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THE FUTURE OF ROBOTICS IN SILVICULTURE

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ABSTRACT

Forestry is a major contributor to Canada's gross national product. Canada is committed to the concept of sustainable development for its forest resources to ensure that the economic, social and ecological benefits accruing from our vast forest land will be enjoyed by Canadians in perpetuity. To achieve these goals, it will be necessary to increase the intensity of silvicultural operations in our forests. It is unlikely that we will have the necessary manpower to carry out the operations, or that intensive manual operations will be economically practical. Thus, we must look at the potential for the use of automated or semi-automated machinery or robotic systems to carry out these intensive operations in a cost-effective manner. Some silviculture operations which might benefit from robotics and artificial intelligence are described. Some of the potential problems, possible solutions and research areas are elaborated.

I. INTRODUCTION

Forestry has always been a key component of Canada's identity. More than 450 million hectares of forest covers nearly half of its total landmass. About two thirds of this is boreal forest, and it accounts for about 40% of the world's total. Nearly 900,000 Canadians are employed in forestry related jobs. Canada provides over one-fifth of the world's trade in forest products, which represents 17% of our total exports (Forestry Canada, 1990).

Our relationship to our forests has changed dramatically since the first European settlers arrived in Canada in the mid-1500s. Initially, the forest was viewed as a source for fur, later as an impediment to transportation and settlement, and over the past 150 years as an important source of wood products. Until fairly recently, mankind has behaved as if all the world's natural resources were unlimited. Canadians tended to view their forest resources as limitless.

Within the past few decades, Canadians have begun to realize that, as vast as our forests may be, they do not represent unlimited resources. With this realization, the Canadian government, through the passage of Bill C-29, the Department of Forestry Act (1989), has made a firm commitment "to promote sustainable development and competitiveness of the Canadian forest sector for the well-being of present and future generations of Canadians." This means that we are determined to ensure that our forests will meet current needs without prejudice to their future productivity, ecological diversity and capacity for regeneration.

For the past few decades, there has been pressure on those harvesting timber from our forests to replace the trees cut. The result is that about a billion new trees are planted each year in Canada, covering about half of the areas harvested. Of course, in many areas, planting is not required since natural regeneration is adequate. Attempts are usually made to visit the plantations after about five years to ensure that the new trees are becoming established. If this is not the case, under ideal circumstances the area is replanted. For the majority of the new plantations, this is the extent of silvicultural treatment until the area is again harvested. Some areas (especially those privately owned) are receiving more intensive care. Treatments may include herbicide spraying, manual cleaning or brushing, pre-commercial thinning, pruning and commercial thinning. The productivity of areas receiving this more intensive treatment will be considerably higher. However, except for the application of herbicides, most of the operations are currently very labour intensive. Not only does this make the operations economically difficult to justify, but even if it were affordable, Canada would not be able to field enough people to treat all the forests. The long term solution to this problem is likely to be through the application of robotics and artificial intelligence technology.

II. SILVICULTURE

Silviculture, is defined as the theory and practice of controlling forest establishment, composition and growth (Smith, 1962). This deals with the technical details of crop production, and the laws underlying the growth of single trees and the forest at the biological unit. At Forestry Canada, in collaboration with the Forest Engineering Institute of Canada (FERIC), we are just beginning to investigate the potential role of robotics technology coupled with image analysis, machine vision, neural networks and expert systems in some labour intensive silvicultural operations.

In Canada, as elsewhere, robotics in forestry has generally focused upon milling and processing, with some movement into the woods operations for logging and harvesting. Most developments have been aimed at teleoperated equipment, or equipment with computer assisted controls to improve the efficiency of manual controls. Thus, the major efforts have been to add high technology assistance to proven machines (Courteau, 1990).

The operations described in this paper represent some that are normally performed manually or manually with some machine assistance. We expect that any projects undertaken at the Petawawa National Forestry Institute (PNFI) will be related to the machine vision (image processing and analysis) and artificial intelligence (expert systems) aspects of a total solution. We expect that any machinery used in our programs will be developed or acquired by FERIC, in cooperation with industry. The silvicultural operations we have examined are described briefly, highlighting potential opportunities for robotics and/or artificial intelligencd (AI).

Biotechnology (embryogenesis). One of the biotechnological methods for improving the productivity of forests is through the cloning of trees which have demonstrated superior rates of growth, efficiency in the use of nutrients and/or disease resistance. Thousands or even millions of genetically identical trees can be grown from a single seed. The technique involves growth of clones of proembryo from zygotic embryos of seeds from trees known to have the genetic quality desired. Using special media containing appropriate hormones, a callus containing proembryo is grown. Every several days, the callus is divided and allowed to continue to grow. To create seedlings, small nodules, called somatic embryo, are separated from the callis and planted in a new medium which promotes the growth of an embling, which is essentially the same as a seedling. Current techniques require the manual separation of each somatic embryo from the callus and placement in new growth media on a petri dish. This operation is performed using tweezers under a microscope. It is a tedious operation which, we believe, could be automated using computer vision and robotics. The process of planting the emblings in growth media in nurseries might also be automated. Before undertaking work in this area, one should realize that, for some agricultural crops, techniques have been developed to separate the somatic embryo from the callis using liquid chemical techniques. Some progress is also being made in encapsulating these to produce artificial seeds, which are much easier to handle and store.

Seed Orchards. Another, more established method of improving the productivity and disease resistance of trees is by the selection of superior specimens and crossing these with other specimens with desired qualities. Once the high quality breeding stock of trees has been selected, it is necessary to collect the seeds these trees produce. To do this, at least for coniferous trees, branches from superior trees found in the woods are grafted onto vigorous young stock planted in the orchard. This results in rapid cone production on trees of a convenient height and location from which mature cones can be picked. Seed orchards could

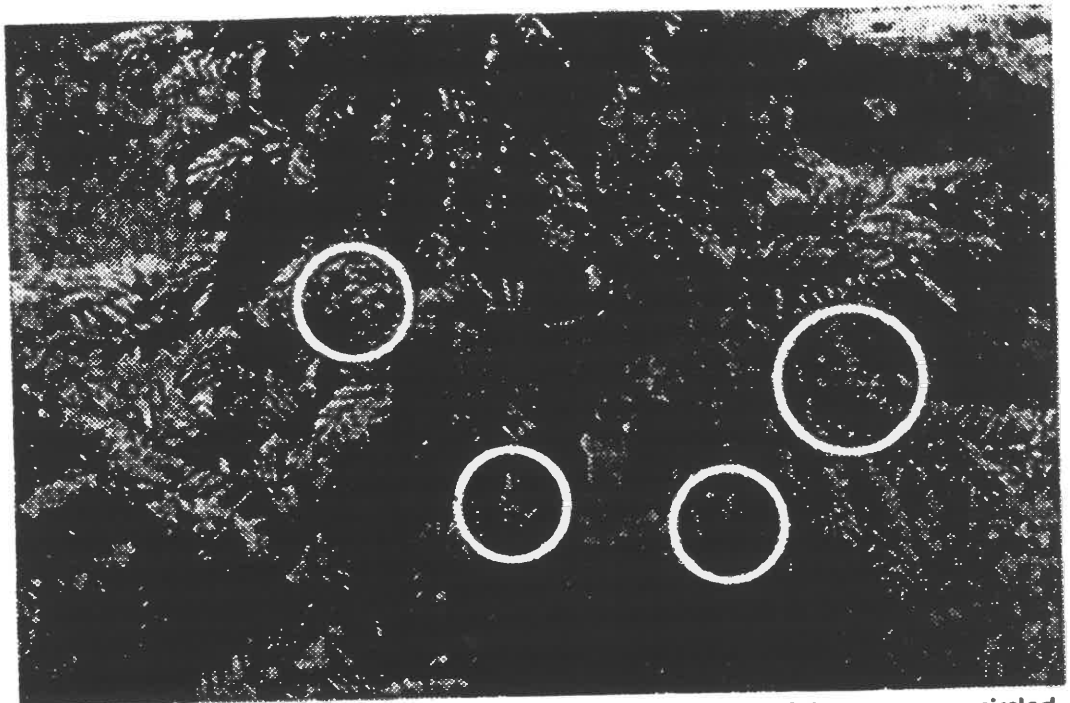

Figure 1. Photograph from J. D. Irving Tree Orchard. Some of the cones are circled.

also be developed from the clonal trees developed through biotechnology as described above.Figure 1 illustrates a typical situation in a tree orchard. We believe that some of the robots that have been developed for harvesting fruit, such as oranges (Tuttle, 1983; Harrell et al., 1990), could be adapted to this operation. Although seed orchards will continue to be important for the next five or ten years, it is possible that embryogenesis could make them obsolete in the future.

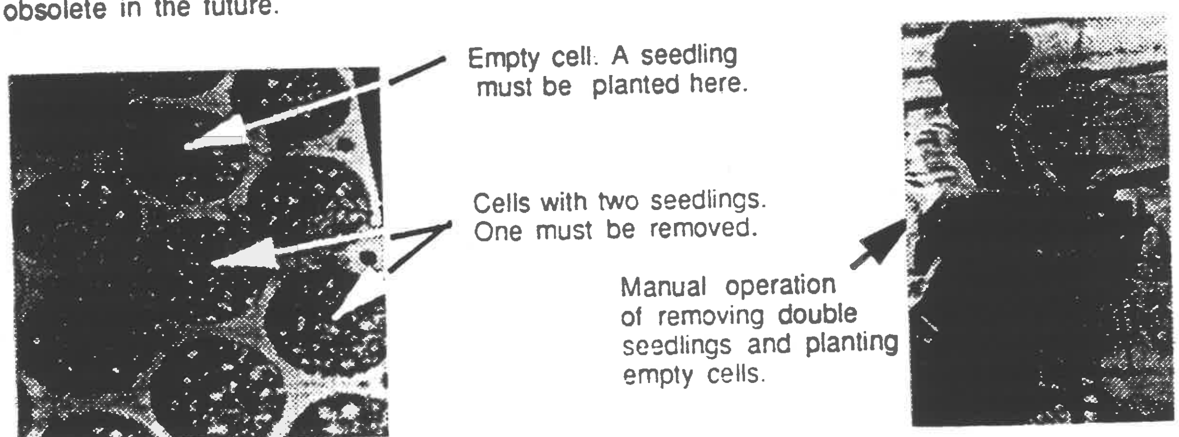

Figure 2. J.D. Irving Tree Nursery Operations, Juniper, Nova Scotia.

Greenhouse. In a typical greenhouse operation, in preparing seedlings for plantation, seeds are planted in specially prepared soil in containers. To compensate for the fact that not all seeds will germinate, more than one seed is planted in a certain percentage of the containers. This depends on the particular species, but a typical amount may be about 10-15%. The result is that a flat of containers will eventually have some slots with no seedlings while others will have two seedlings, as shown in Figure 2. In a very labour intensive operation, one seedling is removed from all those cells containing two. From the seedlings removed, some are selected to populate those cells where the original seeds failed to germinate. It should be possible to use machine vision to identify those cells with zero one and two seedlings, and robotic techniques to remove the duplicate seedlings and to refill those cells which are empty. This operation will be required whether the mechanism for generating the seedlings is from natural seeds or the emblings produced by embryogenesis.

Site Preparation. Prior to the planting of new trees following a harvest, it is generally desirable to perform some site preparation. This may involve prescribed burning to remove the debris left from the harvest, to destroy competitive vegetation, and for some species, to enable the seed to germinate. Another site preparation method often used to prepare the soil for the new trees is scarification, which is roughly comparable to ploughing in agriculture. Both of these operations are fairly straightforward and we do not see any strong need for robotics in this area, although Artificial Intelligence is a tool which could be used to help foresters to make the best decisions regarding site preparation. Expert Systems for planning prescribed burning have been developed at PNFI and the Forestry Service of the U.S.D.A.

Tree Planting. While many seedlings are planted manually in Canada, mechanical planting is also used extensively, especially in nurseries. The operation is to simply prepare a hole and drop the seedling into it. The operation is similar to that of a seed drill in agriculture, however, the task is much more difficult. .In agricultural seeding, a small trough is created using a plow blade. Seeds are dropped into the trough at regular intervals, the spacing determined by the crop type. The trough is then covered by a second blade following behind. In forestry, the terrain is much more rugged. Seedlings rather than seeds are planted, as this has been found to much more reliable for regenerating the forests. Thus, the depth of each hole is much greater (about 15 cm). Sweden has the most sophisticated planting machine we have seen in operation. It uses a weed-eater action to clear weeds and grass from the planting site and a probe to test the suitability of several locations at approximately the correct distance from the last tree planted (usually 1.5-2 meters depending upon the species). If a location with sufficient depth of soil is found, a hole is created and the seedling dropped into it. If not, the machine simply drops the seedling on the ground and moves on to the next spot. Potential improvements in this operation are obvious. One could use sensor techniques, such as electromagnetic, microwave and/or acoustic, to create an "image" of the subsoil and to determine the best possible location for each seedling. It would require some significant research to determine the appropriate sensor and analysis techniques as well as the best decision rules to be applied.

Cleaning, Weeding, Brushing, Pre-Commercial Thinning. Following the harvest of a tree crop, in concert with the philosophy of sustainable development, a new forest must be generated. This might be through natural regeneration or planting of seedlings. Regardless of the method, to obtain a healthy, vigorous and productive forest, it is usually most effective to remove competing vegetation to give the most desirable trees the greatest potential to survive and to thrive. In most areas of Canada, the "best" trees are coniferous. The particular species or groups of species depends upon a wide range of factors. However, these are generally well known to professional foresters and the rules could be easily codified for use by Expert Systems. One treatment which has a low labour cost and which is generally considered to be exceptionally cost-effective for coniferous plantations is the use of herbicides. These selectively kill deciduous trees and broad-leafed brush and weeds, allowing the maximum of sunlight to reach the seedlings. However, there is increasing concern about the effect of continued use of herbicides on the environment. Thus, in many jurisdictions, we see mounting pressure to eventually ban the use of these chemicals.

A much more environmentally friendly way of dealing with the problem of vegetation competition is to cut away the unwanted plants using a device similar to a "weed-eater", such as in Figure 3. The cut material is left lying on the ground. Eventually, it will provide added nutrients to the soil for the trees which are being selected as desirable. From the operational point of view, there is little difference between "cleaning", "weeding", "brushing"

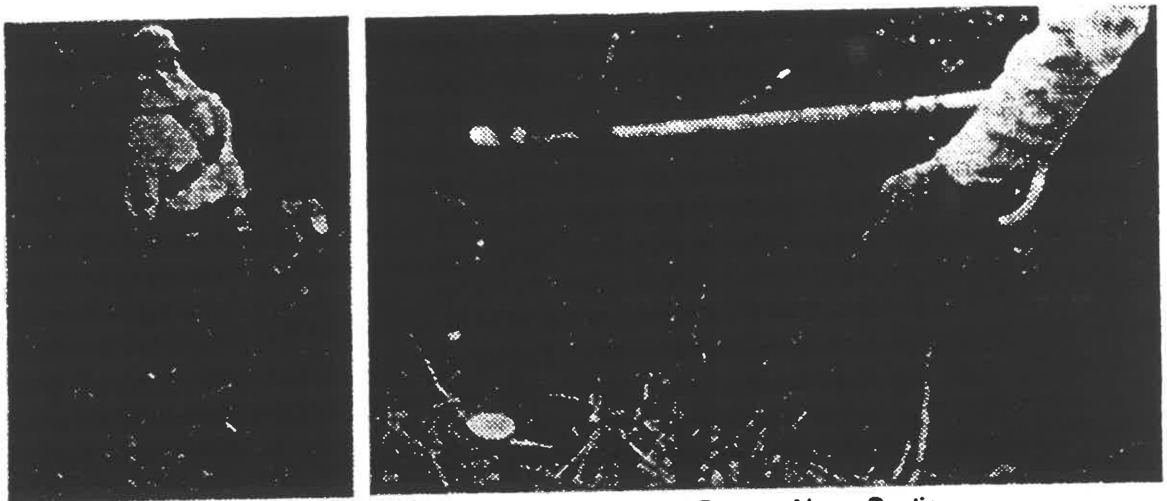

Figure 3. Manual Thinning in Cape Breton, Nova Scotia

and "pre-commercial thinning". Essentially, the trees which are considered to have the greatest potential value are preserved at a spacing which will result in optimum long-term growth. All the remaining vegetation which could impede the growth of the selected trees is cut and left lying on the ground. Ideally, the cleaning operation should be carried out every year or so as needed to ensure that the desired trees will be "free-to-grow", i.e. until the trees are so well established that competitive vegetation will be unable to inhibit their growth. At the very least, this should be done by the fifth year. By the fifth to tenth year, depending upon the intensity of previous efforts, pre-commercial thinning should be carried out to ensure that selected trees are spaced sufficiently far apart to ensure maximum yield for the stand at maturity. This will involve cutting away any undesired trees which could offer competition or which could make eventual harvesting more difficult, and the selection of the "best" tree in the case where two or more desirable specimens are too close to each other. Often, it is desirable to plant the trees with a 1.5-2m spacing to control their form. However, a 3-4 meter spacing is required later to prevent stagnation of the forest.

This class of operations is very labour intensive. Figure 4 shows two machines which can improve one person's productivity by a factor of about five.

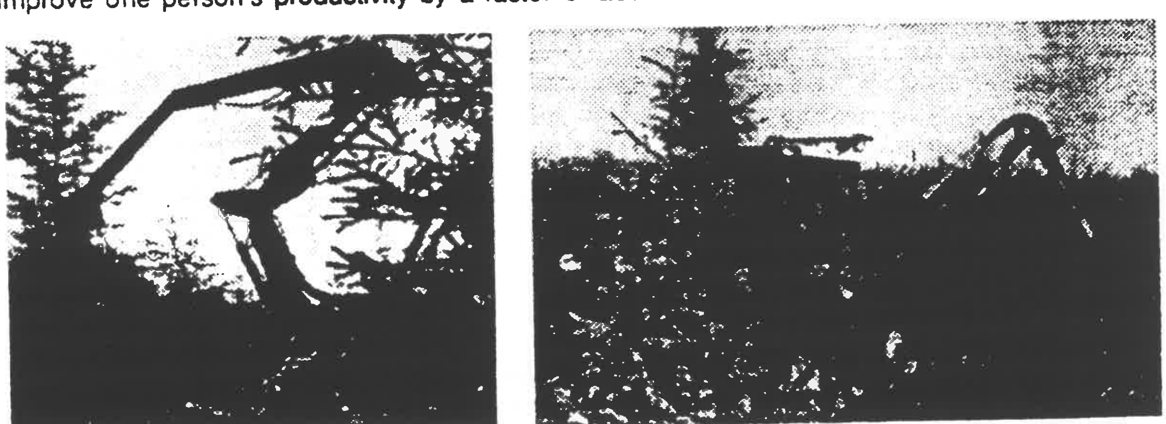

Figure 4. Cleaning, Thinning Machines Based Upon Swedish Technology Operating in Eastern Canada

Depending upon the density of the vegetation, which might typically vary from 30,000 to over 100,000 stems/hectare in the eastern boreal forest, one person can clean or thin one to five hectares per week using the motor-manual method shown in Figure 3.. The cost ranges from about $650-1,000 Canadian per hectare. This operation has the greatest potential for the application of robotics and AI technology. Some work in developing machinery to improve the efficiency of this class of operation has been done in Sweden. FERIC has been following this work with great interest, and through their efforts, much lower cost systems are being developed. The cutting blade, which is the same on both examples, is a disk with four roughly triangular blades as shown in Figure 5. The blades are protected from rocks by guard teeth as shown. After one surface of the blade becomes dull or chipped, it is rotated one position. After all three cutting surfaces become too worn, a new set is installed.

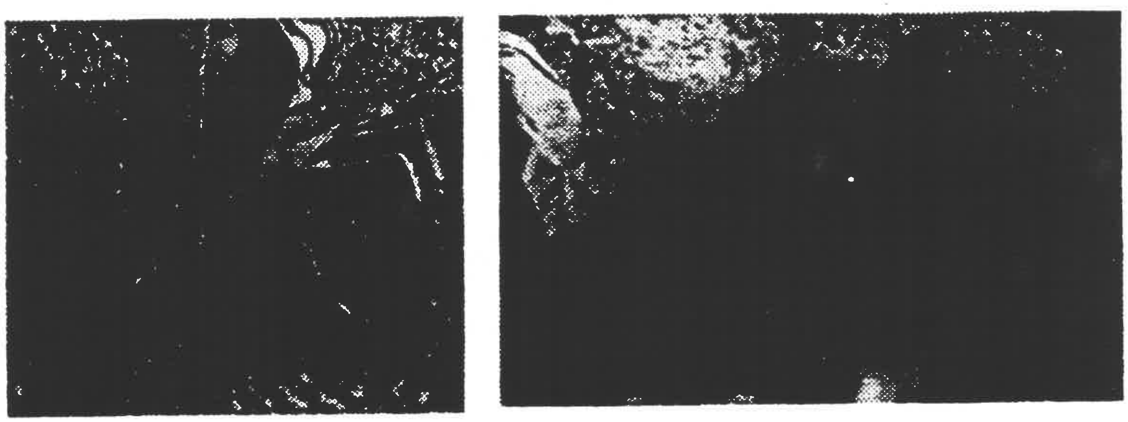

Figure 5. FMG 0450 Cutting Head (left) and One of Four Blades (right)

The vehicle is a key component of a cleaning machine. It must be able to maneuver in typical terrain found after a forest has been harvested, the site prepared and new trees grown either by natural regeneration or planting. Both of these vehicles are tractors equipped with large diameter wheels and which have some degree of articulation. The next component is a flexible arm which can reach over the vegetation and which is equipped with a cutting head at the end. The arm in this system has a pantogram design which keeps the cutting head level as the operator moves the arm. The operator controls the movement of the arm and cutting head by means of two joysticks, one operated by each hand. Intensive training is required before an operator can effectively control these machines. Also, the control system design is relatively unsophisticated, with the result that operation of the system is very fatiguing. However, it is practical to have three shift operation to keep the system operating 24 hours per day. Better vehicles, machine vision, AI techniques and better control of the cutting head all have potential for eventually developing fully autonomous robotic systems to carry out these operations in the future.

Pruning. Effective use of pruning can greatly improve the quality of the wood products from a tree. By removing lower branches as the tree develops, the trunk develops into wood which can be cut into lumber which is reasonably clear and free of objectionable knots. Also, by removing such limbs before or shortly after they lose their foliage, the risk of disease is lessened and the resulting trees, when they reach maturity, will be easier to harvest. Such pruning should be started when the crown has sufficient foliage to feed the tree, usually after crown closure is complete. In Europe, it is common to inspect the forest at about 20 years after planting to select those trees which should be groomed for high grade timber. These are pruned, while the others may be left for use as pulp wood. Several mechanical systems have been developed to perform the pruning operations more efficiently. These could be improved. Indeed, autonomous systems could be devised which could find the trees to be pruned, and then send a cutting device up the trunk to cut the undesired limbs.

Commercial Thinning. In Europe, it is quite common for a forest to receive some silvicultural treatment at least four times between planting and harvesting. For some time, forest practice has been to plant trees with a spacing of about 1.5 meters. After about 20-30 years, about three-quarters of the trees are removed in an operation known as commercial thinning. This doubles the spacing, permitting the remaining trees to grow to their maximum potential. The trees which are cut are removed and used for commercial wood products. Many of the plantations formed in Canada twenty or thirty years ago followed the same philosophy. They are now ready for commercial thinning. However, we do face a dilemma: it costs more to remove the intervening trees to a processing plant than they are worth commercially; if they are not cut, the stand will provide considerably lower economic return using conventional techniquews and systems, depending upon the product required. Thus, whether the trees are cut and removed at a loss or simply cut and left to decay in place, the poorer trees in a forest which was planted on the smaller spacing should be cut. Because of these problems, the spacing in many new plantations is 2.5-3 meters in Eastern Canada.

III. VEHICLES

The operations to be carried out in a laboratory or greenhouse do not require any vehicle. A seed orchard is usually well laid out with smooth terrain between the trees so that almost any vehicle, including a lawn tractor or golf cart could be used.

In the forest, the ground conditions are very rough. Many past attempts at mechanizing the cleaning operations in forests have foundered because of failure of the vehicle to operate in even relatively simple forest environments.

There are really three choices of vehicle for silviculture operations: tracked, wheeled or "walking". The vehicle must not be impeded by steep slopes, very soft ground or large fallen trees. Moreover, it must be able to avoid damaging the trees which are to be protected. Generally, cleaning and brushing will be performed before the trees exceed two meters in height. A tracked vehicle must be able to travel between the trees to be protected, which means that it must be considerably narrower than 2.5 meters. A wheeled vehicle could also be designed to move between the protected trees, as is the case in Figure 4b, or to pass over them as in Figure 4a. These two wheeled vehicles are now operating successfully in fairly typical terrain found in Eastern Canada. In the long term, a walking vehicle such as that developed through DARPA funding may provide the ultimate solution. Such a vehicle should be able to go to any part of the forest which can be reached by a person on foot, and without damaging any of the trees to be protected.

IV. CONTROL

As we see in factories, space and other areas of application of robotics, the ability to control tools either automatically or by teleoperation is quite advanced. We believe that if we can tell the robotics systems engineers where to move a tool and in what directions and speeds, they will be able to design new arms or adapt existing ones to solve our problems. If we are being naive in this belief, we hope the control experts will let us know what problems are unsolved, and that they will be able to solve them.

V. NAVIGATION

It will be necessary for robots working in the field to know where they are with respect to the individual trees they are to preserve, to the perimeter of the stand in which they are to operate and to each other. The Global Positioning System (GPS) is becoming an economical means of determining position. However, for round the clock operations, it is not yet practical as there are lengthy periods of the day when the system is not usable because of inadequate satellite coverage. It is also inoperable under the forest canopy.

LORAN-C is now a very effective and relatively inexpensive method of navigation. However, we can expect that for field operation of robotic systems in the future, we will make extensive use of some of the new forest management technologies, such as Geographic Information Systems containing information on the stands, topography, soils and species identification. Using the Canadian developed Multi-Element Image Scanner (MEIS), we can obtain very detailed information of the forest, and even individual trees, which can be coupled into the system (Till, et al., 1997). Laser and radio ranging within a stand is also practical.

VI. VISION

The problem which is most challenging and interesting to us in all the potential robotic applications is the one of vision. How can we recognize one species from another? In Figure 6, we see an example of three different species of young conifers. A professional forester can distinguish among these very easily. It is more difficult to develop computer algorithms to do so.

Fgure 6. Young Fir (left), Spruce (centre) and Pine (right)

In Figure 7, we see the problem facing the operator of a cleaning machine in a real forest. In this case, he wants to preserve spruce at a specified spacing, eliminating the fir and other trees, most of which are about twice the height of the trees to be protected. This is a relatively easy problem. In most similar cases, the task would be to protect the "best" tree at a given spacing. To do so, one must recognize the various features, such as species, height, stem diameter, "straightness", health and vigour, etc. One advantage we may have over the human eye is that we need not restrict our vision system to the visible part of the spectrum.

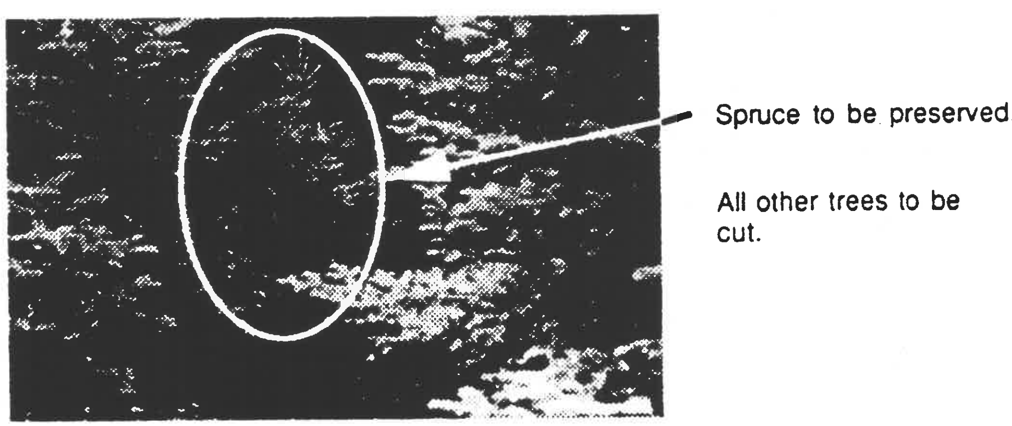

Figure 7. Cleaning/Thinning Operation in Cape Breton, Nova Scotia

In picking cones (Figure 1), the problem is to identify cones from their surroundings. This is relatively easy in comparison with other problems, but it will be more difficult than is the case with the successful orange picker (Tuttle, 1983; Harrell, 1990).

The problem of identifying containers containing zero, one or two seedlings (Figure 2) should not be too difficult. However, determining exactly where and with what orientation to position a tool to extract and replant seedlings will offer some interesting challenges.

In Figure 8, we show a typical jack pine stand which is ready for commercial thinning. In this case, we must remove the poorer quality trees to give the better ones the maximum opportunity to reach their full potential. In this example, we would try to retain those which were single stemmed and straighter. Thus, we need to automatically recognize trees with those qualities.

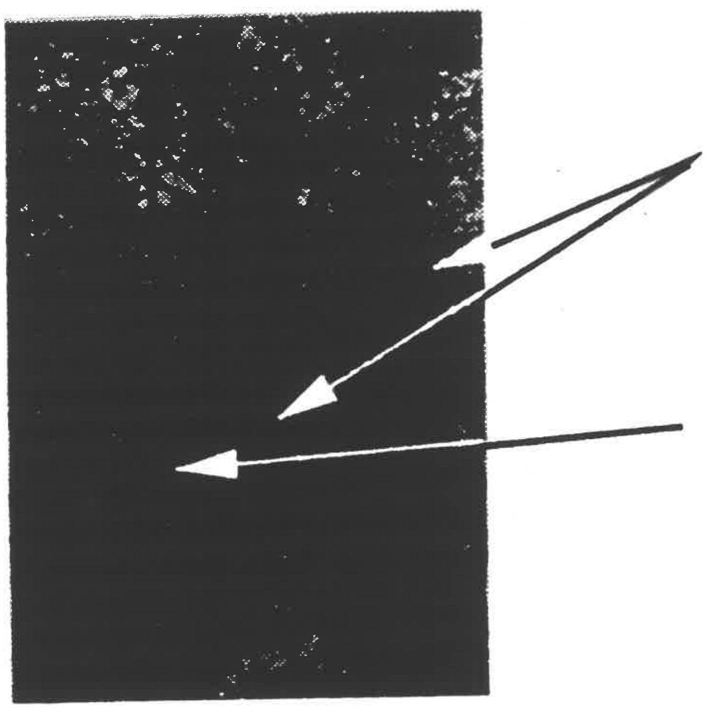

Figure 8. Vision Problem for Commercial Thinning

It is expected that the focus of any research program which may be started at PNFI will be toward solving the machine vision problems. The use of digital image analysis for satellite and airborne remote sensing systems is well established in forestry. Machine vision has evolved considerably in many areas of factory situations and for the recognition of specific shapes for character recognition and for military applications. To our knowledge, very little has been done to apply image analysis and pattern recognition to the forestry vision problems which have been introduced here. Some of the tools which we expect to be applicable and with which we hope to be able to perform some experiments include but are not limited to: mathematical morphology; fractal analysis; neural network analysis; and multichannel classification.

We will also wish to investigate the use of sensors which operate outside the visible region of the spectrum. It is expected that some tests will be made with an infrared imaging laser ranging system being developed for Canada's Space Program by Optech Inc. and PCI Inc. Acoustics and microwave sensors will also be considered.

VII. EXPERT SYSTEMS

Scientists at PNFI have considerable experience in the development of Expert Systems to provide assistance in making management decisions in many areas of forest management (Kourtz, 1990). Coupled with the expertise in forestry which is available at or to the Institute, we are confident that once the vision, control, navigation and mechanical problems are solved for any given task, the decision rules for autonomous or near autonomous operations can be developed.

VIII. ACKNOWLEDGEMENTS

I would like to thank Dr. Peter Kourtz for his visionary dream -- an army of autonomous, cooperative robotics working together to tend our forests some time in the next century. This vision was a major factor in my own decision to join Forestry Canada to attempt to start work in this area. I also appreciate his review of the manuscript and his many helpful suggestions. I would also like to thank all the members of the PNFI Forest Management Systems research team, including its former program director, Dave Brand for helping me to better understand forestry in Canada. The research staff at FERIC especially Mr. E. Heidersdorf and M. St. Amour, have been especially helpful in making the arrangements for me to see the cleaning machines mentioned in operation. I would also like to thank Peter Etheridge and Walter Emrich of J.D. Irving for the time they spent showing me some of their silvicultural operations; Peter Jackson of Stora Wood Products and Jacques Belanger of Coopérative de Travail de Guyenne for their cooperation in showing me their mechanized and manual cleaning operations.

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