Resources

Next Generation Timber Harvesting Systems:

Opportunities for remote controlled and

autonomous machinery

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Next Generation Timber Harvesting Systems: Opportunities for remote controlled and autonomous machinery

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Summary

"The future of timber harvesting systems will certainly be robotic.
The question is, how will we get there?"

Technology development, in terms of both capability and cost-effective integration, is moving at a fast pace. While advanced robotic systems are already commonplace in controlled workspaces such as factories, the use of remote controlled or autonomous machines in more complex environments, such as for forest operations, is in its infancy.

There is little doubt autonomous machinery will play an important role in forest operations in the future. This will also create a large international market for machine development and manufacturers. There are a number of drivers that will facilitate this move, but sustained long-term success will include greater levels of efficiency and cost-effectiveness.

While technology integration and automation in forestry equipment are commonplace, this report focuses on equipment developments and opportunities where no operator is in the machine. The simplest form is remote control of the machine where the operator, typically in clear line-of sight, will work with wireless controls. While teleoperation is simply a more technical term for remote control, often implied is that the operator works from a virtual environment with live video and audio feedback from the machine. Since teleoperation provides a similar operator experience to working in the machine, it is relatively easy for an operator to transition to teleoperation. Autonomous systems are defined by being able to perform certain functions without direct control of a human operator.

Most modern forestry machines can readily be converted for remote control at relatively low cost and many working options already exist. Teleoperation requires the additional cost of creating a virtual environment, but creates the opportunity of working from a remote location. For both systems the machine operation is typically slower, significantly so if the task is complex, and will not be adopted in forest operations strictly based on productivity improvements. However, benefits can quickly accrue when: (a) operator safety might be compromised, (b) where a full-time operator would be underutilised, or (c) where work sites are onerous to reach or suitably qualified operators are hard to find. Remote control or tele-operation will most likely become a cost-effective alternative when both the machine is purpose built (i.e. cableless) and certain machine tasks can be automated, and this could/should be the primary focus of R&D in generating a new market for remotely operated forestry machines.

The hardware and technology exist to make almost any aspect of forest operations autonomous. However, for forest operations that are complex and require visual inputs for decision making, software requirements will restrict its implementation. While there are a plethora of ideas, there are no fully autonomous systems current working in timber harvesting. However, the extraction and subsequent transportation of stems / logs with GPS-guided systems are most likely to be the first operations that become robotic and can be achieved with modest R&D investment in the near future. This will be aided by our current low-cost ability to map terrain using LiDAR and or video using mobile (ground or aerial) platforms. Significant additional gains, especially in terms of creating markets for larger numbers of machines, will be with purpose-built cableless machines. With improved visual recognition software, partial automation will benefit elements such as stem processing, or

more complex machine movements such as grappling a stem. In the longer term, and with a more substantial R&D investment, felling in a plantation environment will also become economically feasible.

This report presents opportunities for remote control, tele-operated and automation of forest operations for the purpose of discussing the near, but also longer term, future of forest equipment. It presents examples of existing developments as well as ideas from both forestry and other industries.

The author recognises that, as with all emerging technologies and sectors, there is plenty of room for differences in opinions as to what will be commercially successful in the future.

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A few helpful definitions

Automation - the technique, method, or system of operating or controlling a process by highly automatic means, as by electronic devices, reducing human intervention to a minimum.

Autonomous - having the freedom to act independently; (of a vehicle) navigated and maneuvered by a computer without a need for human control or intervention under a range of driving situations and conditions.

Drone - an unmanned aircraft or ship that can navigate autonomously, without human control or beyond line of sight.

Remote Control - control of a machine or apparatus from a distance by means of radio or infrared signals transmitted from a device.

Robot - a machine capable of carrying out a complex series of actions automatically, especially one programmable by a computer.

Robotics - the branch of technology that deals with the design, construction, operation, and application of robots.

Slave (machine) - a machine or component controlled by another machine or component.

Teleoperation - the electronic remote control of machines. Teleoperation is the technical term for the operation of a machine, system or robot from a distance.

Introduction

Technology development, in terms of both capability and cost-effective integration, is moving at a fast pace. Robotics recently celebrated its 50 year anniversary: while to date it has mainly allowed people to avoid doing things that are "dirty, dull and dangerous", moving to robotics can also provide "economic growth, improved quality of life and empowerment of people" (Christensen, 2016). The drivers for 'next generation' harvesting systems are already established and include the continuous need for improved efficiency and cost-effectiveness, but also safety, and addressing skilled machine operator shortages in rural areas.

While equipment manufacturers continue to develop and integrate new technologies, they tend to do so at a rate that ensures commercial returns for their investments. For the forest industry one limitation is the lack of larger-scale market demand for harvesting machinery. Automation of forestry equipment lags larger industries such as agriculture, mining or the military. For agriculture and mining, the primary reasons are both the scale of their industry but also the more homogenous work environments. For military, it is the scale of the research and development investment. Advances in autonomous vehicles are also increasingly found in the urban environment with operable bus and waste collection systems.

Agriculture has clearly benefited from higher levels of research and development investments. An example is an agricultural-based conference series and competition for field capable robotic machinery already into its 14th year[i] *. In terms of equipment development, an Economist report predicts farm technologies could become a $240 billion market opportunity for agricultural suppliers, with smaller driverless tractors a $45 billion market on its own[ii]. However, even in agriculture many remote controlled or autonomous machine developments remain in the prototype or pre-commercial stage. A summary including videos is provided on the CNBC website, and Wikipedia has a longer list of projects[iii].

Note: in this report the endnotes are internet links to either the information, further reading or video access to the information source.

Incremental improvements are continuously being made to existing forestry machines. Embedded electronics (e.g. sensors, measuring tools, video feeds) are commonplace and can help to automate specific functions such as processing stems to logs by moving the head to predetermined positions according to log grade. The data captured during felling and processing can be augmented by geospatial information to analyse and optimise machine performance, as well as use this to implement the concept of precision forestry (Olivera and Visser 2016). Another example of software aiding machine control is the new John Deere 'Intelligent Boom Control' system[iv] that allows the operator to control the movement of the head directly, as opposed to moving the individual component of the boom. It has already been shown that the use of such technology makes it easier to learn to operate harvester or forwarder machines (Lofgren, 2006; Englund et al. 2017). Komatsu recently published a vision of using drones[v], communication technologies and cloud services to improve harvesting efficiency (Fig. 1). While these are examples of automated components of our forestry supply chain, this report will focus only on remote control, tele-operated and or autonomous machines.
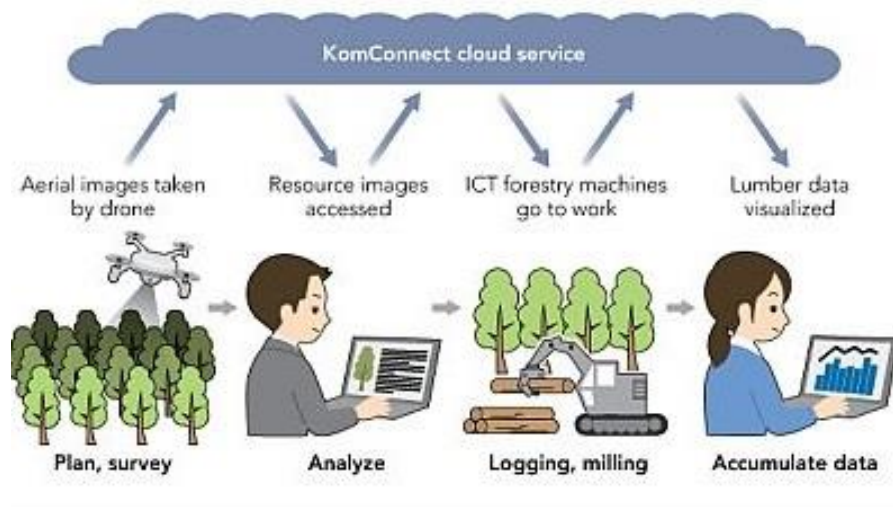
Figure 1: 'Smart' forestry using an array of technologies to
(Image: from Komatsu as shown in FridayOffcuts[v])

Information on robotics in forest operations is primarily found in the 'grey literature' (i.e. websites). However, examples of journal articles start in the late 1980's with Courteau (1989) providing an overview of developments of robotics in forestry. Guimier (1998) concluded that new technology in machines would be equipped with 'intelligent' control systems that allow them adapt to their working environment. Thor (2014) noted that mechanised systems would continue to be automated until robots could be used for harvesting operations. More advanced concepts are presented for specific elements such as development of unmanned forwarders (Ringdahl 2011)[vi] or summary papers that investigated a range of robotic options (Hellstrom et al 2009; Parker et al 2015; Parker Bayne Clinton 2016)[vii]. The first "Robotics in the Forest" conference was held in 2015 (Montreal, Canada) that brought together research specialists from many countries. The meeting was coordinated by FPInnovations and all presentations are available online[viii].

Successful implementation of autonomous equipment will be driven by their productivity and operational cost. Given that labour is typically about 30% of running costs (Hellstrom 2009), an autonomous machine can be less productive but still be more cost effective. However there are other factors to consider; a study by McEwan (2017) highlighted the consideration of additional benefits relating to health and safety, environment, quality (in terms of increasing value or reducing waste), but also social aspects. While modern machines are well designed with regard to ergonomics, this has led to many operators working longer hours per day (Nicholls et al 2004) and has created different health risks to the traditional manual physical risks. For example, harvest operators in thinning are required to make about 4000 control inputs per hour (Magagnotti, 2016) and this can quickly lead to fatigue, or a forwarder operator might spend many hours a day traversing trails that can lead to monotony. A higher degree of machine autonomy could readily decrease these types of occupational health and safety risks.

There is a strong perception that robots will take people's jobs, or reducing pay level for operators to compete with robots. Acemoglu and Restrepo (2017) indicate that each additional robot reduces employment by 5 workers, and every robot that is added to the

workforce per 1000 human workers caused wages to drop by 0.25 per cent[ix]. However, studies also exist showing that over 35% of all robotic related jobs will be vacant by 2020 and that people skilled in robotic development, implementation and maintenance will see salary increased up to 60%. For higher levels of machine automation to succeed in the more remote forestry environments there will be a greater need for people with 'emerging' skill sets (e.g. IT, technology).

An IDC study predicting future worldwide robotic developments has three interesting and relevant findings for the development of forest operations equipment[x]. By 2018, 30% of all new robotic deployments will be smart collaborative robots that operate three times faster than today's robots and are safe for work around humans. By 2019, governments will begin implementing robotics-specific regulations to preserve jobs and to address concerns of security, safety, and privacy. By 2020, 60% of robots will depend on cloud-based software to define new skills, cognitive capabilities, and application programs, leading to the formation of a robotics cloud marketplace. The latter development will be particularly important given the complexity of forest work environments.

Specific to forestry equipment, McEwan (2017), with a focus on equipment for harvesting fast growing Eucalyptus, completed a Delphi questionnaire of 27 international experts that concluded that the majority of machines would adopt smart tablet monitors by 2020, GPS by 2020, and remote control by 2025. However, adoption of LiDAR and or other sensors for tree selection was rated to be 20 years in the future by the majority of experts. For extraction, the opinion that an autonomous skidder would be developed ranged from 5 to 20 years at the 50% confidence level, but nearly all said that 90% adoption of this technology was at least 20 years into the future.

A number of forest operations research groups are experimenting with remote controlled or autonomous vehicles. While there is often much speculation on future benefits, there is almost a complete absence of information on actual productivity improvements of any of the prototypes developed. With manufacturing companies starting to take a stronger interest, such information will become critical for manufacturing companies to invest in development, or for contractors to purchase such equipment for their operation.

This report focusses primarily on timber harvesting systems, including short and long term opportunities. A shorter section also provides some ideas on planting and silviculture machinery.

Developing New Harvesting Systems

Developing new forestry equipment or systems requires ideas, testing, development, prototypes, investment and commercialisation. While ideas can come from many sources, actual development and testing is often done either by researchers or equipment manufacturers. Researchers are typically looking for exciting and futuristic opportunities; machine manufactures tend to be more pragmatic and look for equipment that is likely to be successful in the near-term and at a scale that can create a financial return. Long-term success of a particular technology comes with the new equipment proving itself operationally.

There have been some great examples of researchers and companies combining resources to develop innovations that capture the imagination of many. For example the Plustech six-legged harvesting machine, subsequently owned by Timberjack (Fig. 2). The walking harvester innovation was designed to overcome the challenge of harvesting on steep, sensitive and or uneven forest terrain, that is, to extend the ability of wheeled and tracked machines[xi]. One goal was to be more environmentally friendly on the forest soils by means of spot-ground contact and hence not leaving a continuous track like wheeled or tracked harvesters. While not robotic in terms of machine operation, it certainly pushed robotic technology within the machine system.

Features developed for the system included the capability to move in all directions; turn on the spot; walk over obstacles; adjust ground clearance depending on the irregularity of the terrain; and distribute its weight evenly on uneven ground. The movement, including speed, step height and ground clearance were all programmed to be operated by joystick. As such the software development that allowed the machine to operate was extensive. While the machine functioned well, it was slow and too expensive for it to be commercially successful. However, the technology development within the project was world-leading.

Figure 2: Timberjack walking forest harvester
(Image sourced from www.theoldrobots.com)

There are examples of higher levels of machine automation that have already been introduced into cable yarders – used for extracting timber on steep terrain. Like most extraction systems they follow a typical pattern of unloaded out, accumulate load, loaded in, and drop load on landing. Two of these phases, unloaded and loaded travel, have been automated, thus removing the need for an operator to be on the machine, or allowing the operator to work with an integrated processor. The accumulation phase is managed remotely by the choker-setter, and dropping the stems on the landing by the processor operator. Both have complete control of the yarder by way of a wireless radio remote,

reducing the number of workers while increasing productivity. Other advantages of the computer control system include being able to manage the rate of acceleration and deceleration, setting top speed limit, slowing down in pre-identified areas of concern, as well as the immediate recognition of a load being stuck. The computer can stop the movement of the carriage in 1/100th if the tension monitoring system detects that a turn is stuck. Conversely an operator is likely to take up to 2 seconds and in that time the machine might be severely shock-loaded. Examples of remotely controlled tower yarders include the KMS 12U[xii] and the larger remotely controlled Valentini V1500[xiii] (Fig 3 - see video[xiv] or [xv]).

Figure 3: Left: KMS 12U is a radio-controlled cable crane. Right: the Valentini V1500 tower yarder. Both have automated carriage movement and can be remote controlled. (Photos: R. Spinelli).

The majority of harvesting ('logging') systems worldwide are, like in Australia, ground-based systems. They can readily be organised up into four distinct activities: (1) felling the trees, (2) extracting the trees; (3) sorting, stacking and loading at the landing; and (4) transportation from the landing to the market destination.

Breaking it down by task

Felling: When robotic harvesting systems are discussed, the most popular concept or image people have is invariably a robotic / autonomous tree felling machine. While the technology elements exist to make this a reality, the software requirements, not to mention the safety and social aspects of having such robots working in our forests, are still in its infancy. In the near future, the opportunity will be to expand remote controlled or tele-operated felling machines.
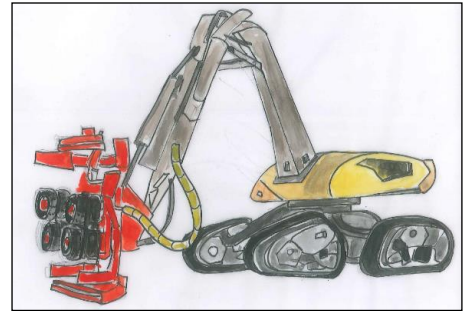
Extraction: The most realistic almost fully autonomous development will be the extraction systems. Agriculture has shown the way for autonomous movement of product from a harvester to a processing or storage area. The technology and control systems for movement in a constrained and controlled environment is mature. However, for such extraction systems to become very productive and cost-effective the clear need is for it to be able to self-load and unload.

Processing: The 'landing' (processing area) is a complex work environment. Cut-to-length (CTL) systems lends itself more readily to robotic unloading, sorting and loading on to trucks. The movement of logs to storage areas is likely to be a longer term project given the complexity of stacking logs. Tree-length systems, where the stems are brought on to the landing, lends itself to some level of automation in terms of quality assessment, including scanning and processing, and subsequent sorting. The design of a readily movable rig to support such operations will be the main challenge.

Transportation: Autonomous trucks for public highways are being extensively developed. Given that forestry trucks don't often need to operate in urban environments, and move between relatively fixed destination of forest to mill (or port), their introduction is likely to arrive sooner than for other industries. If logs are to be moved longer distances using trucks on private, or restricted roads, this will facilitate earlier implementation. Some specific benefits of moving multiple trucks are highlighted.

Near-Future Opportunities (1-5 years)

Autonomous extraction systems

Probably the best, most logical, and the one with the largest commercial machine manufacturing opportunity is the development of an autonomous extraction machine (e.g. Fig. 4). While the machine drawn (from Ringdahl 2011) shows a cabless two-bunk 4-axle 'forwarder', the concept is readily transferable for a grapple skidder as well. Such a 'shuttle' would transport logs (or stems if using a skidder) from the cut-over to a designated processing or storage area ('landing'). Initially it would be expected that the loading is done either by the manned-harvester and or loader in the cut-over, and it would be unloaded again by a loader at the landing. However, unloading and subsequent sorting might also be robotic (see processing). What would be of great advantage, but requiring advanced log recognition software, would be the self-loading boom (Westerberg and Shiriaev, 2013). This would de-couple the shuttle from either the harvester or the loader at the landing. However, a major US review on robotics recognises that, except for in defined and controlled environments, across all applications a major limitation access to gripping mechanisation that allow objects to be picked up (Christiansen, 2016).

Figure 4: Autonomous purpose-built forwarder, including a self-loading (Image from Ringdahl 2011)

It should be noted that while we are describing an autonomous system, nearly all will require the ability to be remotely operated for when the software is unsure about a decision. This might be an object it cannot identify on its chosen path, uncertainty about a log for loading, or simply a log coming off the bunk and preventing it from moving. Tasks that are hard to fully automate may require some supervision – described as being either 'semi-autonomous' or 'continuous assistance systems' (Murphy 2000). Effectively the operator delegates (sub-) task to the machine, but takes over with remote control to overcome difficulties.

While such a system might seem somewhat futuristic, substantial trial work in agriculture has already established the credentials for this development. Based around the idea of precision agriculture and the opportunity to save fuel using the precision afforded by GPS

control, crop farmers have experimented with autonomous harvesting systems since about the 1980s. An example of a working system is the partnering crop harvesters with autonomous tractor-pulled trailers ('carts') (Fig. 5). While autonomous harvesting is still very much a prototype and is GPS guided, the carts will move between the depot area and the harvester. While GPS guides the tractor-trailer back towards the harvester, laser sensors on the cart ensure it remains in the optimum position for loading. This concept could readily be adapted to timber extraction with the shuttle having access to the real-time GPS coordinates of the harvester (and or loader) in the cutover and simply moving towards that machine.

Figure 5: Autonomous carts (tractor-pulled trailers) – they move between
a geo-spatially fixed unloading area and GPS tracker on the harvester.
(Image retrieved from http://robohub.org)

Figure 6 provides details as to how a 'drone' tractor works[xvi]. Key elements include the real time kinetic GPS that allows sub 5 cm level accuracy. This is used to position itself accurately relative to the harvester. Both an automotive radar system and a LiDAR scanner is used to avoid objects. A computer 'brain' is required to operate the systems, but it is noted that the computer is simple and application specific. Camera systems are normally installed to operate the machine remotely when, for whatever reason, the machine stops working.
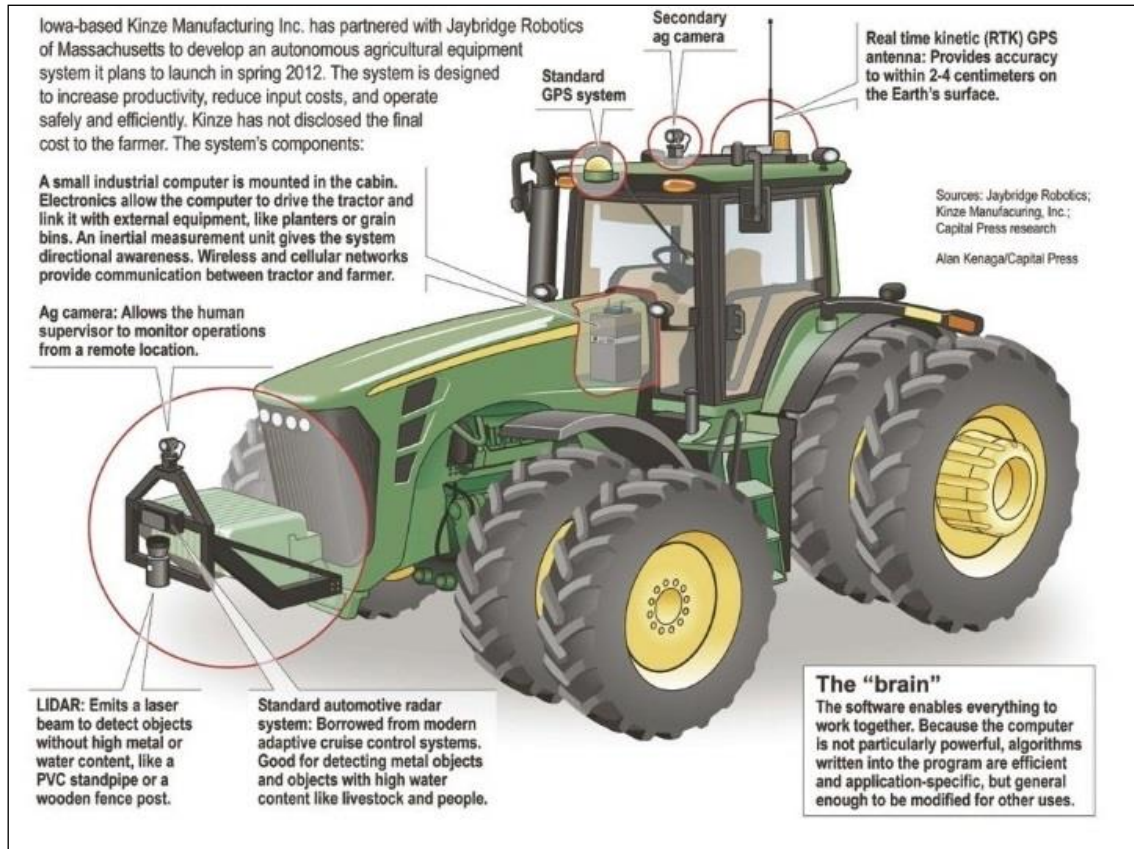
Figure 6: How a drone tractor works" – logical set of components that could readily be applied for autonomous extraction systems.
(Image: Capital Press retrieved from www.country-guide.ca/2015/04/23/here-come-the-farm-robots/46535/)

The logical step for equipment manufacturing is to design the autonomous tractors without a cab. Case IH and New Holland both introduced their new autonomous tractors at 2016 Farm Progress Show[xvii]. Case IH unveiled an autonomous tractor concept that had been developed by combining the latest in tractor engineering and technology (Fig. 7). New Holland showcased their T8 Blue Power tractor that looks like a standard tractor but is an unmanned vehicle that is fully autonomous and can be monitored and controlled via a desktop computer or via a portable tablet interface.

Figure 7: A purpose built autonomous farm tractor
(Source: www.bigag.com/topics/equipment/autonomous-tractors-future-farming/)

There is already an example of such a system working in forestry, with the limitation that it is guided by a wire rope, not GPS. The Konrad 'Pully' is a semi-autonomous / remotely operated ground forwarder (Fig. 8) manufactured with the aim of improving soil conservation and safe downhill hauling on steep slope (Konrad Forsttechnik [xviii]). The Pully runs along a wire rope that connects the steep-slope harvester and the landing / roadside area. The bunk is loaded with processed logs by means of the harvester and needs to be unloaded at roadside (see video[xix]). They are also reported to be progressing on developing a self-loading boom that will automate log pick-up from the ground.

Figure 8: Konrad 'Pully' system that takes logs from the steep terrain harvester down to the roadside guided by a wire rope (photo R. Visser).

Harvesting agricultural crops is typically on relatively flat and obstacle free ground, which is a clear advantage for automation. Forest environments are often characterized by complex paths, with logging residues on the ground surface and highly variable terrain characteristics along the extraction path ('skid-trail'). The task of moving logs from the harvesting site to the roadside requires real-time information of the machine position, the ability to identify and pick up logs, and the coordinates for loading in the forest and unloading at the landing detection and avoidance of obstacles. A group of researchers in Sweden have developed and tested the path tracking capability of an autonomous forwarder in the forest (Ringdahl *et al.*, 2011 – Fig. 9). Using a laser scanner, the machine can identify the forest road and or skid trail. The next step in autonomous forwarder development is for detection of logs on the ground for pick-up.

Figure 9: Valmet 830 forwarder tested for path detection in the forest
(Image sourced from Ringdahl 2011).

An alternative to integrating the path detection onto the forwarder itself is the use of aerial drones. UAV's that are capable of navigating through obstacles in complex environments have been developed that, by deep learning algorithms, navigate through forest trails and trees. A drone called the 'pushbroom stereo' developed by researchers from MIT's Computer Science and Artificial Intelligence Lab (CSAIL) is capable of flying at 50kmh and is able to avoid tree obstacles by means of an obstacle-detection system[xx]. The software developed by the researchers allows the drone to detect objects and build a full map of its surroundings in real-time (see video[xxi]). A group of Swiss researchers from the University of Zurich and NCCR Robotics have also developed the technology that allows a quadcopter drone (Fig. 10) to autonomously navigate a previously-unseen forest trail using the images from its single colour cameras (See video[xxii]). While only in a testing phase, this is an important technological development that can be deployed in autonomous forest machines to efficiently navigate the complex forest terrain[xxiii].

Figure 10: Autonomous forest trail navigating drone – Quadcopter
(Image: www.theverge.com/2015/11/2/9659706/pushbroom-stereo-drone-uav-autonomous-sense-and-avoid)

Remote controlled or teleoperated machines

Remote control or teleoperation of an *existing* machine has the disadvantage that it is invariably harder to control and slower to operate. Opportunities exist that include (a) machine being unsafe to operator with a human in the cab, (b) machines that are not required to operate continuously, or (c) being able to take advantage of operators that would otherwise not travel to forest locations.

A number of forestry machines already have remote control operating systems in place. For example a number of European skidder manufacturers that have a remote control feature (Fig. 11). For operations, this is typically only to reposition the skidder while the operator is out of the cab: for example when pulling out winch rope when setting chokers. While the machine can also be manoeuvred through the forest or along a skid trail, and they are promoted as being quicker and safer[xxiv], no information is available that operating it exclusively as a remote-controlled machine is a commercially viable alternative to operating from the cab.

Figure 11: Operator with controls to remotely operate the skidder.
(Image: www.outofthewoods.eu/news/remote-controlled-skidder-safer-quicker-and-more-productive/)

In New Zealand, as part of a by the Forest Growers Research programme, a tele-operated winch-assisted John Deere 909 Feller-Buncher has been trialed (Fig. 13). While initially the machine was simply remote control, and initial step forward was by providing a video feed for the operator on to the remote control (Fig. 12). The latest development includes a purpose built control booth trailer for full tele-operation (Fig. 14). To provide the operator a sense of terrain slope, the system includes an artificial horizon line and a "head up display" overlaid on one of the screens. This allows the machine to be operated on steep terrain and is commercially available through ATL[xxv]. It has been successfully tested in harvesting operation (Parker *et al.*, 2016) and has also been partnered with a winch-assist system. With the operator taken out of the cab the system can be pushed onto steeper slopes, but the remote control systems in itself does not improved stability and tractability on steep slopes[xxvi].

Figure 12: Purpose built remote control design that includes live video feed (Photo: P. Millikan)

Figure 13: Remotely controlled felling machine developed within the scope of FGR, with the operator in line of sight. (Photo: FGR / ATL)
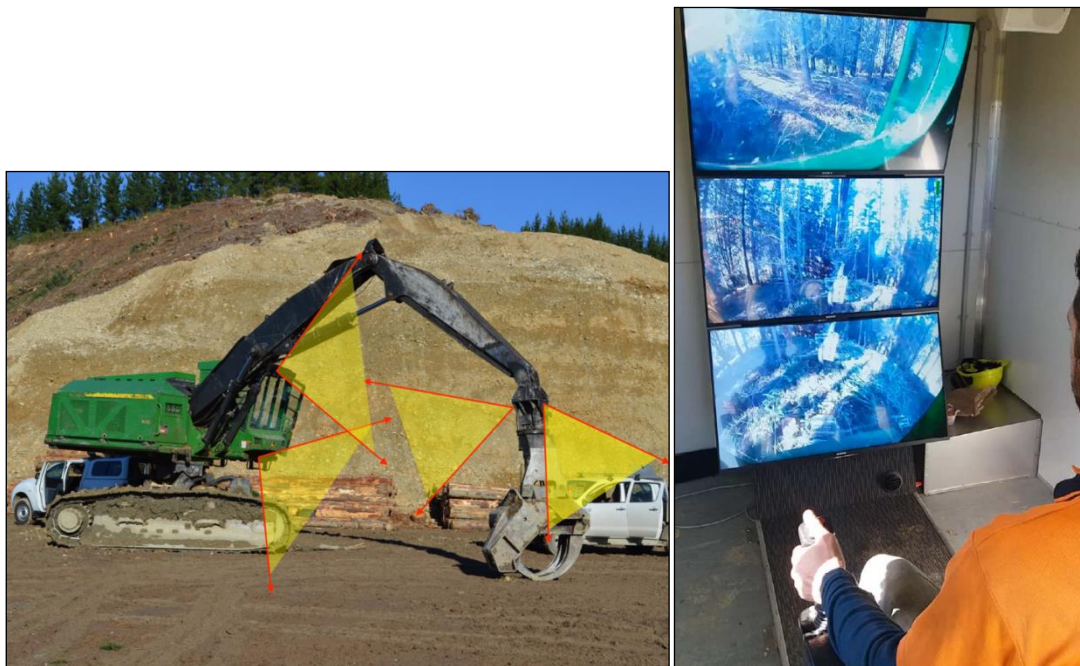

Figure 14: Left: JD909 showing camera angles to enable tele-operation. Right: purpose built trailer where the operator has the standard operator seat and controls, plus video screens.
(Image: K. Raymond and ATL)

Larger specialist companies are also involved in retrofitting machines with remote control or tele-operation. Applied Research Associates (ARA) is an entity involved in tele-operating off-road vehicles to work in complex or difficult working environments. They have developed tele-operation technology relevant to the automation of forestry operations named Modular Robotic Appliqué Kit (M-RAK)[xxvii]. Similarly to the FGR / ATL tele-operation

development, the M-RAK Operator Control Unit provides video of both the operation and the surrounding environment in the range of about 2.4 km. An application of the M-RAK in the field of forestry is the tele-operated-controlled Caterpillar 521B feller-buncher used at the Fort Bragg army site to clear timber on firing ranges without putting the workers in danger (see video[xxviii]). (Fig. 15).

Figure 15: Robotic-controlled Caterpillar 521B Feller-Buncher
(Image sourced from www.youtube.com/watch?v=Ys5QuJ6jaV0)

While the conversions mentioned above are for actively working machines, in forestry we also use machines that are primarily stationary and only need to be move sporadically. In this situation an operator is highly underutilised and remote control makes immediate sense. An example is the ATL remote controlled mobile tail hold used in cable logging[xxix]. The concept is that the yarder operator is able to move the tailhold (Fig. 16) using simple control and a video feed. This removes the need for a machine operator to be near the tailhold machine that might be stationary for hours during extraction, or avoid the delays associated with having an operator travel to the machine simply to move it.

Figure 16: Excavator being used as a mobile tailhold.
(Photo: P. Millikan / ATL).

Retrofitting an existing machine with remote control adds cost. For machines that really only need to be remote controlled, significant savings can be made by designing purpose built equipment. A cab on forestry equipment, with all the connected control systems, will typically add approximately $100k to $150k to a modern machine cost. Using the old rule-of-thumb that hourly operating costs are 0.03% of capital cost, being cables would present at least a $30 per working hour saving (or $1200 per week). One system that has encouraged designers to consider a cabless machine can be found in winch-assist. Both the Canadian made T-Mar LogChamp 150 and the German made T-Winch are machines that acts as both an anchor as well as powering a winch that supports operating a felling / shovelling / extraction machine on steep slopes (Fig. 17). While 'working' this machine can be expected to be stationary for extended periods of time and as such it has little need for an operator or cab. As the machine on the slope comes up, that operator can move the winch-assist machine without exiting their cab. While this presents an operation advantage, the main advantage is in the capital cost saving for the machine itself.

Figure 17: Both the T-Mar LogChamp150 and T-Winch winch-assist machines are constructed without a cab and can only be operated remotely. (Photos: J. Hunt)

Robotic processing or handling on the landing

Nearly all harvesting operations extract timber from the cut-over (in-forest) to a designated processing and or storage area for subsequent transportation to market. Two primary reasons: (1) are that our in-forest extraction systems are not suited to higher speed larger load for on-road transportation, and conversely our on-road trucks are not suited to in-forest condition, and (2) multiple products (log sorts) are being derived from trees that typically require sorting and stacking, and for tree length extraction systems processing into logs in the first place. A landing is a defined and relatively small work space. Many of the activities are relatively simplistic in terms of mechanics (unloading, stacking, and loading), or simple in terms of task (processing, sorting). The new FGR programme, which is a consortium between the NZ Forest Industry and the NZ Government, is focussing on processing at the landing. A typical NZ logging operation will convert the extracted stems into over 15 different log grades. While companies justify the approach with regard to maximising the value recovery, it is costly, constrains the operation and is often the bottleneck. A robotic landing operation vision put forward in the new proposal is illustrated in below (Fig. 18). It contains

robotic elements of scanning and sorting along a conveyer belt, as well as ideas for automated truck loading.
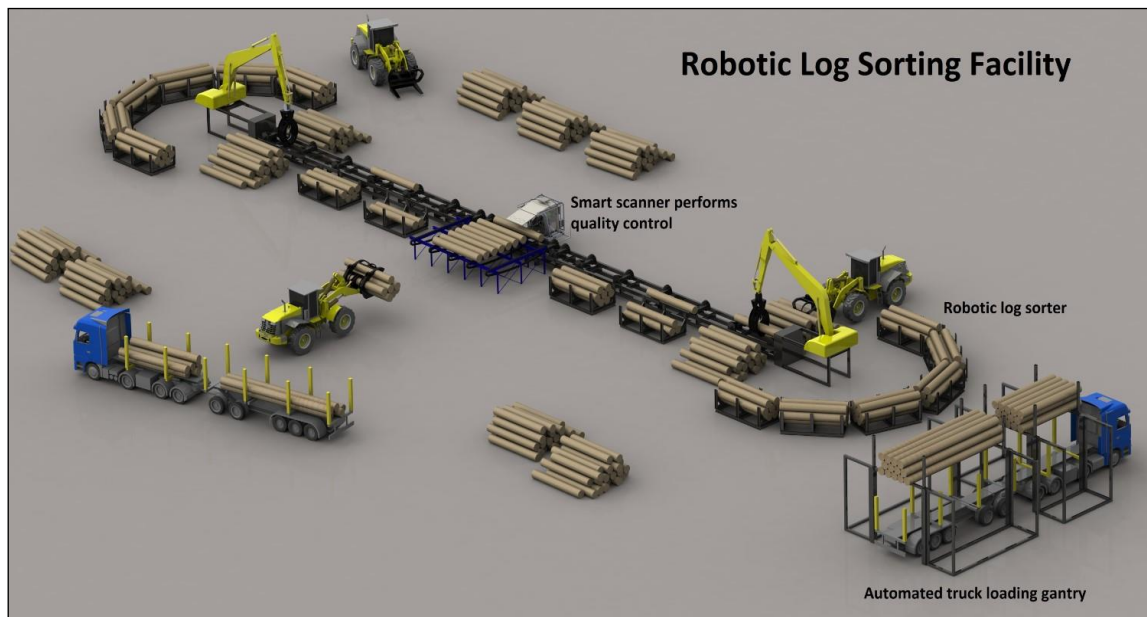

Figure 18: Vision for a robotic landing system to be developed in the 2018-2025 FGR programme.
(Image provided by Raymond / FGR)

FPInnovations' Transport and Energy group initiated a project in 2016 to evaluate possible applications of autonomous vehicles, including their use in mill yards[xxx]. A proposed configuration for the project could be an autonomous vehicle remotely-operated and equipped with proximity detection and alert technology (PDAT) systems, and anti-collision and anti-roll systems performing monotonous task of mill yard transportation. The goal is to optimize mill yard logistics and improve productivity, reduce labour costs, and increase worker safety. For systems dealing with multiple tree species, the University of Laval is working on a computer vision species identification system based on the bark of the tree.

In terms of supporting the concept of being able to load and unload autonomously on a landing site, one relevant example may be the driverless truck technology used in urban waste collection (Fig. 19). In 2017 the Volvo Group, in conjunction with Swedish waste and recycling specialists Renova, began the testing of a pioneering driverless or autonomous refuse truck that has the potential to be used across the urban environment[xxxi]. The truck drives along a pre-programmed route; the operation of the truck including gear changing, steering and speed are constantly optimised for low fuel consumption and emissions. The autonomous refuse truck being tested is fitted with navigation, and guidance technology similar to those used in the autonomous truck for mining operations[xxxii].

Figure 19: Volvo autonomous self-driving refuse truck, illustrating a machine can identify defined object and pick them up.
(Image sourced from: www.volvogroup.com/en-en/news/2017/may/news-2561936.html)

A specific example of being able to move in confined spaces and a more complex working environment is the Volvo FMX (Fig. 20) operating deep underground in a Swedish mine, where it regularly covers a distance of 7 kilometers, 1,320 meters below the earth's surface in the narrow mine tunnels[xxxiii]. The truck is equipped with numerous laser sensors including GPS, radar and LiDAR, and it is able to continuously monitor its surroundings and avoid both fixed and moving obstacles in narrow environment. In the event that an obstacle is detected, the truck is able to stop and contact its control centre (see video[xxxiv]). Furthermore, an on-board transport system gathers data to optimize and coordinate the routes in the mine and fuel consumption. The truck is expected to substantially increase productivity for mining companies due to the fact that it needs no rest and is able to work round the clock, but no time study data is provided to support this claim.

Figure 20: Volvo FMX fully autonomous truck operating underground

(Image: www.volvogroup.com/en-en/news/2016/sep/news-2297091.html)

Autonomous transportation systems

Road transportation of harvested logs is often identified as an aspect of forest operations for improved productivity in the wood supply chain. Developments in the driverless truck technology is growing and rapidly changing with the benefit that autonomous trucking reduces labour requirements and hence costs. Intelligent haulage trucks remotely connected and monitored real-time are now in use in different industries requiring long haulage of products[xxxv]. A number of truck manufacturers claim to have perfected the driverless truck technology for full deployment on highways along. Although the use of intelligent trucks is expected to revolutionize productivity in forest product transportation, its use is yet to materialize in the industry. The primary issue for implementation of autonomous trucks is more a social consideration of driverless vehicles sharing public roads with commuters. While the primary concern is often linked to safety, the greater issue is simply the irrational fear of sharing the road with a robotic vehicle.

For truck movement off-public highways, autonomous vehicles have already been developed and deployed in mining operations. As such, the extension to the forest industry should be realistic. There are many manufacturers that have developed off-road industrial transportation systems including Caterpillar, Hitachi and Komatsu[xxxvi]. These trucks are equipped with high level navigation and guidance, and obstacle detection systems enabling them to move seamlessly from one point to another in a repetitive manner to accomplish the task of moving materials (Fig. 21).

Figure 21: Hitachi autonomous haulage truck operating in an open-cast mine.
(Image sourced from www.youtube.com/watch?v=c9_Os6Ha-Gk)

Given that most logging trucks move from forest to a mill or port facility, the concept of platooning may provide an opportunity for increased efficiency. 'Platooning' involves a driven truck being followed by 'slave' truck(s) that follow the exact path of the driven truck (Fig 22). The platoon of trucks is synchronized and simply share positional and driving information from the lead truck. The platoon trucks shown are only semi-autonomous thus requiring a human driver to take over when the connection is disengaged. In addition to not needing drivers for the slave trucks, trucks can travel closer to each other than would be possible with human drivers. This offers advantages including improved safety and increased fuel efficiencies. Peloton, a truck manufacturing company, reports a combined fuel efficiency savings of 7 % for two trucks platooning (Fig 23). This technology is already in its

developmental stages in Singapore by Scania Group and Toyota with the goal of transporting containers from one port terminal to another with fully automated docking and undocking of cargos[xxxvii]. A more advanced form of platooning is to have a platoon of fully autonomous or driverless trucks on the highway traveling very close to each other.

Figure 22: Concept of platooning with sensors simply keeping the following (slave) trucks at a specific distance. (Image sourced from www.scania.com/group/en/gearing-up-for-platooning)
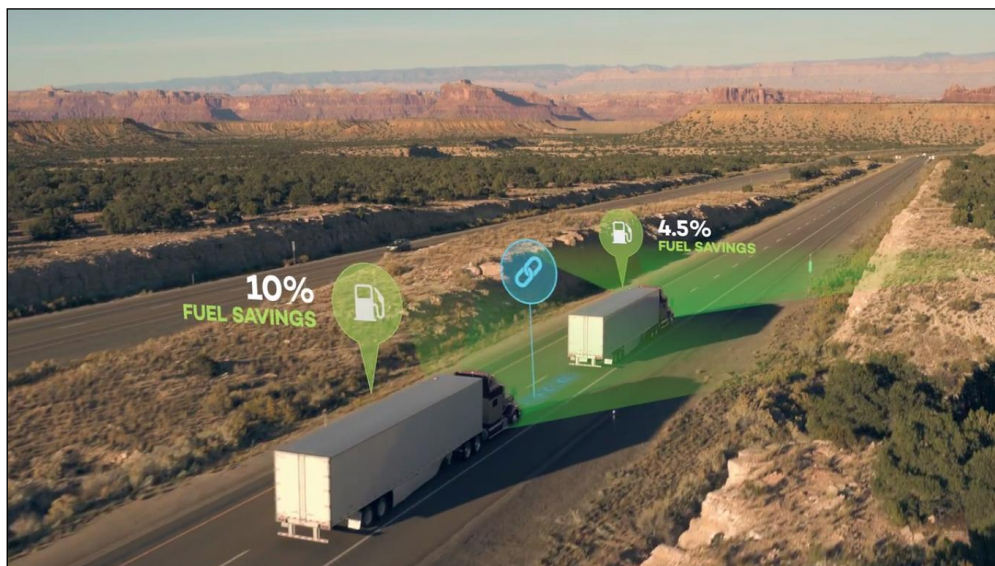
Figure 23: Study showing a potential fuel savings of 7% when two trucks can move together with only a short distance between them.
(Image sourced from www.futuretrucking.co.za/scania-takes-platoon-lead)

Longer-term Opportunities (5-20 years)

Autonomous / remote controlled felling systems

An early example of a commercially available remote controlled harvester is the 'Besten' developed in Sweden (Bergkvist et al., 2006). This system consists of a cabless harvester controlled remotely and used in conjunction with one or two forwarders (Fig. 24). While many publications are available on the potential benefits for productivity and even fuel consumption[xxxviii], in reality machine productivity was always significantly lower and it was never a commercial success[xxxix].

Figure 24: The 'Besten' harvester, shown on the right being operated by the harvester operator, was the first remote controlled tree felling system (photo: R. Visser).

For autonomous harveters to become reality, they must be able to identify individual trees (i.e. from people). Oregon State University, supported by the US Forest Service, has been developing a tree identifiction vision system. Mounted on a harvester, the stero camera systems detect and measure trees in real time with the accuracy of a laser finder (Fig. 25). The first application is real-time cut-tree selection and stem mapping (inventory) during thinning operations. This technology is currently intended to remove pre-harvesting tree-marking and post-harvesting inspection, but can eventually provide 'eyes' to harvesting machines enabling them to be fully autonomous in terms of 'thinking', 'controlling' and 'movement' (Wells and Chung – pers comm 2017).
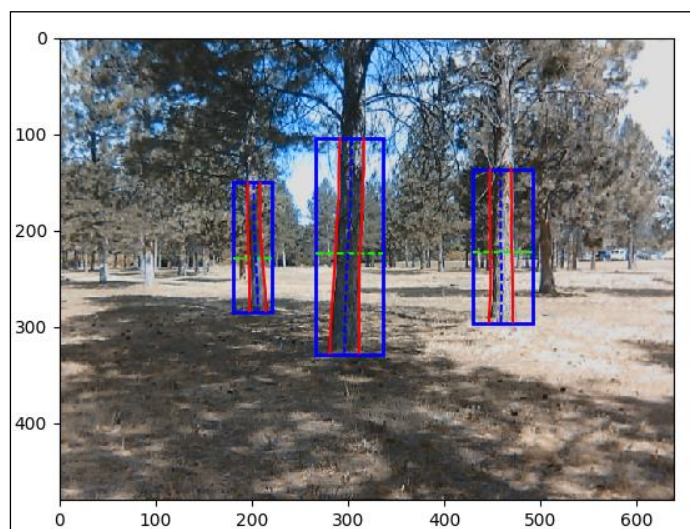
Figure 25: Output from the OSU / USFS tree identification vision system. (Image provided by W. Chung)

One option to consider for harvesters that might bring more immediate advantages can be seen in farm work such as ploughing or harvesting crops in agriculture. It relies on one standard machine (i.e. tractor or crop harvester) being operated, and then multiple 'slave' machines follow at a fixed distance and spacing (Fig. 26). For example, if a feller-buncher is felling a row of trees, two or more machines could fell in tandem working on well-defined rows of trees. They would only need to identify the stem, cut and place them, but overall movement in the stand would still be defined by a human operator in that it would not operate if it lost its proximity.

Figure 26: A manned tractor, partnered with an autonomous 'slave' tractor, scarifying the soil.
(Image sourced from www.interempresas.net/Agricola/Articulos/61084-Fendt-inunda-FIMA-de-innovaciones-tecnicas-a-bordo-de-su-nueva-serie-700-SCR.html).

Ideas for the Future

The tree-to-tree 'swinging' harvester

Scion in conjunction with relevant forest industry partners in New Zealand is developing a conceptual tree-to-tree 'swinging' forest harvesting machine[xl] (Fig. 27). The remotely controlled tree-to-tree locomotion machine was built by Scion and the University of Canterbury Mechanical Engineering and Mechatronics students with funding from industry partners. Although in its developmental stage, the intention is that the machine could operate independent of the terrain condition (steepness, roughness, etc.) by staying above the ground moving from tree-to-tree using the trees for support, reducing soil disturbance. Instrumentation and software that could offer better control for the machine are under development, as are machine sensors to measure tree diameter and custom-built saws for felling.

Figure 27: Tree-to-tree 'swinging' forest harvester (Source: Parker et al., 2015)

BARBRO – autonomous harvester

A very futuristic concept developed for a harvesting machine has also been put forward by Fredrik Ausinsch from the Umeå Institute of Design[xli]. The electric machine has four wheels for motion within the forest, but each wheel has an embedded felling claws that also allow the machine to propel itself through the forest simailry to the tree-to-tree swinging harvester presented above. It can then fell using its arms to stabalise itself, but revert to wheeled motion to move between trees.
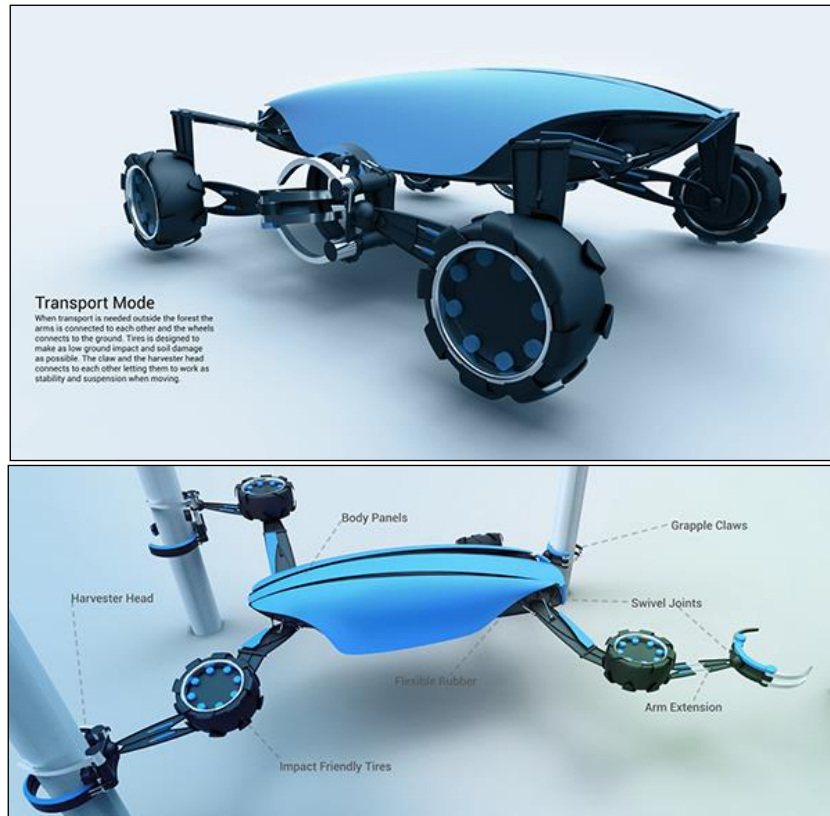
Figure 28: Futuristic harvester design that has wheeled motion when traversing the site (top), but stretches out to grab and fell trees with claws (bottom).
(Images sourced from www.behance.net/gallery/20374037/BARBRO-Autonomous-Harvester)

Planting and Silviculture

With regard to both the mechanics of planting a tree and micro-site selection, tree planting is a complex task. Some mechanised planting units are commercially available but typically only for relatively homogenous terrain, and in most cases not commonly used because of lack of success. However, some ideas and test equipment have been developed for autonomous planting, little real progress has been made. One example of a working tree-planting robot prototype was developed by the University of Victoria in British Columbia, Canada[xlii] (Fig. 29). Currently just remote controlled, it is moved around a site and seedlings are pushed into the ground. No additional information is available on its success.

Figure 29: Tree-planting robot.
(Source: http://vancouversun.com/news/staff-blogs/robots-are-coming-to-work-is-a-guaranteed-income-far-behind)

An even more futuristic design is available from a blog by Anna-Karin Bergkvist [xliii.] The idea is to use a specialised planting arm with rotating head to put the seedlings into the ground (Fig. 30). The seedlings are in their own pods, with the machine designed to carry 320 seedlings in one load.
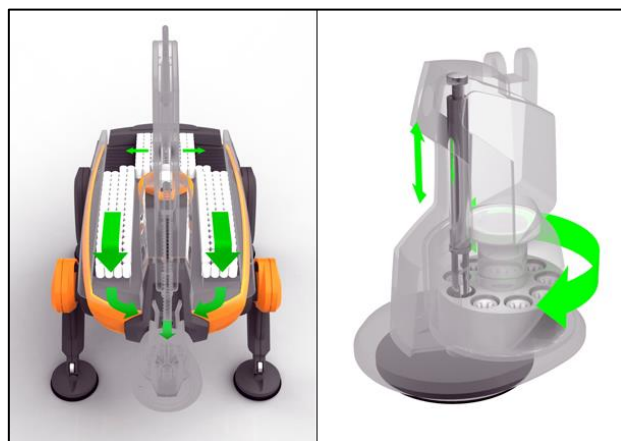
Figure 30: Futuristic tree planting robot, with some level of mechanical detail provided in the sketches on the right. (Images sourced from http://pixgrove.blogspot.co.nz/2010/09/tree-planting-robot.html)

Another concept proposed for planting is using aerial platforms (drones). While there are quite a few proponents of such a system, to date only seeds have been sown from drones. One example of the concept is shown as 'UAV Planting Trees'[xliv] that would both plant the seedlings by dropping them in cone-shaped holders from height, while also potentially applying a fertiliser (Fig. 31).

Figure 31: Concept of planting using drones.
(Image sourced from www.uavcropdustersprayers.com/uav_planting_trees.htm)

In terms of pruning trees, motorised climbing tree pruners have been developed. They typically incorporate a rotation climbing mechanism with a small vertically mounted chainsaw. While it is possible to design such a machine that will climb and delimb (normally using a vertical chainsaw), it is onerous to move from tree to tree and very difficult to retrieve if it loses power while up the tree. None have not had any commercial success. One example of a new lightweight development is the tree pruning robot prototype[xlv] built by Ishigure, Hirai, and Kawasaki from Marutomi Seiko Co. and the University of Gifu, in Japan. The 13 kilogram machine is reported to climb straight up any tree between 6 and 25 cm in diameter at a rate of 0.25 meters per second (Fig. 32). There is no further information with regard to its successful implementation.

Figure 32: Tree pruning robot prototype.
(Image sourced from: www.electronicproducts.com/Electromechanical_Components/Remote-controlled_tree_climbing_chainsaw-wielding_robot.aspx)

Smaller scale, but directly relevant to pruning from below, is a vineyard pruning robot (Fig. 33). This system is commercially available[xlvi], is reported to work up to 12 hours on batteries, can climb slopes up to 40%, while mowing and pruning the vines. In addition it accurately measures vines and grape yield and transfer the georeferenced data back. It would need significant scaling up to be suitable for pruning, however it is conceivable that it may be better suited in forestry to spot-clearing around seedlings, or delivery spot fertiliser.

Figure 33: Vineyard robot; mowing, pruning and measuring.
(Image sourced from http://wall-ye.com)

A larger scale machine built as a prototype is a citrus picking machine[xlvii]. As shown in the Figure 34, the machine still has an operator but sensors on the arm identify and pick the fruit. Modifying the concept to identify and cut branches on a trunk, and making the movement of the machine autonomous guided between rows of trees.

Figure 34: Automated citrus fruit picker.
(Image: www.gizmodo.com.au/2015/02/13-fascinating-farming-robots-that-will-feed-our-future/)

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