integrated Circuit (IC), destroying the IC.

Communication

The robot used serial communication between microcontrollers on the robot, and from the host computer to the primary microcontroller. The host computer communicated with the primary microcontroller using a Bluetooth connection.

Bluetooth

Bluetooth was chosen as the means of communication between the host (control) computer and the primary microcontroller. Bluetooth provided a wireless solution to communicating with the robot. Bluetooth is commonly used for wireless communication, and there is substantial software support online.

The HC-07 Bluetooth module was selected for use on the robot. This module supports the commonly used Human Interface Design (HID) communication protocol, meaning it can easily be interfaced with a computer. The Bluetooth module can be connected to a computer with Bluetooth capabilities.

Inter-Microcontroller

An eight-bit single parity communication protocol was used for communication between the microcontrollers. The UART microcontroller peripheral was used for transmitting and receiving data. The Arduino Application Programming Interface (API) provided support for the UART peripheral of the Arduino microcontrollers used on the robot.

STAGE 5 FELLING SAW DEVELOPMENT

Prototype Development

Design of the prototype felling saw was undertaken by final year students Zachary Lilley, Joe Stadler, Cid Gilani and Cam Bethwaite. The development of the prototype involved the addition of a number of modifications which would give the robot its tree felling characteristics. This involved the development of a conceptual design and a further design approach of the cutting and linear actuation systems.

Conceptual Design

Discussion with the client led to a specific felling approach, similar to conventional manual felling, that the robot would undertake to ensure the tree was felled effectively in the desired direction. Manual tree felling involves breaking the outside fibres of a tree, as this is where the majority of a tree's strength lies. This is done with the use of a scarf cut and a back cut that break the outside fibres and create a hinge on which the tree rotates as shown in Figure 11.

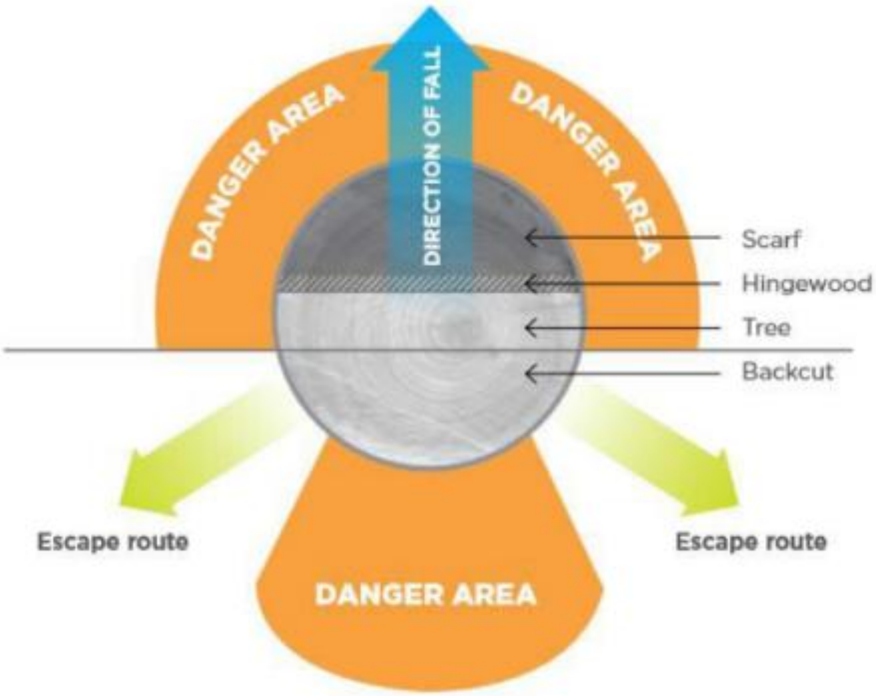

Figure 11: **Manual tree felling cuts relative to felling direction (image courtesy of Worksafe NZ).**

Using this felling approach led to a number of conceptual ideas. It was decided that the robot would cut in a linear motion away from the gripper hands as opposed to the swinging chainsaw action currently used by existing excavator harvesters. This meant that the cutter could employ a wedge, similar to those used in manual felling, to encourage the tree to fall away from the robot.

It was presumed that placement of the cutter above the gripper would be more practical because then the gripper would not have to let go of the falling tree during felling. However, it was important to the client that the robot would cut trees as low as possible to avoid excess wastage of the tree. Therefore it was decided that the cutter would be placed below the gripper.

Design Approach

The initial concept involved the use of a main cutter with linear actuation and a scarf cutter on a mechanical arm for the back cut and scarf cut respectively. The design approach was split into a number of different streams which included the concept development of the cutter, cutter actuation, scarf cutter and sensors. Each work stream went through its own individual concept development to produce a final design.

The evaluation of a number of cutting concepts resulted in choosing a modified chainsaw design. A problem seen in many chainsaws is the constant derailment of the chain. The modified chainsaw design eliminated this problem by employing larger radii on the chain bar that would decrease the centripetal acceleration acting on the chain compared to conventional chainsaws.

The cutter actuation was to act in a linear motion. An evaluation of a number of actuation concepts resulted in a simple ballscrew actuation design. The design was chosen because it could provide the desirable smooth actuation and handle the high moment load and axial force that would act on the actuator. The ballscrews also provide a gearing effect, reducing the size required for any other gearing systems. An electric motor was chosen to power the ballscrews.

The scarf cut is also achieved by the main cutter as the unit can be rotated 180° smoothly around the tree. To do this the major friction point generated at the claws had to be eliminated. To remedy this in order to improve the robot’s maneuverability, rollers were added to the concept design. This is a temporary solution as a separate independent front cutter could be implemented in the future once the weight optimisation has been completed.

The final aspect of the conceptual design is the sensors and control system. The sensors were to be used to sense the movement of the tree to ensure that the tree was falling in the right direction. This information would be fed back to the control system so that the robot had an intelligent cutting system.

Modelling

SolidWorks was used to generate the detailed 3D model of each sub-system, and the desired layout of the overall system was determined.

Analysis

Finite Element Analysis (FEA) was used during the design phase of the project to study the existing robot arm and actuation sub-assembly. ANSYS was used early in the design process to determine the upper limit of the cutting system mass by analysing the strength of the robot arm and actuation forces required. The main structural member of the actuation system was also analysed to inform the final design. Based on the result of these analyses, new actuators were chosen to improve the performance of the robot, and the actuation system was strengthened.

Electronics and software

Initially, research on the sensors required for the cutter was conducted. This process was conducted continuously until the end of second term. The tree falling detection design and was also conducted along with the sensor research. After the motor for the actuator was finalised, the motor driver for it was chosen. A research on chainsaw motors was conducted to decide on the type of motor suitable for the chainsaw. Board interface design was carried out by using Altium Designer after finalising the sensors and motor driver that will be used. However, due to the change of design with the robot and limited space in the cutter, a custom-made microcontroller was designed.

The software was developed using Arduino IDE and Python. The code to control each piece of electronic hardware was developed on Arduino IDE, and they were integrated by ensuring that they could work together without any interference. A Python program was later developed which enabled the cutter to be remotely control by an Xbox360 controller.

Mechanical Design

Overview

Individual components were constructed throughout the third term and in the early fourth term. Aluminium plates used for the chainsaw blade and actuation systems were outsourced and laser cut. The rest of the components were manufactured by the team or the mechanical lab technicians at the University of Canterbury. This included a large amount of work to solve issues with the old tree traversing robot – increasing the existing robot's capacity to lift the extra weight necessary, and eliminating backlash in the wrist drive gears so that PhD work could go ahead as planned. The final versions of several components were manufactured by 3D printing because the geometry of the parts was complex and they were needed only for low stress applications. Manufacturing drawings were completed for the manufacture of all components.

The cutting mechanism was assembled by the project team. The team encountered some problems during the assembly phase, as some fasteners were placed in hard-to-reach places. The bottom plate of the existing gripper was modified to enable attachment of the cutter to the gripper.

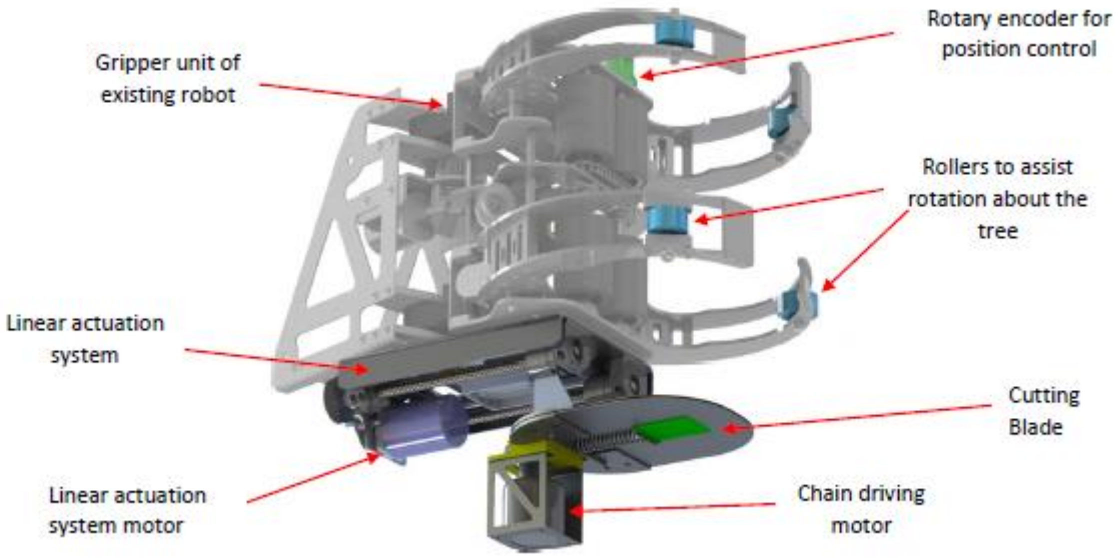

Figure 12: Complete system assembly

Features

The final specifications for the constructed felling mechanism were:

- One-quarter-scale model prototype
- 360 degree rotation around the tree stem
- Maximum linear force of 1150 N generated by the actuation system
- Maximum linear speed of 113 mm/s with a total travel of 240 mm
- Maximum chain speed of 13.5 m/s
- Maximum operational tree diameter, 160 mm.

Design for Assembly

At the beginning of the project, an emphasis was placed on the design being capable of existing separately from the current robot. The design is capable of doing that through the removal of three fasteners. The modular design was generated to simplify the assembly of the complete system while also helping to structure the resource allocation to the work streams. As well as that, each subsystem can be replaced independently of the other systems if an isolated problem occurs. The entire assembly of both sub-assemblies was made solely with mechanical fasteners, therefore no specialised tools were necessary.

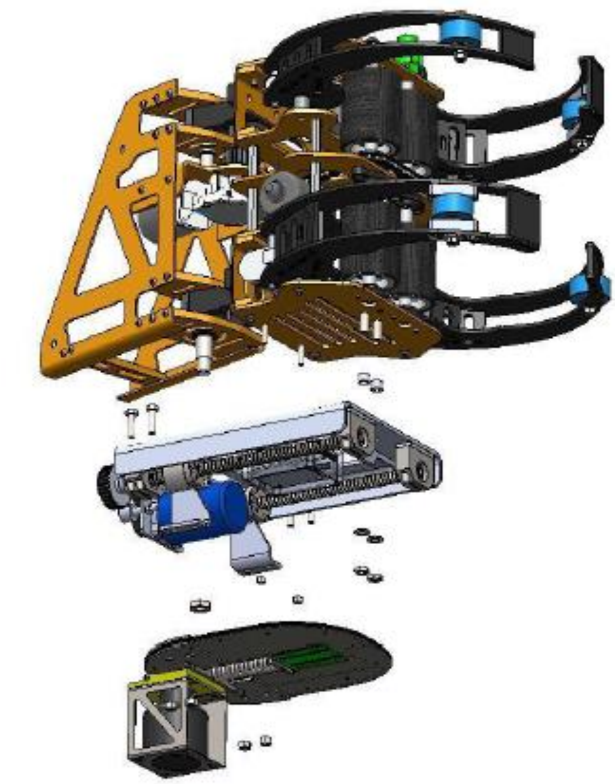

Figure 13: Modular assembly

Mechanical Sub-systems

The following is a more detailed description of each of the mechanical sub-systems described in the modular design section above.

Cutting Mechanism

The cutting mechanism was developed on the principle of the proven chainsaw design. However key improvements to the chainsaw were desired and were implemented into the new design. These improvements were:

- Increases of the corner radii to lower the centripetal acceleration experienced by the chain.
- Alteration of the blade width to accommodate a maximum tree diameter of 200 mm.
- Decrease bending stresses by making the blade as short as possible.
- Flat nose section to enable a solid cutting face at the front to enable the desired cutting

The improvements detailed above were implemented as shown in Figure 14.

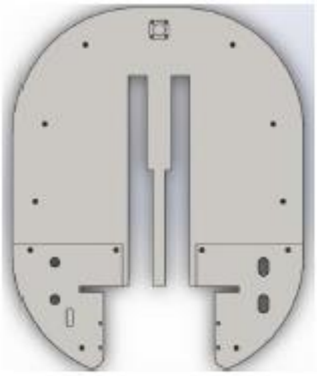

Figure 14: Final cutting blade design, all improvements implemented

The blade depicted in Figure 13 is 235 mm wide, 290 mm long at a total thickness of 4.2 mm with corner radii of 100 mm. Sections have been removed from the centre of the blade to accommodate the driving system for the chain and the wedging set-up.

It was paramount that the cutting mechanism possessed a wedging system that enabled some felling direction control. This wedging system was also needed to stop the cut from pinching down on the blade during the cutting process. This meant that once the wedge was pinched, the blade needed to be able to move relative to the wedge. To enable this to occur, the wedge was spring loaded. A compression spring was custom made in order to generate a loading of 800 N once fully compressed. This is enough to force the wedge the entire way in but not so stiff that the actuation system cannot compress it. This allows the blade to move 30 mm independently and therefore finish the cut with the wedge fully activated. It also generates an automatic reset in the wedge position between each tree the robot will encounter.

In order to increase all corner radii, the driving sprocket was to be increased from Ø 30 mm to Ø 80 mm. As this was a one-off part it was made using CNC machinery. To enable the correct fit of the chain on the sprocket, several iterations of sprocket design were prototyped using a 3D printer. Once the geometry was right the sprocket was then custom made. Knowing the increase in drive sprocket diameter over a standard electric chainsaw, the required motor performance could be calculated; 6 Nm at 3200 rpm.

A brushless DC outrunner electric motor, normally sold for use in hobby aircraft, was selected as the drive motor.

Safety considerations were made while designing the cutting component of this system, all based around catching the chain if it were to come off the blade. It was determined through communication with industry professionals and the University technicians that stopping the “chain whip” that occurs when the chain breaks was sufficient. The current set-up does this, along with the bullet proof plastic and following the safety protocol.

Actuation Mechanism

The actuation mechanism was based around two parallel Hiwin ballscrews. Ballscrews convert rotary motion to linear motion. A 5-mm aluminium mounting plate forms the backbone of the assembly, providing structural strength and the mechanical connection to the existing robot claw and wrist assembly. The mounting plate bolts to the gripper and is attached to the wrist section through the main wrist shaft, allowing the cutting head to pivot ±90° with the gripper. The cutter is attached to the actuation mechanism by two brackets from the ballnuts.

Both ballscrew shafts are located by a triple bearing arrangement. Back-to-back angular contact ball bearings locate the ballscrew shafts axially and provide high axial load carrying capacity. A single deep groove ball bearing locates the front of the ballscrew shafts radially. Bearing housings are bolted to the mounting plate. Figure 15 shows the actuation mechanism before the cutter has been attached.

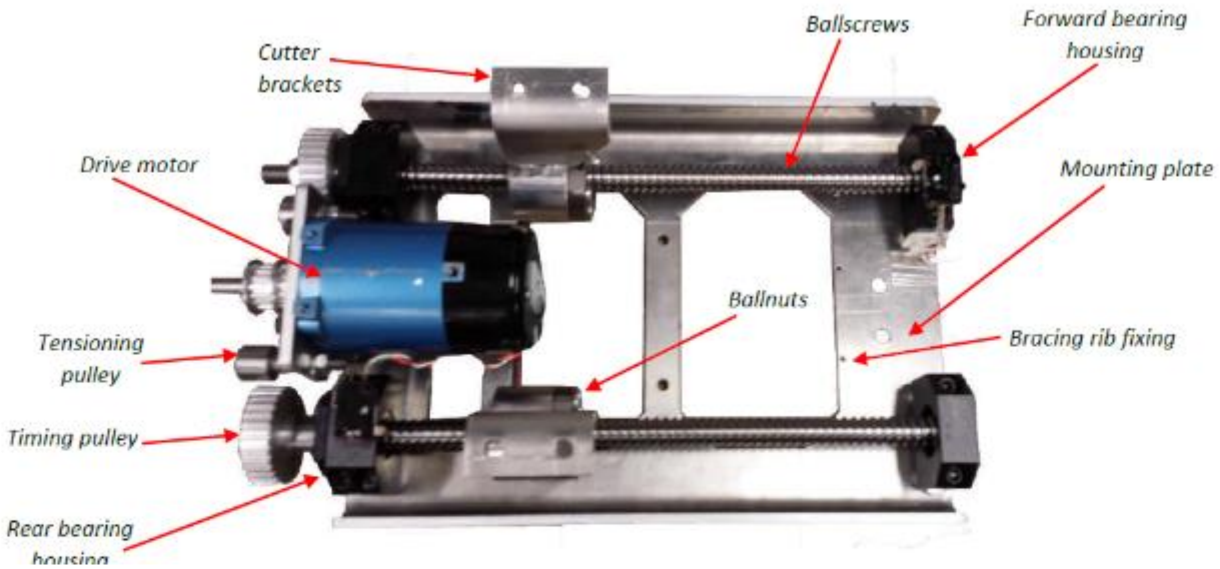

Figure 15: View underneath linear actuation assembly

The drive system consists of a 40W Parvalux PM10 brushed DC motor which is connected to the ballscrews through timing belts and geared timing pulleys. The motor outputs a maximum start torque of 0.4 Nm. This is converted to a maximum linear force at the ballnuts of 1144 N through a 2.28 gear ratio in the timing pulleys, and a 5-mm lead on the ballscrews.

The actuation mechanism was designed to incorporate a linear position strip, which measures the position of the ballnuts on the shaft. Limit switches are also included to provide an extra protection mechanism to prevent the ballnuts hitting the bearing housings at the ends of the ballscrew shafts.

Electrical Design

Motors

The motor used for linear actuation was a brushed DC 40 W Parvalux PM10 which was supplied with 12 V and capable of providing a maximum power at 120 W. The motor was protected from overload current by its driver. The chainsaw motor used was a Turnigy RotoMax 50 cc, an outrunner brushless DC motor. A 24 V supply is required for the chainsaw to spin at the design speed of 13.5 m/s. The motor is capable of drawing 120 A, but this was limited by a 100 A switch fuse added as a safety feature.

Microcontroller

A microcontroller was designed and built to control the motor drivers for the linear cutter actuation system. The custom microcontroller was developed to acquire data from the sensors in the cutter and control the actuation speed and chainsaw motor.

Motor Drivers

There were two motor drivers with in-built microprocessors used for the felling mechanism. A brushed DC motor driver drives the actuation motor, and a brushless DC Motor driver (ESC) drives the chainsaw motor. The drivers were powered by different batteries. The actuation motor driver was powered by the main battery at 12 V, whereas the chainsaw motor driver was powered independently by two truck batteries in series, providing 24 V. The actuation motor driver was controlled by the microcontroller via UART communication. The chainsaw was controlled by sending a PWM signal and +5 V power to its motor driver.

Sensors

A 200-mm long resistive membrane position sensor was implemented to obtain the chainsaw position relative to the robot wrist. Four similar position sensors, but with shorter lengths, were also implemented at the gripper actuators to give feedback control to the grippers and to enable the robot to measure tree size. Force resistive membrane sensors were also implemented in the chainsaw blade and the wedge for tree falling detection. In addition, similar rotatory encoders as last year were installed to the roller and wrist for feedback control.

Power Source

The cutter required two power sources, 12 V from the main power supply of the robot and 24 V from two truck batteries, independent of the robot, connected in series. The chainsaw 24 V power supply was supplied independent of the main power supply of the robot to ensure that any high current draw from the chainsaw would not damage or affect the entire robot hardware. The truck batteries were intended to be used for testing purposes, and they may be replaced with a Lipo battery after conducting a further study of the chainsaw power consumption. A 100-A switch fuse was installed at the truck batteries to ensure that the current to the chainsaw driver would not exceed 120 A. Special high current connectors were also used to connect the chainsaw motor to its driver and the driver to the truck batteries.

Software

Communication Protocol

The UltraNUC is the main computer which controls all the robot parts. The cutter has its own custom-made microcontroller, which controls the actuation and the chainsaw, and acquires readings from sensors. This modulation enabled the cutter to be tested without UltraNUC and made it easier to spot if there is any hardware failure. The UltraNUC communicates with the microcontroller via USB. The microcontroller communicates with the actuation motor driver via UART, which allows half-duplex communication between the two pieces of hardware. The chainsaw motor driver received PWM signals from the microcontroller, and without the signal the motor driver would be disabled.

Control

An open loop control system using a remote controller was implemented to switch on the chainsaw and drive the actuation back and forth. A position sensor in the actuation system was used to limit the movement to within the physical limits of the actuation system. Two limit switches were also installed at the edge of the actuation as extra backup for the position sensor.

Cutter Mechanism Tests

Test environment

A test rig was used to mount the felling mechanism to a 160 mm diameter tree. This was used for the dynamic testing of the felling mechanism as shown in Figure 16.

Figure 16: Cutting mechanism suspended from the test rig

Performance

The performance of the cutting mechanism for both the static and dynamic tests was recorded and documented on camera. The felling mechanism attached without interfering with any of the existing components. The static test showed that the existing robot was capable of carrying the weight of the cutting mechanism. Dynamic testing evaluated the cutting performance. Tests showed that the cutter cleanly cut through the tree to a maximum depth of approximately 120 mm of the tree diameter. Testing was halted at this stage due to technical difficulties.

Static test

The unit was bolted to the existing robot to ensure that the robot would be capable of carrying the new modifications to the existing design. It was found that the existing robot is readily capable of carrying the new modifications as there was no deflection or deformation in the frame.

Dynamic Tests

The dynamic tests showed that the chain can be driven up to speed, the wedging system activates and generates necessary travel, and the actuation system is operational. Standing waves in the chain as it rotates around the nose have been significantly reduced, validating the increase in corner radii. However, the mechanism can efficiently cut a tree as shown in Figure 17, but has been unsuccessful in finishing a complete cut. It was determined that the wedge was being activated too early and the control systems were not reliable enough. Improvements have been made to these areas but are yet to be tested.

Figure 17: Initial cut

Future Work

A review of the robot has been conducted and has found a number of opportunities for future improvement to the cutter and actuation system.

Cutter

Two areas that offer the most opportunity in the future are the wedging system and the chain driving system. The current wedging system is set up for 160 mm diameter trees only. Tree diameters in the forest vary, therefore an active, powered wedge with position control by a linear actuator would be worth investigating. The current drive system would benefit from a clutch installment, which would allow for strengthening of the sprocket casing, as it would no longer need to be the fail-safe mechanism.

Actuation system

An immediate improvement to be made to the actuation system is the timing belt tensioning system. Drive train losses could be reduced by replacing the current tensioner rollers with bearing-mounted pulleys that spin freely. Another solution would be moving the motor position lower to take up slack in the timing belt.

A higher gear ratio would improve the performance of the system. Currently the actuation system can move relatively quickly, which is unnecessary. Increasing the gear ratio to increase the maximum force and lower the maximum speed would likely improve cutting performance. This may be achieved by increasing the large timing pulley size, or using ballscrews with a smaller lead. A more powerful motor may also be worth considering, but will increase the weight of the system.

STAGE 6 SCALE-UP CONSIDERATIONS

Scale-up considerations were analysed by University of Canterbury summer scholar Alasdair Soja from November 2014 to January 2015. One of the key issues in up-scaling the tree-to-tree prototype is producing the forces required to move a full scale version through a forest. From earlier work on path planning it was estimated that the full scale version would have to have a maximum extension of approximately 8.0 metres and could weigh approximately 3-4 tonnes. The current system uses electric actuation, but electric actuation has limits and cannot produce the kind of power density required. Pneumatics can provide fast movement, but due to the compressibility of air, produce inaccurate movement, therefore hydraulic actuation is required. However this system introduces new problems, added components and weights.

Tree vs. Robot

Another problem with up-scaling the tree-to-tree robot is uprooting of trees. *Pinus radiata* trees are known to have weak root structures and so are quite vulnerable to uprooting, commonly being tipped over by strong winds. Therefore it is reasonable to assume that a large and heavy machine cantilevering from a *P. radiata* tree could cause the tree to uproot. This was analysed for the full scale case with a maximum robot extension of 8.8 m. The solving equation is simply a moment balance on the tree. The maximum resistive moment of the tree was found to depend on the age of the tree and its diameter at breast height (dbh). An earlier study had analysed the maximum resistive moment of *P. radiata* trees (Papesch, 1997) which was used to provide the mathematical correlation.

The maximum allowable mass of the robot was calculated from this mathematical equation using the maximum extension. This was solved for tree diameters from 200-700 mm (Figure 18).

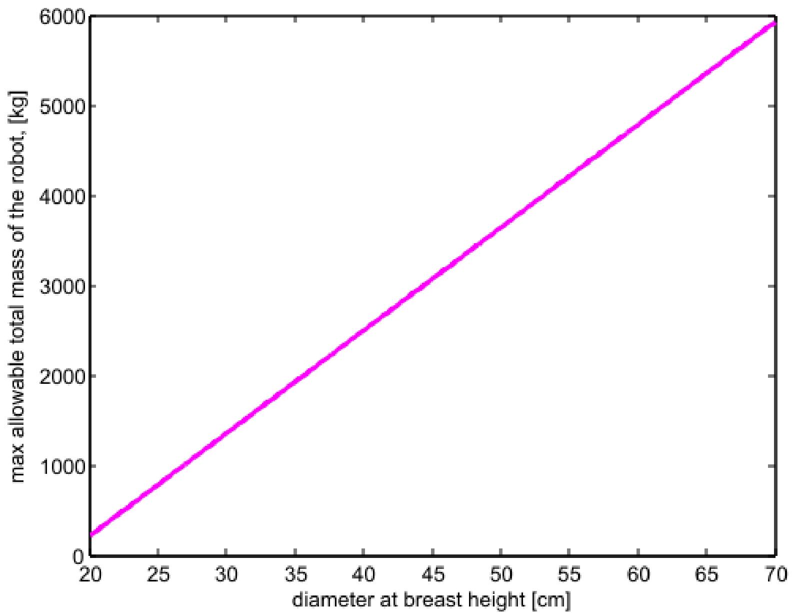

Figure 18: Maximum allowable mass of the robot versus tree diameter

As shown in Figure 18, the total mass of the robot required to cut large diameter trees is a concern. The maximum allowed mass for grasping a 25-cm diameter tree is less than 1000 kg. This calculation also has no factor of safety. Many tree root systems will be weaker than predicted by this model due to variation in soils, the lean of the tree, geographical location and statistical variation.

The weight of the robot was estimated with the main components of the robot each assigned a given mass. The estimated mass was based upon research into current commercial components, such as the diesel engine, as well as up-scaling parts from the quarter-scale prototype and using Solidworks models to determine the components' new mass. Table 2 shows the estimated mass of the components.

Table 2: Estimate of total mass of the full scale robot derived from estimated mass of the main components.

Weight Estimate of full scale robot			
Component	**Description**	**Mass**	
Felling Heads	Two felling heads (Hultdins SuperSaw 555S) at 195 kg each (Ref: Hultdins SuperSaw 2015)	390	kg
Grippers	2 grippers at 600 kg each	1200	kg
Wrists	2 wrists with 10mm steel frame at 110 kg each	220	kg
Wrist motors	2 wrist motors (radial piston) at 95 kg each (Radial Piston Motor (Multi-Stroke) 2015)	190	kg
Arms / Chassis	Arms made from 10-mm steel plate	436	kg
Arm actuators	60 kg per actuator (10 cm bore, 122 cm stroke)	180	kg
Hydraulic Pump	Minimum 200 litres/min	60	kg
Diesel Engine	PowerTech 4045TFM75 Diesel Engine, 80 kW turbocharged (1200 Series 1206E-E66TA Industrial Engine 2012)	460	kg
Hydraulic Fluid	200 litres of hydraulic oil	174	kg
Hydraulic system	Accumulator, valves, manifold, hoses etc.	100	kg
Diesel Fuel	150 litres of fuel	125	kg
Electrical System	Battery, electrical hardware, LIDAR scanner etc.	20	kg
	Total mass	**3555**	**kg**

The final total of the mass of a full scale prototype was estimated to be 3555 kg. Using this mass in accordance with Figure 17 shows that the minimum tree diameter that is safe to cantilever the robot off at full extension is 49 cm (without taking into account potential variation and no factor of safety). This is potentially a problem in a forest environment where the tree diameters can vary.

Potential solutions to this problem are as follows:

- The weight of the robot could be reduced and the whole design optimized, potentially using lighter materials than steel such as composites and titanium alloys.
- The path planning of the robot as it moves through the forest could also be used to ensure maximum extension is rarely reached except when stretching between the largest trees.
- Alternatively a mechanical system could be implanted where a structural support swings out at the greatest extensions to provide a connection to the ground to support the robot and provide another load path. This system would have the added benefit of increasing the stability of the robot during cutting and decreasing the force required in the gripper actuators holding the robot onto the support tree. However this requires a stable footing on the ground which may not be always possible on steep slopes.

Weight Reduction

The weight of the robot is a key issue, needing to be minimised in order to not uproot trees and to allow the power source of the robot to be smaller and so use less fuel, therefore decreasing running costs. Optimisation is an area to be investigated in the future, but as this project is an up-scaling exercise, weight reduction will still be factor in designs for a full-scale solution. Weight reduction will involve an investigation into the materials used to construct the robot. Steel remains the most common engineering material, being cheap and strong, but its relatively high weight means that other materials are to be considered when weight is an issue.

Movement – Degrees of Freedom

The current robot gripper head has 2 degrees of freedom – it can be rotated in the horizontal plane with the wrist motor and it can be moved up and down using the one of the main arm actuators. However the robot gripper head cannot be rotated in the vertical plane. This could be a problem in a real world forest where the trees to be grasped are all tilted slightly, specifically when trying to grasp a tree which is tilted to the side.

Tree Felling

Current commercial felling machines use large excavator bases with large hydraulic systems, and so can effectively lift a tree as it felled to ensure that it falls appropriately. The tree-to-tree robot however will not be able to operate like that, lacking a large stable base, and will likely not have the capacity to have such control over a tree trunk’s felling direction.

Controlling felling direction is vitally important in order to prevent damage to the robot. The prototype felling head includes a wedge in the chain bar which theoretically should be able to provide this control. However it has not been proved to do so yet. The felling direction is also controlled by cuts made in the tree according to its lean.

The current felling head features a large radius chain bar which decreases the chain throw – a common problem in the forestry industry. However this design also limits the chain bar to a linear motion which could only provide a cut from one direction without excessive movement of the robot. Typical commercial felling heads with chainsaws feature a chainsaw bar which cuts radially, and so could potentially allow a front cut and a back cut to be made in order to control felling direction. This means that in order to solve both problems either the current prototype for the felling head will have to be modified without adding excessive weight, or a commercial style chainsaw will have to be revised to prevent chain throw. Neither method of cutting is guaranteed to provide exact tree felling.

Materials Research

For the full-scale robot, many materials may be used for the different components. Aluminium is currently used for all the bodywork on the existing prototype, with steel pins/supports. However in the full-scale version, these materials may not be sufficient or be optimal to provide the best strength and durability while keeping costs and weight down.

The final robot may use many materials for various components. This could introduce problems such as galvanic corrosion, particularly between aluminium and steel when the robot will be operated in a potentially humid forest environment. The materials investigated for use are aluminium alloys, steel alloys, titanium and carbon fibre. The properties of the alloys below can vary greatly depending on the temper, which will have to be precisely specified for the actual design.

Aluminium

There are many aluminium alloys available, but only the main candidates for use in this application are discussed here. Alloy 2024 is a common aerospace alloy which can be resistance-welded or inert gas-welded. Alloy 2099-T83 is a relatively new aluminium-lithium alloy intended for aerospace use and very high strength applications. It is intended to replace 7000 series alloys (such as 7075 and 7050) with similar strength but increased resistance to stress, corrosion, cracking, fatigue and lower density. It can also replace other 2000 series alloys such as 2024, with its higher strength as well as the fore-mentioned benefits. Alloy 6061 is a common medium strength structural alloy, having the lowest yield strength of the alloys investigated. Alloy 7050 is an aerospace alloy of high strength, with good stress-corrosion cracking resistance but cannot be welded. Alloy 7075 Aerospace alloy, similar to 7075, but can only be resistance-welded (Technical Specifications - Aluminium Alloy n.d.).

Alloy Steel

Steel is the traditional material for the construction of heavy machinery due to its well-known properties and behaviours under various conditions and loads. Steel has many desirable properties, as it is strong, tough, has a high fracture toughness and is very inexpensive. Steels also have a fatigue limit, meaning that a steel component needs to have the maximum load kept below this limit in order for the component to have an unlimited life, i.e. to never fail in fatigue. One disadvantage in using steel is its high density of around 7850 kg/m3.

There are many steel alloys that could be used in this application. Only some of these will be discussed here. AISI 1060 carbon steel is a structural steel with good properties. AISI 4130 is a molybdenum and chromium alloy with high strength, and is used for tube structures and has very good weldability. AISI 4340 is a steel alloy containing nickel, molybdenum and chromium. It is noted for its high strength, especially after heat treating, and it can be fusion or resistance welded, with preheat and post-heat procedures needed (Engineering Steels Catalogue 2014).

Titanium Alloy

Titanium alloys have a very high strength-to-weight ratio, and very good corrosion resistance (used in chemical industry and corrosive environments). TI-6Al-4V is the most commonly used and provides the best strength (much better than pure titanium) and it has the highest tensile strength of the materials investigated (Titanium Ti-6Al-4V (Grade 5), Annealed n.d.).

Composites - Carbon Fibre

Carbon fibre composites are the lightest materials investigated, with the best strength-to-weight ratio (Mechanical Properties of Carbon Fibre Composite Materials 2009), but are very expensive, being approximately $22USD/kg for the standard modulus carbon fibre. Higher modulus carbon fibre is much more expensive. However the price of carbon fibre is forecast to drop as automobile companies such a BMW seek to force the price lower to make it a standard for everyday commercial cars, as shown by the recent release of the BMW i3 with a carbon fibre monocoque chassis (Ashley 2013).

Another benefit of composites is that they can be shaped into practically any shape or design, and the properties in each direction can be tailored as needed (adjusted by changing the direction of the fibres in the composite). However carbon fibre is relatively brittle and replacement in case of failure or damage will be much harder and more expensive.

Materials Summary

For the final full scale design a move should be made away from using steel in the construction of the robot due to its relatively high weight. Carbon fibre composites can provide nearly as much strength as steel at about one-fifth the weight. Titanium and aluminium alloys can also provide a cheaper solution for some components, which still provide some weight saving over steel. However, the material of each component of the robot will have its own requirements due to the loads it experiences and the function it performs, so the final design will include a variety of different materials.

Summary of Scale Up Considerations

The tree-to-tree robot has many problems to overcome in order for a functioning full-scale design to be created. However, the problems can be minimized if a simple design philosophy is followed for an initial full scale prototype, and some compromises are made in order to build a full scale prototype.

Providing the forces required to provide the movement of the robot at a sufficient speed in order for the robot to be economical is a challenge. The actuation would need to be provided by a hydraulic system. However, this system would introduce many more control issues which would require a hydraulic engineer to solve.

The modelling program ANSYS, was used to model the main robot chassis, and used to calculate the required forces in the actuators.

An analysis of the forces required by the gripper actuator was conducted, and determined that high forces were required, potentially greater than the main arm actuators. However this requires more investigation due to the coefficient of friction causing the results to change greatly.

The torques required by the roller system and the wrist joint motor were calculated, with high torques being calculated for the worst case scenario. Geared hydraulic motors are recommended to be used in this case, with potentially a cylinder and crank system to be used for the wrist joint. Geared hydraulic motors however may require that the pump be larger in order to provide the higher flow rate required.

The weight of the robot is a huge issue in the design. This weight provides a challenge to provide joints and a chassis that has sufficient strength, as well as increasing the size of the actuators required in order to move the robot. The weight also creates a problem whereby the mass of the robot could cause the tree it uses for support to uproot. This problem can be solved by reducing the weight of the robot with an optimised design, and also using a supporting leg that swings down to brace the robot against the ground when it goes to maximum extension.

Specifications for a full scale tree-to-tree robot

Requirements

- A hydraulic actuation system to provide the large forces required.
- Three double acting hydraulic cylinders to provide the extension and retraction of the robot arms.
- One hydraulic motor, or two telescopic hydraulic actuators and a crank in each wrist joint.
- Two double acting cylinders in each gripper head to provide the gripper claw movement and required force.
- A diesel engine directly connected to an axial piston pump which is either pressure- or load sense-controlled to provide hydraulic pressure.
- Lightweight, optimised chassis utilizing predominantly carbon fibre composites, titanium or aluminium components.
- A gripper head unit which uses two pairs of claws to grasp the tree, similar to the current quarter-scale prototype design.
- A wrist joint which rotates the robot only in one plane, using either two telescopic cylinders and a crank or a geared hydraulic motor to provide the actuation.
- Lightweight felling head design which can control felling direction of the tree.

Preferences

- Removing the roller system for turning the robot around a tree due to the unnecessary weight and complexity.
- A support system which can drop a supporting leg when the robot is at large extensions. This would reduce the load on the robot, lower the holding forces required, provide extra stability and prevent the robot uprooting the supporting tree.

Future Work

- The gripper actuator analysis needs to be verified, in order to check its correlation with the current quarter-scale prototype. This can be verified by mounting the gripper head onto a test tree, and replacing the actuator with a suitably sized aluminium strut with a strain gauge embedded before applying a weight on the end of the gripper to simulate the robot's moment due to its weight. Adjustment of the model for the current prototype and the full-scale model will mean an investigation of the coefficient of friction.
- A hydraulics engineer needs to provide accurate system specifications and specify the control systems such as the pump and valves. The current specifications are an estimate only.
- Weight reduction and optimization will be a key focus area for the full-scale robot. An optimised robot chassis in regard to strength-to-weight ratio needs to be designed.
- In-depth consideration of design concepts for the gripper-wrist joint actuation and the proposed supporting leg.
- The problem of felling a tree accurately needs to be solved. This will involve being able to sense the direction of the lean of a tree, its centre of mass, and sensing the movement/shifting load of the tree during cutting, to check that the tree is falling in the correct direction.

ECONOMIC VIABILITY OF A LIGHTWEIGHT MACHINE

The work in Stage 6 suggests a full-size machine using diesel power and hydraulics could weigh over 3.5 tonnes. Such a machine could be difficult to transport and complex to maintain. A goal for the development programme is to work towards a lighter, simpler machine, which has been assessed in the following costing. The advantage of a lightweight machine is that it can be transported around the forest relatively cheaply by a small helicopter.

The economic analysis of a tree-to-tree felling machine has been based on a lightweight machine that requires a 20 kW engine. The machine would cost $200,000 new and have a life of 2.4 years and should be able to fell trees at the same speed as a conventional motor manual tree faller. Therefore productivity will be slower than a mechanised felling operation.

In its current planned configuration the machine will not be able to bunch, so extraction will be slower than for bunched wood. An FFR report by Evanson & Amishev (2010) demonstrated that bunched wood resulted in a 50% increase in the number of trees hauled per cycle. Similar results should be expected for the robot. An estimate of machine cycle time is given in Table 3.

Table 3: Estimate of machine cycle time for the tree-to-tree machine compared to conventional mechanised felling

Element	Cable assisted felling cycle time (sec)	Tree-to-Tree machine cycle time (sec)
Move	30.1	30
Position head	7.9	10
Fell	15.2	180
Slew	3.2	10
Bunch	35.8	-
Windrow	5.7	-
Clear slash	6.5	-
Other	2.4	10
Total cycle time	**106.8**	**240**

For calculation of the machine rate, the following assumptions have been made:

Assumptions - production

- Cycle time = 4 minutes / tree
- Scheduled work hours = 18 hours / day operation
- Daily production = 270 trees / day
- Average tree size = 1.5-tonne piece size

Assumptions – costs

- Engine power = 20 kW
- Capital cost = $200,000
- Machine life = 10,000 hours (@230 work days / year = 2.4 years)
- Operator costs = $40 / hour

Table 4: Estimate of machine costs for the tree-to-tree felling machine

Type Machine			Tree-to-Tree
Power (kw)			20
Year purchased			2015
Machine Life	Workdays per year		230
	Productive Hours per day		18
	Hours per year		4,140
	Hours to be owned		10,000
	Machine Life (years)		2.4
Fixed costs			
Capital Cost	Current new price		$200,000
	Resale value (as a % of cost)		25%
	Current used price (after hours to be owned)		$50,000
	Grippers life (hrs)		1,000
	New grippers price		$1,000
	Annual depreciation		$61,686
	Depreciation ($/Workday)		**$268.20**
Interest	Proportion of ACI as loan		75%
	Proportion of ACI as owners' equity		25%
	Loan interest rate		11.00%
	Owner's interest rate		10.50%
	Weighted interest rate		10.875%
	Average capital invested		$156,050
	Interest ($/Workday)		**$73.78**
Insurance	Insurance Rate (Percentage of ACI)		2.0%
	Insurance ($/Workday)		**$13.57**
Total Fixed Costs ($/Workday)			**$355.55**
Operating costs			
Fuel	Fuel price ($ per litre)		$1.42
	Fuel Usage (litres/kW/hr)		0.15
	Fuel Cost ($/Workday)		**$76.68**
Oil	Oil as a % of Fuel		15%
	Oil Costs ($/Workday)		**$11.50**
R+M	Repair and Maintenance (Percentage of depreciation)		70%
	Repairs and Maintenance		**$187.74**
	Grippers		**$18.00**
	Rigging		**$0.00**
Total Operating Costs ($/Workday)			**$293.92**
Total Machine Rate ($/Workday)			**$649.47**
Total Machine Rate Per Hour			**$36.08**

Summary of Felling Cost

Daily cost = ($36.08 + $40.00) = $1,369.44
Daily production = 270 x 1.5 = 405 tonnes per day
Felling cost = ($1,369.44 / 405 tonne = **$3.38 / tonne**

Comparison with existing tethered ClimbMAX steep slope harvester costs (Evanson, pers. comm.) showed that for felling 2.0-tonne trees, operating 7 productive hours per day, cost estimates were $4.03 / tonne (downhill felling) and $5.28 / tonne uphill felling. Both estimates included bunching time of 30 sec per tree. The advantage of the tree-to-tree machine is that, although as slow as a motor-manual faller it can work at night as it is designed to be teleoperated.

CONCLUSIONS

The work in Stage 4 has demonstrated that a self-powered mechanical platform can traverse between trees in the forest. Those trees may be only 2.5 m apart but the principle of tree to tree locomotion is sound. A novel chainsaw has been designed, built and tested in Stage 5. This chainsaw may solve the issue of chain-throw (chain derailing from the chain bar) which is a major hurdle to full remote operation of felling machines. In Stage 6 an investigation was made of scale-up issues and the potential complexity and weight of a “conventional design” was estimated. This came to 3.5 tonnes. The research programme should be aiming for a lighter and simpler device which can be transported by a helicopter. A costing of a smaller 20 kW machine showed a relatively low cost of $36 / hour. The overall philosophy of the programme should continue to aim for simple, lightweight tree-to-tree machines which make a profit for the owner.

REFERENCES

Aluminium Alloy 2099. Smiths High Performance. http://www.smithshp.com/downloads/2099_SHP.pdf.

Aluminum 7050-T7451 (7050-T73651). http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA7050T745.

Ashley, Steven. Cutting costs of carbon composites . February 27, 2013. http://articles.sae.org/11618/.

Bentley, T.; Parker, R. & Ashby, L. (2004). *Understanding felling safety in the New Zealand forest industry*. Applied Ergonomics, 36, 165-175.

Engineering Steels Catalogue. Steel and Tube. May 2014. http://stainless.steelandtube.co.nz/wp-content/uploads/2014/06/Engineering-Steels-Catalogue-May-14.pdf.

Evanson, T. & Amishev, D. (2010) *A steep slope excavator feller buncher*. Harvesting Technical Note 3(2). Future Forests Research.

Mechanical Properties of Carbon Fibre Composite Materials. July 2009. http://www.performance-composites.com/carbonfibre/mechanicalproperties_2.asp.

Milne, B.; Buchanan, G.; Paulin, S.; Chen, X.; Hann, C.; Geldenhuis, A.; Parker, R. (2013) *Robotic arm kinematics and bilateral haptic feedback over an ethernet communications link*. Paper presented at the Ninth IEEE International Conference on Automation Science and Engineering (CASE 2013), Madison, Wisconsin, USA, August 17-21, 2013.

Papesch, A.; Moore, J. Hawke. A. "Mechanical Stability of Pinus Radiata Trees At Eyrewell Forest Investigated Using Static Tests." New Zealand Journal of Forestry Science, 1997: 188-204.

Parker, R.; Kirk, P. & Sullman, M. (1996) *Learning curves of mechanised harvester and forwarder operators*. LIRO Report 21(29):1-6.

Technical Specifications - Aluminium Alloy. http://www.wilsonsmetals.com/datasheets/?gId=1.

Titanium Ti-6Al-4V (Grade 5), Annealed. http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MTP641.

Wareing, G.; Gilbert, T.; Paulin, S. & Bayley, S. (2013) Project 21*: Biped felling machine – Final year report*. Scion & University of Canterbury.

Appendix

Bill of materials for tree-to-tree platform

Bill of Materials

Item	Part Number	Description	Material / Manufacturers Description	Supplier	Stocker Location	Qty
1	G-001	OUTER BASE PLATE	7075 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	4
2	G-002	INTERMEDIATE BASE PLATE	7075 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	4
3	G-003	MIDDLE BASE PLATE/MOTOR MOUNTING PLATE	7075 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	2
4	G-004	LINKAGE	7075 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	4
5	G-005	LARGE HEX SPACER ROD	UA 1607 SOLID HEXAGON (Ø11.11mm)	ULLRICH ALUMINIUM	CHCH	8
6	G-006	SMALL HEX SPACER ROD	UA 1607 SOLID HEXAGON (Ø11.11mm)	ULLRICH ALUMINIUM	CHCH	8
7	G-007	TOP WIDE HAND GRIPPER SHAFT	UA2038 SOLID ROUND (Ø19)	ULLRICH ALUMINIUM	CHCH	2
8	G-008	TOP THIN HAND GRIPPER SHAFT	UA2038 SOLID ROUND (Ø20)	ULLRICH ALUMINIUM	CHCH	2
9	G-009	BOTTOM WIDE HAND GRIPPER SHAFT	UA2038 SOLID ROUND (Ø20)	ULLRICH ALUMINIUM	CHCH	2
10	G-010	BOTTOM THIN HAND GRIPPER SHAFT	UA2038 SOLID ROUND (Ø20)	ULLRICH ALUMINIUM	CHCH	2
11	G-011	ACTUATOR-GRIPPER CONNECTION ROD	Ø6 MILD STEEL ROD	UC WORKSHOP	CHCH	4
12	G-012	ACTUATOR CENTERING SLEEVE	UA1927 EXTRUDED ROUND TUBE	ULLRICH ALUMINIUM	CHCH	8
13	G-013	SHAFT FOR ROLLERS	AUS 8009 SOLID ROUND (Ø16)	ULLRICH ALUMINIUM	CHCH	4
14	G-014	ROLLER HUB	SOLID FREE MACHINING ROD (Ø63.5)	ULLRICH ALUMINIUM	CHCH	8
15	G-015	TOP SLEEVE - LONG	UA2038 SOLID ROUND (Ø20)	ULLRICH ALUMINIUM	CHCH	2
16	G-016	TOP SLEEVE - SHORT	UA2038 SOLID ROUND (Ø20)	ULLRICH ALUMINIUM	CHCH	2
17	G-017	BOTTOM SLEEVE - LONG	UA2038 SOLID ROUND (Ø20)	ULLRICH ALUMINIUM	CHCH	2
18	G-018	BOTTOM SLEEVE - SHORT	UA2038 SOLID ROUND (Ø20)	ULLRICH ALUMINIUM	CHCH	2
19	G-019	CHANNEL SECTION TOP	UA 1150 CHANNEL	ULLRICH ALUMINIUM	CHCH	2
20	G-020	CHANNEL SECTION BOTTOM	UA 1150 CHANNEL	ULLRICH ALUMINIUM	CHCH	2
21	G-023	ACTUATOR-GRIPPER CONNECTION ROD 2	Ø6 MILD STEEL ROD	UC WORKSHOP	CHCH	4
22	G-024	ACTUATOR CENTERING SLEEVE 2	UA1927 EXTRUDED ROUND TUBE	ULLRICH ALUMINIUM	CHCH	8
23	H-001-01	INNER GRIPPER HAND 1	5251 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	4
24	H-001-02	INNER GRIPPER HAND 2	5252 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	4
25	H-002-01	OUTER GRIPPER HAND 1	5253 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	4
26	H-002-02	OUTER GRIPPER HAND 2	5254 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	4
27	H-003	OUTER HAND UPRIGHT 1	5255 AL PL (8mm)	PROMETAL INDUSTRIES	CHCH	4
28	H-004	OUTER HAND UPRIGHT 2	5256 AL PL (8mm)	PROMETAL INDUSTRIES	CHCH	4
29	H-005	INNER HAND UPRIGHT 1	5257 AL PL (8mm)	PROMETAL INDUSTRIES	CHCH	4
30	H-006	INNER HAND UPRIGHT 2	5258 AL PL (8mm)	PROMETAL INDUSTRIES	CHCH	4
31		GRIPPER ARM ACTUATOR	FA-240-S-12-4" (90kg-100mm STROKE)	FIRGELLI AUTOMATIONS	VICTORIA (AUS)	4
32		ROLLER DRIVE MOTOR + WRISR MOTORS	AME-226-SERIES 12V UNTILITY GEARHEAD	ROBOT MARKETPLACE	FLORIDA (USA)	2
33		FLANGED BEARING UNIT	IGUS EFOM-16	RS NEW ZEALAND	AKLD	12
34		6mm FLANGED BUSHES	IGUS GFM-0608-04	RS NEW ZEALAND	AKLD	24
35		12mm FLANGED BUSHES	IGUS GFM-1214-07	RS NEW ZEALAND	AKLD	16
36		SPROCKETS FOR ROLLER DRIVE	06B BS CHAIN 15 TOOTH SPROCKET	RS NEW ZEALAND	AKLD	6
37		CHAIN FOR ROLLER DRIVE	06B BS CHAIN	RS NEW ZEALAND	AKLD	0.2m
38		CONNECTING LINK FOR CHAINS	06B BS CONNECTING LINK	RS NEW ZEALAND	AKLD	2
39		SHAFT CLAMPS FOR ROLLERS	16mm BORE MILD STEEL 1 PC CLAMP COLLAR	RS NEW ZEALAND	AKLD	16
40		ROLLER RUBBER OVERMOLDING	NEOPRENE RUBBER STRIP (100mm WIDE)	PARA RUBBER	CHCH	8
41	J-001	ENCODER JOINT AXLE	MILD STEEL	UC WORKSHOP	CHCH	3
42	J-002	3D PRINTED ENCODER COVER	ABS PLASTIC	UC WORKSHOP	CHCH	3
43		FLANGED BEARINGS FOR ARM JOINTS	10 x 19 FLANGED BEARING	RS NEW ZEALAND	AKLD	3
44		ABSOLUTE ENCODER	MA3 ABSOLUTE ENCODER	US DIGITAL	WASHINGTON (USA)	3
45	A-001	SHORT ARM	7075 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	1
46	A-001-M	SHORT ARM MIRRORED	7075 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	1
47	A-002	LONG ARM	7075 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	1
48	A-002-M	LONG ARM MIRRORED	7075 AL PL (5mm)	PROMETAL INDUSTRIES	CHCH	1
49	A-003	LONG ARM SPACER	UA2038 SOLID ROUND (Ø20)	ULLRICH ALUMINIUM	CHCH	3

BOM Cont.

Item	Part Number	Description	Material / Manufacturers Description	Supplier	Stocker Location	Qty
50	A-004	SHORT ARM SPACER	UA2038 SOLID ROUND (Ø20)	ULLRICH ALUMINIUM	CHCH	2
51	A-005	GAP FILLER SPACERS	UA2038 SOLID ROUND (Ø20)	ULLRICH ALUMINIUM	CHCH	6
52	A-006	ARM ACTUATOR PIN	Ø10 MILD STEEL ROD	UC WORKSHOP	CHCH	6
53	A-007	ARM ACTUATOR PIN SPACER	UA1927 EXTRUDED ROUND TUBE	ULLRICH ALUMINIUM	CHCH	12
54		TOP ARM ACTUATOR	PA-02-12-400	PROGRESSIVE AUTOMATIONS	CANADA	1
55		END ARM ACTUATOR	PA-02-10-400	PROGRESSIVE AUTOMATIONS	CANADA	2
56	E-001	END FLAT SECTION	7075 AL PL (3mm)	PROMETAL INDUSTRIES	CHCH	2
57	E-001-M	END FLAT SECTION MIRRORED	7075 AL PL (3mm)	PROMETAL INDUSTRIES	CHCH	2
58	E-002	WRIST SHAFT	MILD STEEL	UC WORKSHOP	CHCH	2
59	E-002-2	WRIST SHAFT BOTTOM	MILD STEEL	UC WORKSHOP	CHCH	2
60	E-003	CLAMP FRONT	7075 ALUMINIUM BLOCK	UC WORKSHOP	CHCH	4
61	E-004	CLAMP REAR	7075 ALUMINIUM BLOCK	UC WORKSHOP	CHCH	4
62	E-005-v2	MOTOR BRACKET	7075 AL PL (3mm)	PROMETAL INDUSTRIES	CHCH	2
63	E-006	TOP BEARING BLOCK	7075 AL PL (10mm)	PROMETAL INDUSTRIES	CHCH	4
64	E-007	BOTTOM BEARING BLOCK	7075 AL PL (10mm)	PROMETAL INDUSTRIES	CHCH	4
65		20mm FLANGED BUSHES	IGUS GFM-2023-11	RS NEW ZEALAND	AKLD	8
66		20mm THRUST WASHER	IGUS GTM-2036-015	RS NEW ZEALAND	AKLD	8
67		PINION- 12 TOOTH STEEL SPUR GEAR	STEEL SPUR GEAR, 2.0 MODULE, 12 TEETH	RS NEW ZEALAND	AKLD	2
68		GEAR-30 TOOTH STEEL SPUR GEAR	STEEL SPUR GEAR, 2.0 MODULE, 30 TEETH	RS NEW ZEALAND	AKLD	2
69		WRIST DRIVE MOTOR	AME-226-SERIES 12V UNTILITY GEARHEAD	ROBOT MARKETPLACE	FLORIDA (USA)	2
70			M3 x 4 GRUB SCREW	BLACKS FASTENERS	CHCH	10
71			M5 x 8 GRUB SCREW	BLACKS FASTENERS	CHCH	12
72			M8 x 30 CSK BOLT	BLACKS FASTENERS	CHCH	10
73			M8 x 30 CAP BOLT	BLACKS FASTENERS	CHCH	4
74			M6 x 16 CAP BOLTS	BLACKS FASTENERS	CHCH	20
75			M6 x 12 BUTTON HEAD SOCKET SCREW	BLACKS FASTENERS	CHCH	4
76			M6 x 16 BUTTON HEAD SOCKET SCREW	BLACKS FASTENERS	CHCH	100
77			M8 x 20 BUTTON HEAD SOCKET SCREW	BLACKS FASTENERS	CHCH	50
78			M10 x 20 BUTTON HEAD SOCKET SCREW	BLACKS FASTENERS	CHCH	10
79			SIZE 10 SHOULDER BOLT - 16mm SHOULDER (M8)	BLACKS FASTENERS	CHCH	3
80			M6 (THIN IF POSSIBLE) NYLOCK NUT	BLACKS FASTENERS	CHCH	25
81			M8 NYLOCK NUT	BLACKS FASTENERS	CHCH	20
82			M10 NYLOCK NUTS	BLACKS FASTENERS	CHCH	15
83			M20 EXTERNAL CIRCLIP BLACK	BLACKS FASTENERS	CHCH	4
84			M6 SPRING WASHER	BLACKS FASTENERS	CHCH	10
85			M6 PLAIN WASHER	BLACKS FASTENERS	CHCH	15
86			M8 PLAIN WASHER	BLACKS FASTENERS	CHCH	15
87			M10 PLAIN WASHER	BLACKS FASTENERS	CHCH	10
88			M6 INTERNAL TOOTH WASHER	BLACKS FASTENERS	CHCH	100
89			M8 INTERNAL TOOTH WASHER	BLACKS FASTENERS	CHCH	100
90			M20 PLAIN WASHER	BLACKS FASTENERS	CHCH	10
91			6 x 12.5 x 1 BRASS WASHER	BLACKS FASTENERS	CHCH	20
92			M4 x 20 CAP BOLTS	BLACKS FASTENERS	CHCH	40
93			SIZE 6 SHOULDER BOLT - 10mm SHOULDER (M5)	BLACKS FASTENERS	CHCH	4
94			M5 x 16 CKS BOLT	BLACKS FASTENERS	CHCH	120
95			M3 x 16 CSK BOLT	BLACKS FASTENERS	CHCH	50
96			M5 x 6 SOCKET GRUB SCREW	BLACKS FASTENERS	CHCH	4
97			M5 x 10 SOCKET GRUB SCREW	BLACKS FASTENERS	CHCH	4
98			M3 x 8 BUTTON HEAD SOCKET SCREW	BLACKS FASTENERS	CHCH	6