Pesticides Research **Nr. 59** 2002
Bekæmpelsesmiddelforskning fra Miljøstyrelsen

Autonomous weeders for Christmas tree plantations - a feasibility study

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Danish Environmental Protection Agency
Danish Ministry of the Environment

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Preface

Agriculture, horticulture and forestry have in the past benefited from a succession of technological developments that have brought greater productivity and economic efficiency. Historically, the emphasis of these developments has been on the mechanisation to increase work rates through use of larger and more powerful machines. The newer information based technologies have already been used for some time to improve functions and controls of machinery, especially for spatial graduation of treatments. These technologies have now reached a stage which seems to make autonomous field machinery and individual treatment of plants realistic.

Mechanical weeding in Christmas tree plantations is a well suited area to begin development of such equipment because of the relatively large size of the plants, the difficulties of using standard agricultural machinery and present extensive use of herbicides.

This report presents results from a study on the feasibility of developing an autonomous Christmas tree weeder, including the technical, economic and environmental aspects, as well as the possibilities of using it for automatic data collection for management decisions.

The study was carried out in a collaborative project between The Royal Veterinary and Agricultural University, Section for AgroTechnology and The Research Centre of Forestry and Landscape, Department of Forest Management. The study has been financially financed by the Ministry of Energy and Environment.

I acknowledge with thanks the valuable assistance we have received from:
Tomas Nordfjell, The Research Centre of Forestry and Landscape,
Hans-Werner Griepentrog, The Royal Veterinary and Agricultural University
Bent K. Christensen, The Christmas Tree Growers Association,
Sten Gellerstedt, Forestry Robot Research Group, Agricultural University Sweden,
Andreas Bergstedt, The Royal Veterinary and Agricultural University,
Mogens Blanke, The Technical University of Denmark
Søren Honoré, Danish Forest and Nature Agency,
Esben Pedersen, Silvatec A/S, and
Morten Sørensen, Wedellsborg Estate.

Dvoralai Wulfsohn has checked the language.

Henrik Have

Sammenfatning

Den danske juletræsproduktionen dækker ca. 31000 ha og har en samlet omsætning på 500-600 mill. kr. Omkring 4100 producenter er involveret. De fleste har mindre end 1 ha.

For at opnå god vækst og kvalitet af juletræer er det nødvendigt med hyppig ukrudtsbekæmpelse. Dette gennemføres i langt de fleste tilfælde med herbicider, hvilket fører til helt rene kulturer med ringe levemuligheder for andre arter. Endvidere medfører det risiko for forurening af grundvandet.

For at reducere disse problemer er der udviklet maskiner til mekanisk renholdelse. De første ca. 2 år efter plantningen kan anvendes såkaldte langfingerharver, der kan bekæmpe mindre ukrudt uden at beskadige træerne for meget. I de efterfølgende vækststadier er det nødvendigt at anvende radrensere eller andre tilsvarende maskiner. Disse maskiner er imidlertid for det meste kun i stand til at bearbejder jorden mellem rækkerne. Bekæmpelsen er således mindre effektiv. Samtidig er omkostningerne omkring dobbelt så høje som for sprøjtning. Endvidere har jordbearbejdningen uhensigtsmæssige virkninger i form af udvaskningen af næringsstoffer og øget jorderosion.

Nærværende projekt præsentere muligheder og ideer for udvikling af en lille autonom maskine til mekaniske ukrudtsbekæmpelsen på en mere miljøvenlig måde. Studiet er indledt med en undersøgelse af det minimale behov for ukrudtsbekæmpelse på basis af løbende forsøg ved Forskningscenter for Skov og Landskab. Den viste, at det er tilstrækkeligt at bekæmpe ukrudtet i cirkler af 40 cm radius omkring det enkelte træ, hvilket svarer til ca. 40% af det totale areal. Det ikke bekæmpede ukrudt på den øvrige del af arealet må gerne blive stående, da det giver en vis læ og derfor har en positiv virkning på væksten af træerne.

På basis af et litteraturstudium vedrørende robotteknologi er der i projektet udarbejdet konceptforslag til nogle forskellige systemer, herunder operationsmønstre, design af køretøj, behov for sensorsystemer, databaser og navigationssystem. Også et estimat for omkostningerne ved brug af en sådan maskine er blevet udarbejdet for at kunne sammenligne med maskinstationstakster for nuværende operationer.

Undersøgelsen konkluderer, at det ud fra et tekniske synspunkt er realistisk at udvikle en sådan lugemaskine, og at den vil kunne opfylde målsætningen om at renholde arealet omkring træerne og at lade det meste af floraen stå. Endvidere konkluderes det at maskinen for små omkostninger vil kunne udvikles til i forbindelse med arbejdet, at indsamle data om det enkelte træ vedrørende tilstand og kvalitet med henblik på anvendelse i driftsledelsens beslutningstagning og dokumentation.

Det vurderes, at maskinen vil have væsentlige lavere miljømæssige effekter og give en lidt bedre tilvækst end de nuværende teknologier (sprøjtning og mekanisk ukrudtsbekæmpelse). Det vurderes endvidere, at maskinkonceptet vil have betydelig interesse i forbindelse med ukrudtsbekæmpelse i andre specialkulturer, som f.eks. frugt- og bærplantager.

Det valgte koncept bygger på nøjagtig bestemmelse af positionerne for de enkelte træer og for den autonome maskine ved hjælp af et meget præcist global positioneringssystem (RTK GPS). Træernes position tænkes målt og kortlagt automatisk i forbindelse med plantningen, idet et elektronisk system måler positionen, hvor de placeres i jorden. Det fremkomne kort anvendes derpå gennem hele plantagens levetid af den autonome maskinen som grundlag for navigation under arbejdet. Ud over positionen vil der også være behov for løbende måling af en række andre parametre for tilstanden omkring og på maskinen til brug for navigation, styring og kontrol, herunder et integreret sikkerhedssystem, der skal forhindre sammenstød med forhindringer, beskadigelse af træer og materiel, samt tilskadekomst af mennesker og dyr. Disse styrings - og kontrolfunktioner er struktureret i en særlig systemarkitektur.

Til bekæmpelse af ukrudtet er valgt en rotorklipper, der har mindre energiforbrug og næsten lige så god effekt som et jordbearbejdningsværktøj. Som operationsmønster er valgt en tilnærmelsesvis retlinet bevægelse langs den enkelt række, hvilket har vist sig at være det mest effektive og økonomiske. Det er endvidere valgt, at styre rotorklipperens horisontale finpositionering i forhold til det enkelte træ via en mekanisk eller optisk sensor.

To typer af platforme er undersøgt: 1) En lille, lav 4 hjulet maskine, der kan køre under grenene og ind mellem træerne, og 2) En portal maskine, der kan "skræve" over en række og bearbejde på begge sider. Den førstnævnte type vurderes at være den enkleste og mest velegnede.

Det er valgt at opbygge systemarkitekturen i flere lag, der bl.a. omfatter "koordinatoren", som er det menneske, der sætter maskinen i gang og løbende er i kontakt med maskinen via en PC, "vejlederen", der er en computer på maskinen, som primært via "mode changer" sørger for at maskinen opfører sig hensigtsmæssigt (navigation, ruteplanlægning, sikkerhedscheck og udførelse af arbejdsopgaver mm.), sekundært vejleder de forskellige stadier af maskinens sikkerhedsadfærd og endelig kommunikerer maskinens situation eller tilstand til koordinatoren.

Med hensyn til omkostningerne ved anvendelsen af maskinen må der i de første tid efter udviklingen forventes et noget højere niveau end for de kendte teknologier. Men den generelle udvikling i elektroniske komponenter og udstyr, sammen med stigende produktionstal må forventes ret hurtigt at bringe omkostninger ned på et niveau mellem de nuværende mekaniske og kemiske metoder. Ud over dette vil maskinen antagelig kunne give tillægsværdier i form af indsamlede data for det enkelte træ som grundlag for til driftslederens beslutninger og kundeinformation.

Summary

The Danish Christmas trees production covers about 31000 ha and has an annual turnover about 500-600 million DKK. About 4100 producers own this area. The majority have less than 1 ha.

To obtain good growth and quality frequent weed control is essential. This is mainly done by application of chemicals, which leads to clean stands with poor living conditions for other species and risks of pesticide leaching.

To reduce these problems of chemical weed control machinery has been developed for mechanical weeding. The first approximately two years after planting it is possible to use special spring tooth harrows with long flexible tines, which are effective in control of small weed plants without damaging the trees too much. In the following growth phases it is necessary to use row crop weeders. These weeders, however, are generally only able to control weeds between the rows an also less effective and more costly to use than herbicides. In addition the tillage process may cause negative effects of nutrient leaching and soil erosion.

This project report presents the feasibility of developing a small autonomous machine for mechanical weed control in a more environmentally friendly way. The study was initiated by defining the minimum requirements to weeding using results from an ongoing investigation at The Danish Forestry and Landscape Research Institute. This investigation has shown, that maximum tree growth and development is achieved by weeding of concentric circle areas of only 40 cm radius around each tree. The left over weeds on the remaining area have beneficial effects on the trees because of shelter effects.

On the basis of a literature review the idea and overall concepts of a small autonomous weeding machines is outlined, including suggestions of operation patterns, physical designs of the vehicle and the system architecture with sensors, databases, navigation system, and actuators. Also the likely costs of using such a machine were estimated and compared to currents contractor rates.

The study has led to the conclusion, that it from a technical point of view is realistic to develop an autonomous Christmas tree weeder and possible to fulfil the aim of cleaning only part of the area. In addition the machine is considered suitable for collection of tree specific data concerning condition and development for use in plantation management and product documentation.

It is estimated that the machine will have significantly lower environmental effects and facilitate better tree growth than present technologies (spraying and mechanical weeding). Further on it is estimated, that the machine as concept will have considerable interest for weed control in other special cultures as fruit and berry plantations.

The chosen concept is based on centimetre precision determination of the position of each tree as well as the current position of the ACW by means of a

RTH GPS (Real Time Cinematic Global Positioning System). The positions of the trees are to be measures automatically during machine planting by recording of the position where the tree is placed in the soil. The map produced in this way can then be used by the autonomous machine as basis for navigation during weeding over the entire lifetime of the plantation. Apart from the position it would also be necessary to measure a number of other parameters of the conditions around and in the machine itself for navigation, steering and controls, including an integrated safety system, which is to avoid collisions with obstructions, and injury of humans, animals and trees. These steering and control functions are structurized in the system architecture.

As weed control tool is chosen a rotor cutter similar to those used in certain lawn mowers, as this needs less energy than tillage, and the effect is nearly the same as for mechanical weeding. As operation pattern is chosen a nearly linear movement along the rows as this was found to be the most economic. It was suggested to control the horizontal fine position of the rotor relative to the single tree by means of an optical or mechanical distance sensor.

Two platforms were considered: 1) A small, low machine being able to move below the branches and in between the trees. 2) A portal machine that have a set of wheels and a working tool on either side of the row. The first is estimated to be the simplest and best suited.

The system architecture, which is to be built up in several layers, comprises a *coordinator*, who is the person that runs the vehicle via a PC, a *supervisor*, which is a computer, that primarily via a ”mode changer” controls the machine to behave appropriate, i.e. to navigate, to do route planning, safety check, and secondary supervision at the different stages of the safety behaviour, as well as communicating the situation and conditions to the coordinator.

As regards economy it is estimated that the continued price reductions of electronic equipment together with increasing production numbers rather quickly will bring the costs dawn at a level between the present costs of mechanical weeding and spraying. On top of that added values may be achieved in terms of tree specific data for management decisions and costumer information.

1 Introduction

To achieve good growth and quality of Christmas trees it is traditionally considered necessary to weed very intensively to compensate for the weak competitiveness of Christmas trees, especially Nordmann's fir, which is the most grown species. Intensive weed control is in most cases achieved by application of persistent soil herbicides with a broad spectrum of effect.

In resent years many growers have shifted to screened spraying with foliage acting herbicides. The rate of application is usually close to the allowed maximum, and the spraying takes place every year over the entire production period (app. 10-12 year).

The extensive use of herbicides is alarming in itself, especially seen in the light of the latest investigations, which show that it is leaching into the soil (Jacobsen et al. 2000). Leaching of nutrients – especially nitrates – from a soil almost without vegetation is also considerable, as the sparsely placed trees are only able to utilise an insignificant fraction (Rubow et al. 2000). The biodiversity of total cleaned areas is probably very low as a result of the lack of food and hiding places.

This makes Christmas tree plantations a high priority area for alternative weeding methods (Bichel, 1998). Some growers have moved in that direction during the past years and are beginning to use mechanical weeding (Keller, 1997). The weeding implements developed for the purpose are well able to remove weeds between the rows, but mostly not in the rows, where the need is greatest. Most of the implements are rather heavy, of low capacity, and costly to use. The general strategy of weeding using these machines is the same as for spraying: to achieve a total clean area. Therefore, this also leads to problems of leaching and relatively low biodiversity.

The purpose of the present project was to investigate the feasibility of developing a light, autonomous weeding machine being able to perform mechanical weed control more competitively within a relatively short period of time and also to reduce the environmental problems associated with the present methods. The machine should have an acceptable behaviour, be able to operate unattended and safely for longer periods of time.

The project comprises:

- a description of the present Christmas tree cultivation systems,
- an investigation of the need for weed control around single Christmas trees,
- specification of the conditions in which the autonomous systems should work,
- specification of the stakeholder requirements of an autonomous system,
- specification of the technical requirements of the system
- two proposed machine concepts,
- a proposal for a system architecture, including navigation system, safety system and overall control system,
- an evaluation of the proposed concepts compared to present methods, including biological, technical, economic, environmental and safety issues

as well as the possibility to achieve added values by collection of information on the trees for management decisions.

2 The economic significance of Christmas tree production

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According to the registrations at The Production Fee for Christmas Trees and Greenery (PAF) that the production area in Denmark is 31.370 hectare. From this Nordmann's fir constitutes the major part (approx. 22.000 hectare) and noble fir approximately 9.000 hectare. Further there are some special productions of cypress, Serbian spruce, holly, cryptermeria and others. And finally there is Norway spruce, which is either produced in field plantations or taken from forest plantations as thinning trees. The total area is thus app. 35.000 hectare.

2.1 Structure

About 4.100 producers are registered, of which the majority are operating with area units < 1 hectare. It is estimated that the size of an average production unit is about 1,5 hectare; however, there has been a tendency towards larger production units during the later years.

2.2 Export

Denmark is the country in Europe that exports the most Christmas trees and greenery cuttings. Each year 6-8 million Christmas trees and 30 – 35.000 tonnes of greenery cuttings are exported. The major buyer is Germany with 50 – 60% of the Christmas trees and 70 – 75% of the greenery cuttings. Next in place are France, Austria, England, Switzerland and Norway.

2.3 Economics

The annual turnover is 500-600 million DKK and makes up 50% of the total turnover of Danish forestry. For each producer this involves a very intensive production in which about 100.000 DKK per hectare is tied up in one crop for a period of 10 years. An essential condition for a reasonable yield of the investment is that the plantation is weeded. Today this is to a great extent (app. 70% of the area) done chemically, amounting to 20-25% of the total cultivation costs equivalent to around 25.000 DKK per hectare.

3 Current cultivation methods

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This chapter provide an introduction to the most common methods of Christmas tree production in Denmark with focus on mechanical weeding. Other control methods are described briefly.

3.1 Establishment

At present Christmas tree plantations are established on considerable areas. The majority of the plantations are established on previously cultivated land, and only a small part on forestland. When establishing plantations the area is in most cases prepared with thorough brushwood clearing and stumping, sometimes followed with several haulages with a *spring tine harrow* to remove irregularities. The area is on the whole ready to be treated like previously cultivated land.

Today three cultivation methods are used:

1. Clear cutting (planting - harvesting of all trees – planting). This is the most prevalent cultivation system. It is highly systematic and is easy to manage regarding planning. The planting is generally done with planters. The planting distance is typically 1,2 x 1,2 m, equal to app. 6.000 plants per hectare (Figure 3.1).

2. Current planting (planting every time a tree is cut). Planning within this cultivation system is much more difficult because the trees in each area are of different ages and thus have different demands regarding treatment. However this system gives a more even division of expenses and income. Here planting is always carried out manually. The method has some biological as well as environmental advantages.

3. Regeneration (new trees develop from the stumps of the cut trees). This method is only used to some extent because it is technically difficult, hard to manage, and often gives a poorer quality. The advantages are that there are no planting expenses, and as the plant already is established there will be no period of stagnation of establishment.

Figure 3.1. Normann´s firs planted in rows.

3.2 Weed control methods

There are advantages as well as disadvantages to the presence of weeds in the cultivation area.

Advantages:

- Leaching of nutrients is diminished
- Microclimate is improved
- Risk of wind- and water erosion is diminished
- The biodiversity is improved

Disadvantages:

- Increased competition for water, light and nutrients
- Physical damage such as wear on the trees
- Grass vegetation increases the risk of spring night frost damage
- Complicates trafficking

Normally the disadvantages are rated to carry great weight and this is why a very intensive weeding is started. This weeding can be chemical, mechanical or using animals.

3.2.1 Chemical

Chemical weeding is by far the most used weeding method. Traditionally slowly degradable broad-spectrum soil weed control was used. The rate of application was always close to or the maximum allowed dose, and the application was repeated each year throughout the rotation, which was 10-12 years. Several of the traditionally used persistent soil weed controls are now either forbidden or are being re-evaluated, and many of the producers have now started using screened spraying with leaf spray. The purpose of weeding is still the same – to keep the cultivation totally or almost free weeds.

3.2.2 Mechanical

Mechanical weeding of Christmas trees is the method that at present is regarded to be the best alternative to chemical weeding. Mechanical weeding in plantations on previous forestland demands careful brush wood clearing and either stump removal or stumping, as the available tools have been produced for cultivated land without obstacles in the soil.

Mechanical weed control can be done by mowing plants above the ground or by soil tillage. Soil tillage is superior and the safest method. Mowing does not reduce the risk of spring night frost like soil tillage, and the competition from the weeds for water will not be completely reduced. A high occurrence of natural vegetation has a beneficial effect however, during winter as it reduces the risk of winter frost damage, and a certain competition from the vegetation can probably have a beneficial restrictive effect on leader shoot growth. Therefore mowing can sometimes be justified, for example combined with other weed control methods (sheep grazing) and at certain times in the rotation or growth season. The following descriptions focus on soil tillage methods only.

The weed controlling effect of soil tillage consists of detaching and covering of the weed. The effect of this depends on a number of factors: among others the weather, the soil structure and moisture, the structure of the weed and the stage of development of the weed, travelling speed and depth of tillage. The effect is very dependent on the weather and can be considerably reduced in moist weather and soil. The effect is highest when the weed control is carried out in a dry period, as the detached weed will dry more rapidly. In moist weather the weed will often strike roots and keep on growing. Most tools operate better in sandy soil than in heavy clay soil, where the effect can be very poor. Furthermore moist clay soil is restricted to drier periods. Root weeds are difficult to control mechanically, whereas seed weed is easy to control. The majority of the tools known today have not sufficient effect on strong and well-developed weeds, but are effective against smaller weeds. For many tools the effect is better speeds of 8-12 km/h than at 4-6 km/h, however, it can be difficult to drive at high speed without damaging the trees if the trees have not been planted correctly at equal distances. The depth of soil tillage has great influence on the effect on root weeds and larger seed weeds; deep soil tillage can damage tree roots.

To obtain a satisfactory result with mechanical weeding it is therefore important to weed frequently, while the weeds are still small. One should not clean but <u>keep</u> clean. Blind harrowing – before the weeds starts to grow – often gives extremely satisfactory results. However, early actions can be hindered by moist soil, which is not suitable for traffic and tillage. The weeds start to grow in April and grow tremendously from May and onwards. Since the risk of tools damaging the newly busted buds is large, it is advisable not to drive in the plantations for 2-3 weeks in the period of bud breaking. It is therefore essential to weed before bud breaking. Depending on the circumstances the treatments have to be repeated 4-8 times per growing season.

Only very few tools have the capacity to clean in the actual rows (spring tine harrow, hydraulic Dutch hoe, rotor harrow on flexible arm), most tools are only able to weed in the inter-row area. In that case weeds are left around the trees, where competition for water for the first 2-3 years probably is most intensive. When the tree crown has grown bigger and denser the competition for water will be most intensive in the periphery of the crown. The trees are by now shading away the majority of weeds near the stem, nevertheless there will still be competition for light, and wear on the branches by tall weeds present in the row.

3.2.2.1 Conditions for mechanical weeding

The planning is one of the most important conditions for a successful mechanical weeding. The whole sequence of the cultivation has to be thoroughly considered and carefully planned. Firstly to make sure that the weeding practically can be carried out with the tools and machines at disposal, and secondly to ensure as low weeding costs as possible

Row length. It is crucial for the achievement and with this the economy of mechanical weeding, that the rows are as long as possible to minimise the number of turnings.

Appropriate headland. It is important that the rows do not continue all the way out to any fence around the plantation. A headland sufficiently broad for the later operating machines and tools is necessary. If the headland is too narrow the operator of the machine is forced to go forward and backwards to bring the machine in position.

Irregular areas. Irregular areas should as far as possible be avoided or be adjusted, as wedge-shaped areas with the direction of row tapering proportional to the headland are time-consuming and space demanding to weed. It is comparatively time-consuming to turn and bring tractor and tool in position. The headland, which is an unproductive but indispensable area, must also be considerably wider for the tractor and tool to make turns.

Distance between the rows. The distance between the rows must match the tools and machines to be used. It almost seems commonplace to mention this, but it is very often seen that the plan of cultivation had to be rearranged because the distance between the rows appeared not to fit to the machines at disposal.

Straight parallel rows. To carry out mechanical weeding at a sufficiently high speed the rows should be straight and parallel, at least in sets corresponding to the width of the weeding implement. Sufficiently accurate planting can be obtained either by a planting machine with a number of rows which fit the subsequent tools, or by drilling the area with a suitable number of holes before the plants are manually planted. Manual planting after two or more sticks does not give a satisfactory result.

The size of the weed. In general only a small number of the tools on the market right now can manage taller weed. The tools normally operate satisfactory on weed sizes up to 5 cm. If the weeds get much higher they may cause implement clogging or get entangled.

Soil conditions. Mechanical weeding is most successful and easy on light soil. The heavier the soil the harder mechanical weeding is to perform. On very stiff clay soils the traffic conditions in wet or moist periods can be so difficult, as to exclude the possibility of mechanical weeding.

The weather. The ideal weather for mechanical weeding is warm, dry and a little windy. The detached weed dries quickly and does not strike roots again. In practise it is not always possible to wait until the weather is ideal because of the risk tat the weeds will grow too high. Therefore weeding is often carried out on wet soil and in weather conditions. This means that a lot of weeds strikes roots and keep on growing. Even though the weeds are not controlled they are impeded and will not get so high that the tools can no longer manage.

3.2.2.2 Tools for mechanical weeding

Several types of soil tillage tools are used in Christmas trees. These are described below.

Spring tine harrow. This is one of the few tools able to weed in the rows. However, as it worksng in full width and thus running over the trees, the use of it is limited to the second and in rare cases to the third year after planting. Then the trees have become too high and will be damaged. In some cases where the spring tine harrow has been used, damage as found to on the underside of the branch on the lowest branch whorl from the second or third growth year. However the survival and the growth of the trees does not seem to be influenced considerably neither in the short nor the long term. There is a particularly great risk of damage when using the spring tine harrow during and just after bud breaking. The tool works best on sandy to medium heavy sand, whereas the effect on heavy clay soil is poor. On sandy soil the tool works best on dry soil. On clay soil the effect is normally best on moist soil. By regulation the weight of the harrow e.g. by means of hydraulics, the effect can be increased even on dry clay soil. The harrowing depth can also be adjusted to fit to soil, weed and so on.

The effectiveness of the tool is due to covering of the weed plants. This means that the impact is highest on little seed weeds from the stage of seed leaf and up to 5 cm height. The spring tine harrow has poor influence on larger seed and root weeds. If the spring tine harrow is the only tool used for weeding in the first 2-3 years, there is risk of extensive couch grass development.

As the spring tine harrow works independently of rows, there are no demands as to accuracy when planting. However as the tool has a highly reduced effect on weeds higher than 5 cm it is necessary to carry out 5-8 haulages per season.

The spring tine harrow has many advantages on lighter soils:

- it works in the full width and is thus weeding in the rows close to the trees,
- it has a wide working width and therefore a high field capacity,
- it is easy to manage and suitable for fast driving, because it is not necessary to drive accurately in relation to the rows,
- it does not demand specific distances between the rows.

However the spring tine harrow also has some distinct limitations:

- the suitability on heavy soil is limited,
- it can only be used in quite young cultivation, as explained above.

Disc harrow or spade-roller harrow. The Lindenborg harrow, which is a disc harrow, is usual in forestry for soil tillage. It has a good effect on seed as well as root weeds. The tool leaves comparatively broad unprepared streaks around the trees, and sometimes it causes problems with banks or soil thrown at the planted trees.

The Loft spade-roller harrow runs over every second row and weeds in the two row spacing. High weed can get entangled in the spade rollers, which then cannot work freely. To avoid one-sided moving of soil and banking the spade rollers are placed on two axles working towards each other. The effect of the harrow depends on the travelling speed. It takes quite some speed – 12 km/h or more – to obtain a satisfactory effect.

Hoe. A hoe is a tool that follows the rows. The working organs can have different shape, but the most common is tines with one- or two-winged shares. If mounting half shares towards the row the roots of the trees will be spared damages. The tool undercuts and covers the weed; the most important effect is the undercutting. The tool controls weed efficiently; the hoe normally even has an effect on root weeds – e.g. couch grass . Due to the aggressive undercutting it has a good effect on higher weed, and is much less dependent on the size of the weed than the spring tine harrow. At any rate this also concerns the hoe the less weed the easier the control. The hoe can be used throughout the rotation. Only the height of trees compared to the tool bearer's free height reduces its utility. The decisive disadvantage of hoe, is that it can only weed in the spacing between the rows and not in the actual rows.

The conditions of success with this type of tool:

- that the rigidity of the tines fits the type of soil,
- that the winged shares give full cutting of the soil and have a good overlap,
- that the tines, to give the highest possible material flow, are placed with large distance
- that the tines do not go deeper than app. 5 cm, often even higher,
- that the travelling speed is at least 5 to 6 km/h, so that the tines are vibrating, keeping themselves cleaned, and bringing the cut off or detached weed to the ground surface.

Hydraulic Dutch hoe. The hydraulic Dutch hoe can be used for weeding in the actual rows. A hydraulic run knife of 50-65 cm undercuts the weed at the depth of 2-5 cm. The tool is mounted with a mechanically or ultrasonic sensor that disconnect the hydraulic system when it senses some resistance – e.g. the stem of a tree. As the tool is driven forward due to the resistance from the soil, the knife is pushed back and turns out into the space between the rows. After the tree has been passed the knife is then again hydraulically activated into the row. Hydraulic Dutch hoes are used in ecological as well as conventional fruit plantations. In the fruit plantations 7-8 haulages per season are needed to achieve sufficient effect. The travelling speed is 7-10 km/h.

Rotary cultivator. The rotary cultivator is also an option. The knives are mounted on a horizontal-rotating axle. The rotary cultivator works by tearing up, cutting up and covering. The effect on weeds is good, and the rotary cultivator can handle even large amounts of weeds and thick grass. Root weeds, however, can only be controlled with repeated treatments. The rotary cultivator can be problematic to use for repeated haulages in the cultivation due to the risk of damaging the soil structure. The rotary cultivator is only weeding in the space between the rows. The PTO run rotary cultivator has a low performance, whereas the friction driven rotary cultivator has a high performance.

Under the category of rotary cultivators also belongs the hydraulic driven cultivator from the firm PolyTrac Inc. – the so-called "Mulcher". The Mulcher can tear up and break even high weed without getting entangled.

Rotary harrow. The rotary harrow has vertical stiff tine rotors that has a cycloidal movement through the soil. This levels the soil fairly well across the direction of travel. The firm of Silvatec produces a PTO driven rotary harrow intended for weed control in Christmas tree plantations. The rotary harrow is also available mounted on a flexible arm, which makes it possible to weed in the actual rows between trees big enough to reject the tool. The rotary harrow is suitable for weeding in overgrown cultivations.

3.2.3 Animals

Together with mechanical weeding grazing is among one of the most promising methods of weed control in Christmas tree cultivations at the moment. In principle grazing can be carried out with many different species of grazing animals; however, sheep of improved fattening breeds – especially Shropshire – are the most used.

3.3 Harvesting

The harvest of Christmas Trees starts in the early autumn with classification and marking every tree. In the middle of November the actual harvesting starts. Felling is accomplished using handsaws, brush cutters or chain saws. During the past years there has been a development within mechanic felling machines. After felling the trees are dragged or carried out manually to the tractor tracks in the cultivation, where the trees are wrapped to protect them and facilitate further transportation to a central loading place easier. The trees are then loaded on lorries. Over the past years there has been a development of more mechanized transport systems, where the trees after wrapping are placed on pallets, which makes the further transport considerably easier.

3.4 Contractors and contractor costs

The use of contractors has become more common within Christmas tree cultivations. This is partly because of the general reduction of the permanent staff within the trade, and partly because the individual Christmas tree producer gets the work done by experts having special machines at their disposal; machines that would not be economical for the individual Christmas tree producers to own. The contractor can today carry out all the tasks within Christmas tree cultivation, from little isolated jobs to turnkey contracts.

It is difficult to get an exact overview of the contractor costs, as these are strongly dependent on the conditions. Some contractors operate with a fixed rate per hour and a special road rate. Others have fixed prices per hectare with extra charges for small or difficult jobs/areas. Others again are not paid per hour or hectare but work out an offer for each contract

On good areas without road transport the contractor costs for mechanical weeding with a tractor mounted harrow are estimated to be between 2.200 to 3.000 DKK/ hectare/year at a price per hour of about 400 DKK weeding with rotary cultivator/mulcher mounted at a special tool carriers will amount from 1.250 to 2.850 DKK/hectare/year at a price per hour of about 475 DKK. depending on the planting and weeding system.

3.5 Costs of the various operations

In table 3.1 is shown a typical cultivation model for 1 hectare of Nordmann's fir Christmas tree cultivation on former farmland. Planting is assumed to be carried out manually, and spraying with leaf and soil herbicides is used for weed control.

Table 3.1. Estimated cultivation costs (DKK/hectare).

Year from establishing	0	1	2	3	4	5	6	7	8	9	10	11	Total
Costs, DKK													
Preparing chemical weeding	907												907
Soil preparation	1.155												1.155
Plants	13.889	1.389											15.278
Planting including transportation	5.884	833											6.717
Fence	8.716											2.309	11.025
Chemical weeding	1.245	1.991	3.581	1.991	3.581	1.991	3.581	1.991	2.336	779	779		23.846
Insect control						679	679	679	679	679	679	679	4.753
Fertilisation					771	826	892	892	892	892	892		6.057
Pruning			200		500		1.000	1.000	1.000	1.000	1.000		5.700
Various	600	600	600	600	600	600	600	1.200	1.200	1.200	1.200	1.200	10.200
Cultivation costs total	32.396	4.813	4.381	2.591	5.452	4.096	6.752	5.762	6.107	4.550	4.550	4.188	85.638

4 Weed control requirements in Christmas tree Production

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This chapter present results from an ongoing experiment that has the purpose of investigating the influence of different spatial weeding intensity on Christmas tree growth and survival on former agricultural land.

4.1 Method

The species in the experiment are Nordmann fir (*Abies nordmanniana).* Two parallel test areas were established; one in Randbøl National Forest District – at Tønballegård, and one in Wedellsborg Forest District. The experimental area at Tønballegård is on a clay loam soil and the area at Wedellsborg is on a light sandy soil. Planting was done with machines. Around each tree a circle is weeded mechanically.

The following treatments are included in the test (the percentage area is calculated on the basis of a planting distance, which leaves a circular growth space of app. 1.2 m^2 for each tree. The actual planting distance in the trial is wider):

1. 0% (un-weeded)
2. 20% (mechanically weeded, r=28 cm or 0.25m^2)
3. 40% (mechanically weeded, r=39 cm or 0.48 m^2)
4. 60% (mechanically weeded, r=48 cm or 0.72m^2)
5. 80% (mechanically weeded, r=56 cm or 0.99 m^2)
6. 100% (mechanically weeded, r=62 cm or 1.21 m^2)
7. 20% (chemically weeded)
8. 40% (mechanically weeded planting place without plants (only 10 circles for TDR measurements))

The trial is on singletree basis with 30 trees per treatment, for a total of 210 trees plus 10 empty planting spots. The trees are inspected for shoot development at the start of each growing season. Plant survival, health, height, leader shot length, number of leader shots, number of branches in the top branch whorl, root collar diameter are measured/registered after each growing season.

In 10 circles of each treatment, the soil moisture content in the ploughing layer (25 cm) is measured using the TDR method. In each circle the soil moisture content is measured five times in increasing distance from the centre: 15, 30, 45, 60 and 75 cm. The soil water content is expressed in terms of percent of field capacity. Field capacity is determined by measurements of the soil water content in winter about 2 days after the last rainfall.

4.2 Results

4.2.1 The average height of the trees.

The average height of the trees can be seen in table 4.1 and 4.2.

Table 4.1. Mean height of trees (cm), Tønballegaard.

Treatment	1996	1997	1998	1999	2000
0 %	14,6	20,2	28,9	50,3	78,4
20 %	16,2	22,7 *	34,1 *	55,6	88,2
40 %	15,7	22,7 *	32,6	52,4	81,3
60 %	15,9	24,1 ***	35,9 ***	57,4	90,4 *
80 %	14,6	22,0	33,4 *	51,5	81,0
100 %	14,3	22,8 *	36,3 ***	54,5	86,0
20 % chemically weeded	14,9	22,2	29,9	50,0	80,1

On the solid soil of Tønballegård the trial shows that there has been no unambiguous effect of the treatment on the average height of the trees. The weeded trees have obtained a slightly higher average height, which in year 2000 only in one single case is significant.

Table 4.2. Mean height (cm), Wedellsborg.

Treatment	1996	1997	1998	1999	2000
0 %	11,1	13,4	17,8	28,1	37,3
20 %	10,8	16,7 ***	21,6 **	35,0 **	49,3 **
40 %	11,6	16,5 **	22,9 ***	37,0 ***	55,0 ***
60 %	11,2	16,5 **	23,0 ***	36,3 ***	56,1 ***
80 %	11,1	16,2 **	22,7 ***	36,2 ***	53,5 ***
100 %	11,6	16,3 **	22,6 ***	35,4 **	54,8 ***
20 % chemically weeded	10,3	14,5	18,3	31,5	42,8

In the Wedellsborg trial on the poor sandy soil the picture is considerably different. From growing seasons 1997 to 2000 all the mechanical treatments had considerably larger height than the untreated (0 %). Apparently the 20 % treatment differs from the other treatments with a somewhat lower average height in year 2000, however, the difference is not significant.

The chemical treatment does not at any time differ significant from the untreated. On the other hand the average height in year 2000 is significant lower then the 40, 60, 80 and 100 % treatments (p-values 0,0004 0,0001 0,0011 and 0,0001).

4.2.2 Root collar diameter of the trees

The root collar diameter of the trees can be seen in table 4.3 and 4.4.

Table 4.3. Mean root collar diameter (mm), Tønballegaard.

Treatment	1996	1997	1998	1999	2000
0 %	6,7	10,9	16,2	23,2	29,7
20 %	7,3	13,0 **	20,8 ***	29,2 ***	35,9 **
40 %	7,3	13,0 **	20,5 ***	27,8 **	34,1 *
60 %	8,0 **	14,5 ***	23,0 ***	32,0 ***	38,8 ***
80 %	7,8 **	14,1 ***	22,4 ***	29,7 ***	36,2 **
100 %	8,2 ***	14,2 ***	23,0 ***	31,0 ***	38,2 ***
20 % chemically weeded	7,6 *	12,2 *	18,4 *	25,2	33,2

It is evident that all the mechanical treatments have given a significantly larger root collar diameter from 1997 to 2000. The 60, 80 and 100 % treatments have already even given a significant larger root collar diameter after the first growing season. The chemical weeded trees do not differ significantly from the untreated in the years 1999 and 2000.

Table 4.4. Mean root collar diameter (mm), Wedellsborg.

Treatment	1996	1997	1998	1999	2000
0 %	6,4	6,1	9,2	11,0	14,8
20 %	6,1	8,0 ***	12,7 ***	18,2 ***	23,7 ***
40 %	6,2	8,6 ***	14,4 ***	20,4 ***	26,6 ***
60 %	6,3	8,6 ***	14,7 ***	21,1 ***	27,7 ***
80 %	6,1	8,3 ***	14,4 ***	20,2 ***	26,5 ***
100 %	6,0	8,4 ***	14,9 ***	20,2 ***	27,1 ***
20 % chemically weeded	6,0	7,6 ***	11,4 **	15,0 ***	20,0 ***

From 1997 and further on all the treatments have given significant larger root collar diameters than the untreated. In the year 2000 the chemical weeded trees have a significant smaller root collar diameter than all the mechanical treated (p-values 0,0151 0,0001 0,0001 0,0001 0,0001).

4.2.3 Health score of the living trees.

The state of health of the trees can be seen in table 4.5 and 4.6.

Table 4.5. Tønballegaard. Health score of the living trees (0 to 10, where 0 = dead)

Treatment	1996	1997	1998	1999	2000
0 %	7,8	9,2	9,3	8,5	8,4
20 %	8,3	8,6	9,0	8,4	9,0
40 %	8,5 *	8,7	8,6 *	7,9	8,3
60 %	8,8 **	9,1	8,5 *	8,1	8,7
80 %	8,3	8,9	8,3 **	7,4 *	8,6
100 %	8,7 **	8,5 *	8,6 *	7,9	8,9
20 % chemically weeded	7,6	8,3 *	8,9	8,0	8,4

It is evident that no immediate evidence of effects of the treatment on the state of health of the trees on the rich soil. There are significant manifestations in the years 1996, 1997, 1998 and 1999. In 1996 an improved healthiness has been obtained by weeding. The other years the health of the weeded trees has been poorer than the health of the untreated trees.

Table 4.6. Health score of the living trees (0 to 10, where 0 = dead), Wedellsborg,

Treatment	1996	1997	1998	1999	2000
0 %	7,6	7,5	9,0	7,2	8,8
20 %	7,9	8,5 *	9,0	8,5 ***	8,9
40 %	7,8	8,8 **	8,9	9,0 ***	9,4 *
60 %	7,7	8,7 **	8,6	8,8 ***	9,2
80 %	8,2	8,6 **	8,8	8,8 ***	9,4 *
100 %	7,9	8,5 *	8,4	8,5 ***	9,3 *
20 % chemically weeded	7,4	8,1	8,6	8,3 **	8,8

On the light sand soil there are significant effects of the treatments in the years of 1997, 1999 and 2000. In all cases there are positive effects due to the weeding.

4.2.4 Soil moisture

Soil moisture is presented in the following figures as percent of the field capacity. This means that the curves will have a very characteristic course. Before the start of the growth season the moisture will be close to 100%, which is equal to the field capacity. During the growth season the level will fall rapidly in the vegetation-covered areas and somewhat slower in the weeded areas because of the evapo transpiration. In drought periods the level will equalise almost to the point of wither limit.

4.2.4.1 Tønballegård

Figures 4.1 and 4.2 show the soil moisture in a normal and a dryer situation.

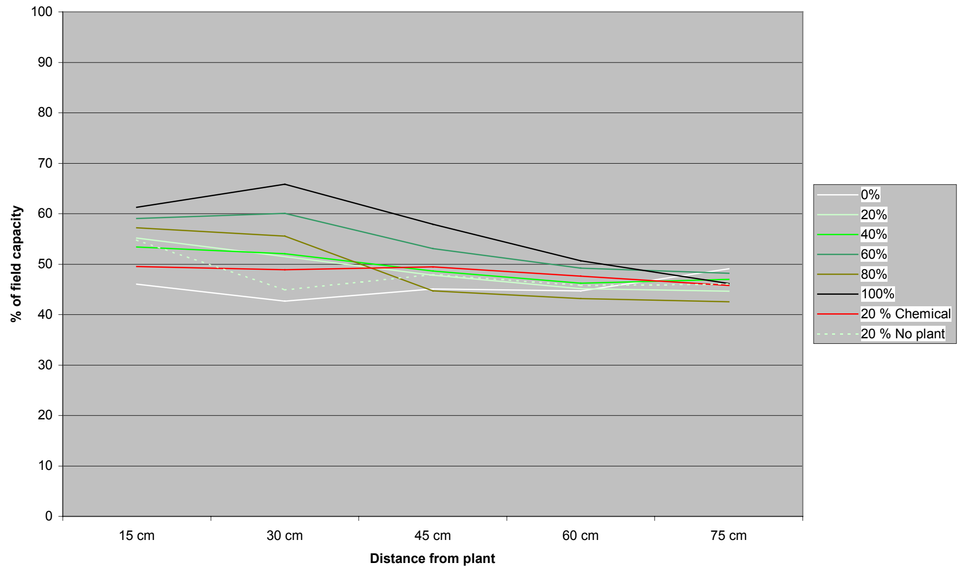

Figure 4.1. Soil moisture as % of field capacity. Tønballegård 16/6 1998.

In the normal situation in figure 4.1 it can be seen, that there is a distinct effect of the treatments. There is in the mechanically weeded trees a clear gradient, which reflects the effect of treatment, showing that the soil moisture has a tendency to fall away from the weeded area close to the plant.

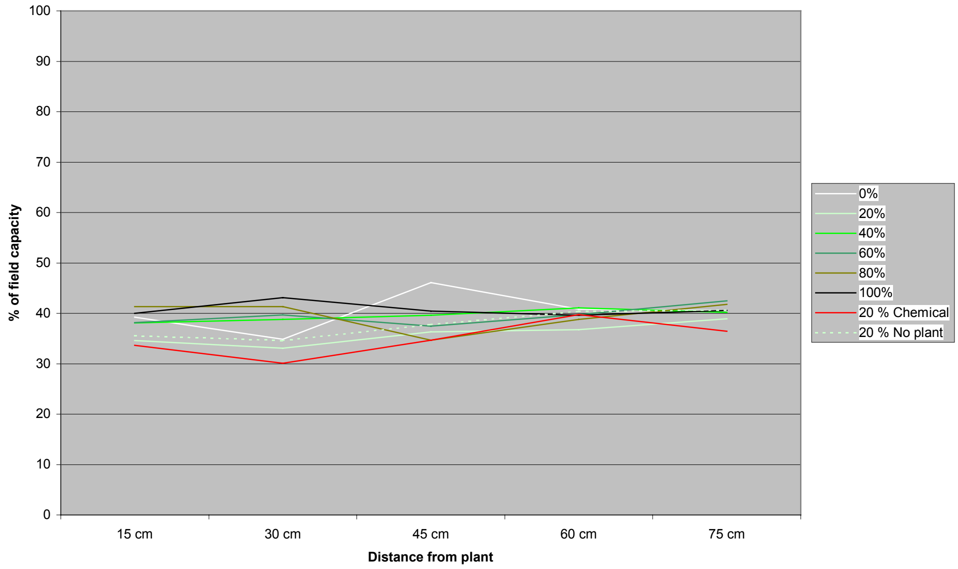

Figure 4.2 Illustration of a very dry situation, where the level probably is very close to the wither limit. There are not seen any significant differences in treatment.

4.2.4.2 Wedellsborg

The corresponding curves for the Wedellsborg trial can be seen in figures 4.3 and 4.4.

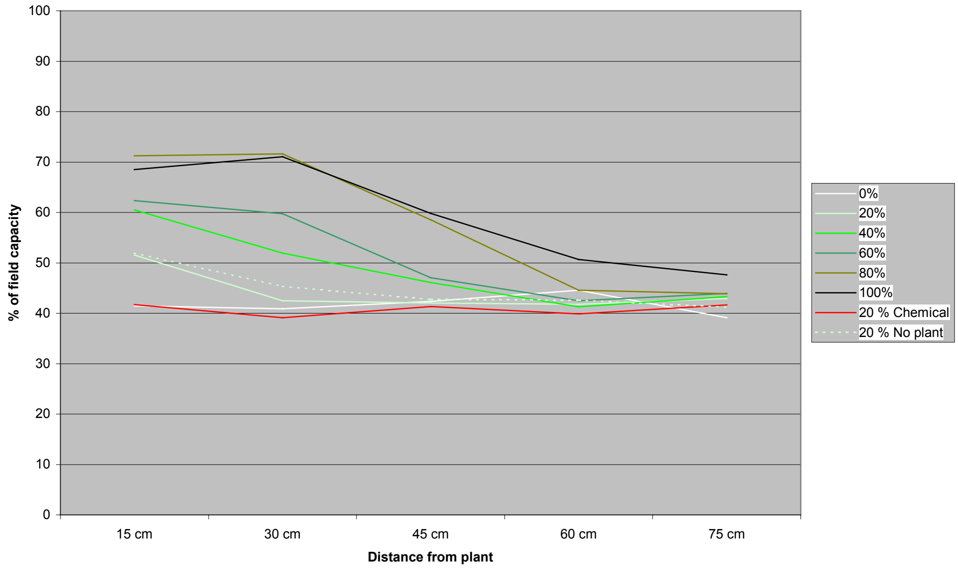

Figure 4.3. Soil moisture as % of field capacity. Weedelsborg 21/6 1998.

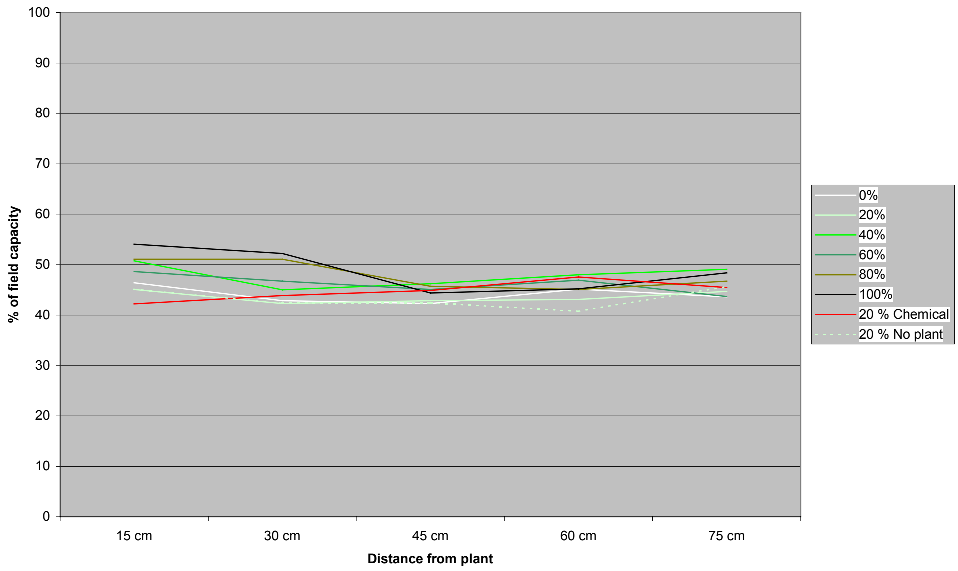

Figure 4.4. Soil moisture as % of field capacity. Weedelsborg 21/8 1997.

The gradient in the normal situation in figure 4.3 is much more distinct and reflects the effect of the treatment.

In the dry situation the level of moist in the mechanical weeded areas near the plants has come down to almost the same level as in the not weeded areas.

4.3 Other investigations

In each growing season the time of bud breaking, frequencies of leader shots and mean number of branches in the top whorl were recorded. These parameters, however, were not affected significantly by the different treatments.

4.4 Discussion

Christmas Tree producers are basing their cultivation systems on tradition and practical experience, which has indicated that the Nordmann's fir is responding to the weeding with better prosperity, growth and quality. Traditionally a 100 % weeding is therefore carried out in the Christmas tree plantations. In the trials reported here the trees have appeared to be surprisingly little influenced by the degrees of weeding above 40 %. Thus it can be expected that fully satisfactory cultivation can be maintained with a considerably reduced level of weeding.

On both study sites the development of height has only been slightly influenced by degrees of weeding above 40%. The root collar diameter, which notoriously is a parameter very sensitive to treatment, only responds very little on degrees of weeding above 40%. The general state of health of the trees has hardly been affected by degrees of weeding above 20%. Regarding the architecture of the trees the trials show that the number of trees with leader shot defects does not seem to be influenced by the degree of weeding, just as the type of defect also seems to not be influenced. This last issue is very important as trees with more than one leader shot can be corrected by cutting off the extra leader shoots, and thus get into perfect shape. In contrast trees with no leader shot at all are very difficult to repair. Also the number of branches in the branch whorl does not seem to be influenced by the degree of weeding. The missing influence of the degree of weeding on the architecture of the trees is in good accordance with the fact that the time of bud breaking is also not influenced by the degree of weeding in the trials. In this connection it is important to remember that the risk of spring night frost damages partly depends on the time of bud breaking and partly on the locality. The trials are placed on coastal areas and are thus not very likely to be exposed to spring night frost damages.

Regarding the soil moisture the TDR measurements from the trial shows that under normal circumstances in he areas with graduated mechanical weeding, there is more plant available water close to the trees than in areas with untreated soil. The TDR data also show that the mechanical weeding can be regarded as an insurance because soil drying out in drought situations occurs more slowly in the mechanical weeded soil than in the vegetation covered soil.

4.5 Sub conclusion

To date, the he trials show that fully satisfactory cultivation results can be achieved on light as well as relatively heavy soils with area graduated mechanical weeding with a weeding degree of 40%, corresponding to a weeded circle shaped area of app. 0,5 m^2 around each plant.

5 Specification of stakeholder requirements

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An important part of developing new technology is to define the desires or requirements of stakeholders, i.e. the future growers, operators, manufacturers and maintainers of the system. Those users know the circumstances under which the system should work as well as the function and shortcomings of present systems. They are also the people that have to live with the new system and its properties in relation to people, work tasks and the environment.

To get a good basis for the development work a workshop was organised with the project team and representatives from important stakeholder categories on the 5th of March 2001. The participants contributed with presentations on various aspects of Christmas tree production and on ideas in relation to development of an autonomous Christmas tree plantation (ACW). After this a brainstorm session was arranged to identify the current level of satisfaction with spraying and mechanical weeding as well as a specification of stakeholder requirements and wishes for an ACW. The main outcome of this process is reported in the following.

5.1 The current level of satisfaction with spraying and mechanical weeding technology

Weeding in the plantations is primarily done to reduce the direct competition for water, nutrients and light; however heavy weeds in Christmas tree productions can also lead to wear damages, which are deteriorating to the quality of the trees. Furthermore, various weed species which are deeply rooted in the plantation can restrain or even totally ruin a Christmas tree plantation. In general the need for weeding is greatest in the phase of establishing the plantation to secure survival.

Approximately 70% of the producers are using chemical weed control to some extent. Especially when using system 1, which mainly is used within field plantations, the use of chemical control is widespread.

Among growers the general attitude is that it is desirable to introduce more environmentally compatible weed control methods, if these also technically, economically and effectively are alternatives. The use of chemical weed control, especially the use of chemical soil weed control, has been strongly reduced in the recent years. The improvement in spreading techniques, e.g.

band spraying and screened spraying, has also contributed to a reduction of the use of pesticides.

A political wish to reduce the use of pesticides has also contributed to the introduction of various alternative weeding methods such as mechanical weed control and weed control with animals. These methods are currently being improved and refined, but in general they are still too expensive. The cost of these alternative methods are 10-100% higher than spraying. At a time with decreasing income per tree produced it is only natural if the producers are trying to avoid increasing production costs, including weed control costs.

In general it is not the quality of the alternative weed control methods that is the main problem, but the higher requirement of manpower that these methods imply.

5.2 Stakeholder requirements to an ACW

In the project stakeholder requirements were specified on the basis of a workshop with participants from the various stakeholder categories:

Requirements:

- Costs should be at most at the same level as chemical weed control
- Able to work on steep gradients and irregular soil surfaces
- Able to carry different tools, e.g. weed cutter and tillage tools
- Safe in relation to humans and animals
- Less than 5% trees damaged
- Simple ACW transport
- Easy maintenance (standard spare parts)
- Secured against theft
- Able to record important properties of trees and plantation

Wishes of additional work tasks:

- Basal pruning
- Fertilizer application
- Spot spraying
- Tree marking for sale
- Shape regulation
- Growth regulation
- Transport of equipment for production measurements
- Recording of tree properties for management and on line sale purposes
- Selective planting of new trees
- Selective tree felling (and possibly transport trees to a field handling point)
- Selective replanting
- Spatially selective processing according to needs.

In relation to the development stakeholders indicated that it is essential to get clarification about:

- The frequency of treatment
- The appropriate periods of treatment (from the middle of May, the beginning of July should be avoided for bud breaking reasons)
- The possibility of combining different working operations.

5.3 Sub conclusion

The stakeholders found it desirable to introduce autonomous technology for mechanical weeding in order to reduces environmental effects and labour requirements, but this new technology should be competitive to the present methods. Also the stakeholders were interested in autonomous machines for a number of other work tasks.

6 Specification of technical requirements for an autonomous Christmas tree weeder

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On basis of the described cultivation methods, minimum weed control requirements and stakeholder requirements the following full and reduced operation scenarios and requirement specifications have been specified as goals for the first generation autonomous Christmas tree weeder (ACW).

6.1 Overview of cultivation methodology

Christmas trees are mostly grown on farmland in rows 90 to 125 cm apart and with similar intra row spacing. Another pattern is a 60° triangular pattern (referred to as rhombic), which corresponds to closest packing of equal size circles. Using this latter pattern about 20% more trees can be grown on the same area. Different tree species are chosen depending on the soil types.

The production cycle starts when typically two year old trees (about 20 cm high) are planted on prepared land, and it ends after 6 to 10 years when the trees are cut selectively. In some cases new, small trees are planted in between trees remaining from this selective harvest.

Mechanical weeding during the first two years after planting is normally performed with special spring tine harrow (langfingerharve) developed for weeding in agriculture (see chapter 4), which is relatively cheap, and yields a satisfactory result. At the later growth stages this method is not suitable. This is when the ACW is to be employed.

Weeding is needed until the trees are about 1,5 m high. It must at least cover a circular area of 40 cm radius from the stem to avoid competition and stiff shoots of perennial weeds (including trees) to cause mechanical damage to the branches.

The weed control may be performed either as shallow soil tillage or as weed cutting near the ground. The latter provide sufficient reduction of weed competition, but in some areas it is an advantage to clear the soil around the trees during springtime, as it reduces the risk of frost damage of emerging shoots. A shallow form of soil tillage is considered suitable for this purpose. Weeding should be done 4 – 8 times a year (chapter 4). Recently emerged shoots are brittle and easily damaged mechanically.

About 6 years from planting, when the trees are about 1 m high, some of the lower branches of the trees are removed to reduce the top shoot growth. This operation is in some cases done twice. Further growth regulation is some times made by removing part of the bark around the lower part of the stem.

Late in the growing period tracks may be cleared in the plantations for transport depending on the harvest strategy (chapter 3).

6.2 Definition of operation scenarios for the ACW development

It is clear that the full range of plantation scenarios occurring in practical conditions is wide, and that it would be difficult and costly to develop an autonomous machine that could cope with all situations. Therefore a somewhat narrower range of scenarios is chosen for the analyses.

Table 6.1. Christmas plantation parameters and requirements chosen for the ACW development.

Category	Parameter	Occurring conditions	Chosen machine requirements
Soil surface	Unevenness	< 5 cm from average	< 5 cm from average
	Amount and type of residue	First generation: No residue. Second generation: Branches and stubbles	None: Residue to be cleared before second generation planting
	Inclination	< 12 %	<10 %
	Traffic ability	Dry to slippery	Dry until normal traffic ability level
	Physical obstructions	Stones, stubbles from previous generations, branches	None
	Plant coverage	Bare to dense	Bare to dense
Weeds	Height	5 to 200 cm	25 cm
	Coverage	None to dense	None to dense
Tree size, and shape	Height	0.2 to 2.5 m	0.2 to 1.5 m
	Age	2 to 12 years	Third to fifth year
	Branch location above ground: • at the trunk -> • at the branch tip ->	Depends on species and age • 0–20 cm • 0–30 cm	Min. 5 cm
	Trunk diameter	3 – 8 cm	3 – 8 cm
Climate	Temperature	-5 to + 35	-5 to 35
	Precipitation	All	Resistance to rain
Uncon-trolled objects	Animals	Dears Nests and youngsters	Avoid stationary items greater than 10 cm
	People	Curiosity, larceny	Stop, send alarm

In addition the mechanical damage of trees between planting and harvest should be less than 5%. Also any contact between trees and the ACW should be gentle or avoided during 3 weeks from medium May when the bud are very sensitive to damage.

6.3 Definition of work tasks

During the workshop and further analyses (chapter 5) the following occurring as well as new work tasks were identified as suitable for one or more autonomous machines. However it was decided to limit this initial work to weeding while keeping the other potential tasks in mind (Table 6.2).

Table 6.2. Work tasks considered in the present analysis.

Work tasks	Main parameters	Possibilities	Choice
Weed control	Method	Weed cutting, tillage and others	Weed cutting
	Tool	Rotary cutters, drum cutters	Rotary cutter with hinged exchangeable knifes
	Weed development stage	Early to late	Relatively early
	Frequency of operation	Four to eight	Ad-hoc
Frost risk reduction	Removal of weeds and trash around trees	Usual cultivation method. ACW with tillage tool.	Usual cultivation method

6.4 Sub conclusion

In conclusion it is recommended to focus on development of an autonomous vehicle for weeding with rotor cutter near the ground in a slightly reduced range of occurring scenarios. Further development of the vehicle for some of the other tasks appears feasible, but should be postponed to a later stage.

7 Autonomous vehicle technology – a literature review

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Autonomous vehicles (also called mobile robots and robotic vehicles) are normally categorized as developments from automatic steered vehicles and remote controlled vehicles, while the term robot usually is used for materials handling and tool operating automata mostly used in industry. Varieties of the two have found use in agriculture. An example is the experimental, robotic fruit harvesters developed years ago, which moved (autonomously) from tree to tree and picked the fruit by mean of an robotic arm. Another example is the milking robots, which are used in practical farming, milking the cows when they prefer. Human like robots ought to be regarded as an entertainment industry phenomena.

The most primitive robots, sometimes called industrial robots are just material handlers, mostly pneumatic, typically running through a process of gripping a work piece, carrying it and placing it in another place and returning to start the next cycle. True industrial robots are versatile equipments able to be set up to perform work tasks like seam welding, painting, moving a work piece and assemble components. To do this it should be reprogram able in an easy way without physical changes, have a memory and logic to be able to work independently and automatically and further have a physical structure of a fashion that allows for its use for several tasks without major restructuring (Lundquist, 1996).

Another area relevant to mention about work on robotics and autonomous vehicles is toys. The LEGO Mind stones products have by themselves contributed to the development, but the products have also been found useful as experimental modelling tools. Works like Rooker & Lund (2001) may be applicable for developing the man-machine interface for the operators setting up the work of autonomous machinery. This reference describes a programming tool for LEGO robots to be used by children for setting up autonomous robot soccer players.

Autonomous mini sub-marines designed for under-sea prospecting and search are mentioned by different sources, their relevance for the actual purpose is judged to be limited.

Going into the real life of designing autonomous vehicles, Gomi (2001) stated the priorities of hardware units to be: Battery, motor, connector, sensor, cpu.

The greatest future application of autonomous vehicles, many with robotic actions, is expected to be for domestic purposes including assistance to disabled people (Christensen, 2001; Gomi, 2001). At present most work in this area is at the pre-commercial stage. An exception is a vacuum cleaner from Electrolux. Although the research on other of these types of equipment has reached a rather high level of perfection, marketing for end users must probably wait for some time for safety reasons. However there is a great range of commercial vehicle types available as platforms for research purposes (figure 7.1). Some of these contain controllers with great computing capacity.

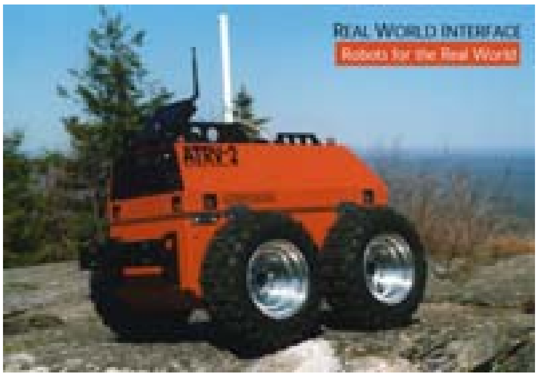

Figure 7.1: Example of skid steered commercial available autonomous vehicle platform for experiments. The unit is electric powered from batteries and fitted with basic sensors, computers and communication equipment, which are open for addition of supplementary units.

7.1 Automatic and autonomous vehicles in agriculture, forestry and horticulture

Petersen (1985) described some possibilities for application of robots in agriculture and mentioned picking of fruit, harvesting of vegetables as well as transplanting and spraying. Research has been reported on robotic harvest of apples, grapes and oranges (Burely et al. 1990), robotic harvest of apples (Kataoka et al. 1997), robotic pruning of grapes (Lee et al. 1994) and robotic harvest of vegetables (Hilton, 1997).

Kondo & Ting (1998) describes a number of robots for fruit and vegetable harvesting. Robots for other crop growing operations are also shown. Many of the robots are mounted on vehicles, some without an operator. Apparently the described robots rank from commercial to experimental. The treatment shows the importance of sensors as part of the robots. Reports related to robotic weeding, e.g. Molto (1997) mostly consider weed sensing, in most cases using vision systems. According to Kondo & Ting (1998) the interest for robotic tractors (~autonomous tractors) in Japan is increasing.

Except for some robotic equipment mentioned above the only autonomous vehicle marketed for agriculture-related purposes seems to be lawn movers. Most well-known are two types sold by Husquarna, one solar powered another with battery loading from a mains connected servicing station that the machinery drive to when needed. These lawn movers move the grass in a random linear pattern like the abovementioned vacuum cleaner form Electrolux.

Autonomous vehicle platforms for experiments are commercially available, e.g. from Applied AI Systems, Inc. (2001)(figure 7.1). This firm offers a number of different types (called robots), mostly for indoors use; a few can be used outdoor. The problem is that the latter types are skid-steered, which is not very suitable for weeding purposes. Up to now no commercial vehicle platforms, which are easy to adapt for development of an autonomous weeder have been found.

An apparently more suitable vehicle platform has been made by Madsen & Jacobsen (2001) (Figure A.2, appendix A) as their M.Sc. thesis project. This is a robotic vehicle designed as a carrier for weeding purposes. The vehicle has four-wheel drive four-wheel steer and is designed by mechatronics principles with individual steering motors at each wheel

7.2 Evolution of automatic steering for agricultural vehicle

Experiments on ideas of removing the tractor driver or easing his steering job have already been reported from 1909 (AGRI/WP.2/69, 1962). Since then the technology has developed to make automatic steered vehicles possible. As stated in a review by Wilson (2000) the fact is that for automatic steering of agricultural vehicles of today the guidance will in most cases use GPS (Global Position System) for absolute position sensing and vision systems (image processing systems) for relative position sensing. A further element necessary for practical automatic steering are controllers based on computers with reasonable computing capacity.

The history of automatic steering of agricultural vehicles can briefly be divided in two epochs. Until about 1940 the experimens had mostly been on mechanical systems. A prominent result was furrow followers delivered as standard equipment for some tractors. Remote radio control of tractors was demonstrated in 1936. During the second world war servomechanisms were put into general use. This developed the theory of control systems.

From the 1950’es to the 1980’es a great amount of research on automatic steered agricultural machinery was performed. Reviews of this is found in the references above and in Jahns (1976) and Nielsen et al. (1976). A great part of this research considers sensor principles for guidance information. Further research considers design of the control systems, some on more generally applicable principles and mostly on detailed electronic design with minor relevance today. Liljedahl et al. (1962) applied the theory of automatic control on automatic tractor steering and by this introduced application of mathematical modelling or systems analysis into the subject.

In the 1970’es the increased application of electronic instrumentation for agricultural engineering research was crossbreed with electronic control for the advance of both topics, and at the end of the decennium the microprocessor was introduced in some systems. The decade also saw the first simple electronic monitoring instruments in practical farming.

During the 1980’es electronic equipment found more widespread use in practical farming, mostly monitoring equipment and some simple controls. In this decade also targeted work to increase the quality of farm electronics had been performed. Development and standardization of data bus systems for agricultural tractors were also started up in this period.

In the 1990’es the concept of precision farming brought position measurement (~ navigation systems) into practical farming with GPS (Global Positional System) in practice becoming the universal sensor for absolute position. To obtain sufficient accuracy error correction using differential GPS had to be used, but since the intentionally introduced error (selective availability) has been removed other means of obtaining accuracy have become possible. However, for guidance purposes the accuracy obtained by these systems is not sufficient. In stead RTK GPS (Real Time Kinematic GPS) has to be used. The RTK system extends the differential principle with corrections based on application of the GPS carrier wave phase.

The 1990'es also saw the development of image processing systems able to process relatively complicated images nearer to real time. These systems were partly developed to become research measurement tools, partly researched for post harvest processing of horticultural products (Bennedsen et al., 1996; Bennedsen & Kohsel, 1996; Bennedsen, 1997). Some of the latter have been developed into systems, which now are inserted into production lines in horticulture (Anonymous, 1997). Further research has been made on application of image processing systems for application by control of field machinery, e.g. fruit picking (Peterson & Bennedsen, 1999), weed detection (Pedersen, 2001) and guidance in row crops. The latter has been developed into control systems marketed for guidance of row crop cultivators (Bundgaard, 2001).

An updated broader overview on automatic steering of farm vehicles can be found in a thematic issue (no. 25, 2000) of Computers and Electronics in Farming.

7.3 Sensors for navigation

The primary sensors needed for navigation are systems that can provide information on absolute and relative position, vehicle absolute and relative orientation and speed. Supplementary systems may be needed for specific purposes. Many other sensor types may also be used internally in machinery and for crop sensing, e.g. tactile sensors for mechanically sensing presence of material or force from material. It is worth noting that some in general outdated guidance principles have properties, which may make them candidates for special applications.

7.3.1 Real time Kinematic global position system

As mentioned above navigation (~guidance) of automatically steered vehicle in future is today assumed mostly to be based on measurement of the absolute position based on RTK GPS (Real time kinematic global position system) and relative position determined by vision.

The RTK GPS is based on measurements of the propagation time for the radio waves from the Navstar satellites. The RTK principle is based on application on a local ground based reference station and obtains centimetre level accuracy using the carrier wave phase difference. The principles are described in a number of textbooks and articles. A short technical description of an actual system is, e.g. found in a manual from Trimble (1999). As a minimum a GPS equipment will deliver horizontal coordinates in a ground based coordinate system, but most provide also the vertical coordinate, time and additional information, e.g. about accuracy.

7.3.2 Computer vision

This technology is in many cases based on use of video cameras, often common colour cameras (giving RGB colour information) or grey level cameras. In some cases cameras with other spectral sensitivities or even more special camera types are used. The camera signals are after digitising processed computationally to extract relevant sensor information, e.g. the vehicle heading relative to a crop row. A great amount of literature exists about vision systems and image processing. A part of this is about vision for guidance purposes.

7.3.3 Supplementary sensors

Besides both the above primary navigational sensor systems reliable guidance often will depend on supplementary sensors, among others to detect the angular orientation/attitude of the vehicle. This comprises the three parameters: *Heading, roll* and *pitch.* The heading is the direction of driving expressed as an angle relative to another direction; it is primary information for control of the steering. Absolute measure for heading is the compass course. Different compass sensors are available, but the heading can also be calculated from a number of subsequent position measures when driving. Roll and pitch are the angular deviation of the vehicle's vertical axis from the actual vertical, roll is the sideward angle and pitch is the up-down angle of the vehicle's forward direction. Both can be measured with inclination sensors. For accurate position determination with RTK GPS roll and pitch are often needed for correction because the GPS aerial is placed at a higher level than the tool to be positioned.

In some cases information on driving distance and velocity are needed for a good control of vehicle driving. This can be supplied by an odometer. For measurement of shorter distances or as an alternative to vision, sensors based on ultrasound can be used.

7.3.4 The leader-cable principle

By this principle the vehicle follows a single cable buried below the track. The cable carries a voice frequency alternating current. The approach is commonly used for automatic transport systems in industrial plants, where the driver-less vehicles have bumpers operating safety stops to avoid damage on persons or other objects in the vehicle path. Variants of this system have been used or been tried for quite a lot of applications. A system for farm use was described by Morgan (1958) and since then more advanced experimental systems have been described, e.g. Jahns (1976,b). Bearing some resemblance to the present project, is the application for automatic lawn movers where the cable signals the limit of the area to be moved. Some automatic movers also use a leader cable for homing guidance to a servicing station. In a GPS-based system a leader cable could be used as part of an emergency subsystem.

7.3.5 Laser-based principles

The use of lasers has possibilities for high accuracy in areas where line of sight can be obtained. Using a laser beam as a very straight guidance line is used for different purposes. Lasers can be used for accurate measurement of angles in one or two dimensions by mechanically scanning the beam in a plane angle or a solid angle respectively. Further the distance can be measured by means of a modulated laser beam reflected back into the instrument with the laser. Distance measurement and angle scanning is sometimes combined in one instrument.

A commercial version of this combined principle made for accurate guidance in limited areas is described by Arnex (1995) and Søgaard (1998). The system has a laser scanner on the vehicle and uses reflective fix-points installed around the field in positions accurately surveyed. The system delivers two measurements per second for each reflector. Because of the low measurement frequency the equipment has a Kalman filter, which is a software estimator to extrapolate into the time interval between last measurement and the time when next position coordinates have been measured and calculated. Another remarkable feature is optics to broaden the laser beam so the light intensity is reduced to eye-safe level.

Laser scanners and laser distance-meters may be used as test instruments. Kalman filtering is generally applicable for real time purposes e.g. in control systems with time discrete and noisy signals. Laser scanners may also be applicable for replacements of vision systems, especially if range data are requested for 3d imaging.

7.3.6 Other principles

Other relative position sensors with possible relevance are mechanical types with a feeler arm. For instance the type used for sensing maize stalks (Kutzbach & Quick, 1999; Suggs et al., 1972), could be modified for sensing Christmas tree trunks.

Simple optical sensors sensing presence or non-presence of material have been used for many purposes, but not very many have been used in field machinery because of the risk of contamination.

Simple optical sensors with ability of discriminating between green plants and other materials have been used experimentally in the 1970'es (Palmer & Owen, 1971; Hooper et al., 1976). The special relevance is that these sensor types, instead of using the green colour used the more pronounced difference between red reflectance and near-infrared reflectance of green plant materials; this feature is also used in some modern vision-based systems.

Tillet (1991) has produced a more recent review of automatic guidance sensors for agricultural field machines.

The topic "degree of autonomy" has been discussed by Castelfranchi (2001). Degree of autonomy is approximately the same as "level of delegation". The topic brings in a lot of implications partly of rather philosophical nature.

7.4 Safety

Safety of machinery working without continuous human supervision is critical. Apart from the functional reliability the machinery must not hurt human or animals and should neither damage third persons property. For unmanned machinery working in open country the problem of possible entry by unwanted persons into the work area is serious.

The controller must handle safety problems as part of its operation. In the case of damage to the machinery or other error conditions the design of the controller and the rest of the machinery must assure a safe function with a graceful degradation.

For the matter of safety of third parties and the operator an alternative outer layer of safety must be provided. In most cases this will be performed by a hardware safety system independent of the controller. In particular the machinery must stop if children or animals are coming near, but not if the operator or another authorized person is present in a safe way.

The safety systems must comply with the rules set up by safety at work authorities. A first approach for safety of an area with working machines is fencing with safety switches stopping the machines in case the fence is opened, a solution which may be prohibitively costly in the case of weeding machinery and also a problem in relation to the work of an operator supervising the work now and then. In general if a specific machine is not covered by special rules the safety system of an actual machine will be judged to comply or not with a generalized set of rules. Danish rules possibly applicable to the safety of autonomous field machinery are at least partly covered by the rules for remote control of technical equipment (Arbejdstilsynet, 1995a) and the rules for automatic controlled machinery, industrial robots included (Arbejdstilsynet, 1995b).

An elementary set of safety demands to automatic steered agricultural vehicles have been set up by Jahns (1975).

7.5 Systems Architecture

An architecture is a description of how a system is constructed from basics and how those components fit together to form the whole (Albus, 1991).

Mobile robots, if they are to perform useful tasks and become accepted in open environments, must be autonomous: capable of acquiring information and performing tasks without programmatic intervention. Due to the complexity and intelligence of an autonomous vehicle it is necessary to incorporate systems architecture already in the design phase. As a result, the literature review is derived by the Artificial Intelligence and Robotics.

There are not many references about systems architectures for autonomous vehicles in agriculture. Nilsson (1980), states that a control system for an autonomous tractor should be decomposed into three functional elements: a sensing system, a planning system, and en execution system. The job of the sensing system is to translate raw sensor input into a world model. The job of the planner is to take the world model and a goal and generate a plan to achieve the goal. The job of the execution system is to take the plan and generate the actions it prescribes.

Later on, the sense-plan-act approach (SPA) became the dominant one in this area. The SPA approach has two significant architectural features. First, the flow of control among these components is unidirectional and linear. Second, the execution of an SPA plan is analogous to the execution of a computer program. Executing a plan or a program is easy when compared with generating one. Therefore, the intelligence of the system lies on the planner or the programmer and not on the execution mechanism (Connell, 1989).

The next step of the sense-plan-act (SPA) approach was the "subsumption" approach, applying task-dependent constraints to the subsumption layers to make SPA more efficient. The most well known example of this approach is the mobile robot called Herbett's which was programmed to find and retrieve soda cans in an office environment (Connell, 1989).

Rzevski (1995) mentions three main types of three systems architectures for mobile robots. The hierarchies, networks and layered architectures.

A **hierarchy** is an architecture that consists of elements linked as “parents” and “children”. Each parent can have one or more children. Each child may be a parent of other children. In this way multilevel hierarchies are constructed. Hierarchies are used whenever it is necessary to reduce the perceived complexity of a system caused by its scale (size).

In **networks**, in contrast to hierarchies, there are no levels of importance and all elements may be connected to each other. These architectures are used when there is a need for cooperation between units that are equal in importance but different in terms of skills or capabilities.

Layered architectures, consist of self-contained elements, called layers, each connected to a set of inputs and outputs and thus each capable of creating a system behaviour.

Moreover, from the artificial intelligence literature for mobile robots, the following are some dominant system architectures, which have been widely used in autonomous vehicles:

7.5.1 Three-layer architecture

The three-layer architecture consists of three components: a reactive feedback control mechanism, a reactive plan-execution mechanism, and a mechanism for performing time-consuming deliberative computations. These components run as separate computational processes. According to the algorithms, which are going, to be executed in the processes they should fall into three major equivalence classes.

The first one is the fast, mostly stateless reactive algorithms with hard real time bound on execution time, slow deliberative algorithms like planning, and intermediate algorithms with hard real-time bounds on execution time. Slow deliberative algorithms like planning, and intermediate algorithms, which are fairly fast, but can not provide hard real-time guarantees. “Fast” and “slow” are measured with respect to the rate of change of the environment (Gat, 1998).

7.5.2 The Saphira architecture

This architecture design consists of three central aspects. The ability to attend to another agent, to take advice about the environment and to carry out assigned tasks. All three involve complex sensing and planning operations on the part of the robot, including the use of visual tracking of humans, co-ordination of motor controls and planning. To be able to achieve these aspects, the Saphira architecture uses the concepts of co-ordination of behaviour, coherence of modelling and communication with other agents. (Konolige and Myers, 1998)

At the coherence concept, a mobile robot must have a conception of its environment that is appropriate for its tasks and consequently the more open-added the environment and the more complex the tasks, the more the mobile vehicle will have to understand and represent the environments. At this architecture, an internal model is used, the local perceptual space (LPS) which uses connected layers of interpretation to support reactivity and deliberation. The communication concept implies the ability to understand task commands as well as integrate advice about the environment or its behaviour.

7.5.3 The animate agent architecture

The aim of the animate agent architecture is to design software systems for intelligent robotic agents. Such agents need to be able to pursue a wide variety of goals and interact naturally with people when deciding which goals to achieve and how to achieve them. This type of architecture addresses these issues using a two level model for encoding robot behaviour. A lower level consisting of continuous processes that control the robot's sensors and effectors and a higher level consisting of a reactive plan executor that selects sequences of actions and programs the lower level at run-time (Firby, et al., 1996).

The two level approaches is designed to cope with the following issues:

- The details of the world
- Dynamic situations
- Contingencies, problems and opportunities
- The control of continuous processes
- The integration of purposive vision

The architecture in general consists of a reactive task execution system, using a hierarchical library of discrete plans and plan steps, and a continuous control system using composable modules called skills. A two level architecture is used to allow the encoding of two quite different, but complementary, types of robot behaviour. The skill level supports the description of continuous control processes, while the task execution level supports the description of multistep plans.

7.5.4 Behavioural reactive system architecture

A behavioural reactive system architecture tightly couples perception to action without the use of intervening abstract representations or time history. This is drawn from the behaviourist school of psychology which considers that behaviour is simply a reaction to a stimulus. The reactive robotic systems have the following characteristics (Arkin, 1998):

- Behaviours serve as the basic building blocks for robotic actions
- Use of explicit abstract representational knowledge is avoided in the generation of a response
- Animal models of behaviour often serve as a basis for these systems
- These systems are inherently modular from a software design perspective

7.6 Sub conclusion

Autonomous vehicles, also called mobile robots and robotic vehicles, for use in open environments are in an early stage of development. No real autonomous machines have yet been marketed for practical purposes, but a few experimental types are being built and offered for sale for research purposes. A range of sensing systems is being developed to perceive necessary information on position and structure of surroundings. Other work has been done on processes for navigation, steering, safety precautions and other operational purposes. Various system architectures, including a range of databases and processors, have been developed to facilitate this information collection, processing and utilization in an organised way.

8 Proposed outline of an autonomous Christmas tree weeder

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The idea of developing an autonomous machine for weeding in Christmas tree plantations has come up in connection to general considerations of a new mechanization concept of using small agricultural autonomous machines. As a consequence the present feasibility study has been made as part of a general concept development, which is presented in the three appendices:

- *A specification of behavioural requirements for an autonomous tractor*,
- *Proposed Systems architecture*, and
- *General motivation of using autonomous vehicle systems*.

These general considerations together with information and requirements presented in the previous chapters forms the basis of the following proposed outlines of autonomous Christmas tree weeder.

8.1 Weeder tool

The specified requirements of weeding (chapter 4) are that the weeds as a minimum should be cut within a 40 cm radius circle area around each tree as close as possible to the ground. The operation scenarios that an ACW should cope with are specified in table 6.1, while the work tasks considered and the methods chosen are specified in table 6.2.

The simplest and most robust method for weed cutting is a rotary cutter, which is well-known from lawn mowers and agricultural forage mowers, which are available in many different designs and sizes. Figure 8.1 show some different cutter unit designs with the cutter blade shielded in a housing. This is a good safety precaution but will require rather frequent cutting to prevent weed plants from growing too large and vigorous to be bent beneath the cutter shielding.

8.2 Optimum operation pattern and vehicle positioning

Cutting of the minimum required circular areas around each tree may be performed by a loop type operation pattern where the ACW travels around each tree while cutting a band of 40 cm. Alternatively the ACW could travel parallel to the rows on either side (figure 8.2). Of these the parallel operation pattern is found to be the simplest and most favourable in terms of efficiency and costs (see chapter 9).

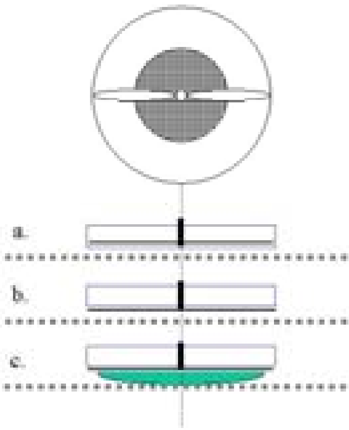

Figure 8.1. Outline of different rotor cutter designs. The rotor may be mounted within a housing (a) to achieve maximum safety on the expense of ability to cut high robust weeds, or the rotor may be mounted just below the housing (b and c) to improve the ability to cut such weeds on the expense of safety. In all cases the shield will protect the trees, if the vehicle positioning should be insufficiently accurate. Type a and b are considered suitable for vehicle designs having the trailing wheels mounted close to the rotor, while type c, which has a skid-pan underneath the rotor, is suitable for rotor placement in larger distance from the trailing wheels.

The parallel operation pattern means that the vehicle travels along the row with the rotor cutter overlapping the row centre line by a few cm. When approaching a tree it may be designed to go about it by a quick sideward reciprocal movement. Alternatively the rotor cutter may be moved side wards in a similar way.

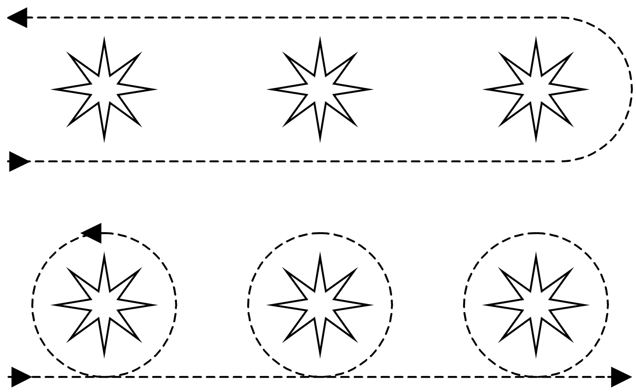

Figure 8.2. Parallel (top) and loop type operation patterns.

8.3 Vehicle concepts

Of the vehicle concepts described in appendix A the “beetle type” and the portal type was selected for closer examination.

8.3.1 The beetle type

The “beetle type” is a small lawn mower type of machine (figure 8.3). It only travels within the cut swath and is small enough to move relatively close to the trees has a size suitable to move underneath branches and in between any two trees in a plantation. It would not have any restrictions from the size of the trees and would not cause problems of tree damage at headlands. In addition it would be suitable for weeding in a number of other tree and bush cultures, e.g. in horticulture.

It is probably also the simplest possible design with a minimum of moving parts as the wheels are used to do all positioning relative to the ground and to the trees. For the same reason 4-wheel drive and 4-wheel steering would be important.

The larger beetle type (figure 8.4) is somewhat more complicated but because of the floating rotor cutter suspension and skid-pad, it may have better abilities to work on uneven ground and to pass obstacles. The relative positioning of the rotor to the trees may in this case be done by one set of steering wheels, but it may be simpler to have the vehicle to travel on a strait line and to position the rotor cutter relatively to the vehicle by means of a simple control system.

This beetle version could even carry a rotor cutter on either side with individual near positioning systems, which would double the capacity, but also make turning more difficult. Another disadvantage would be the low clearance, which would affect the leftover weeds between the rows. Also, extra space would have to be provided between the field border and the first row to provide enough space for the wider machine.

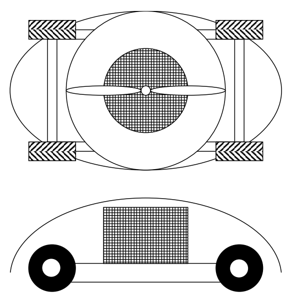

Figure 8.3. Outline of small "beetle type" ACW mounted with central placed rotor cutter.

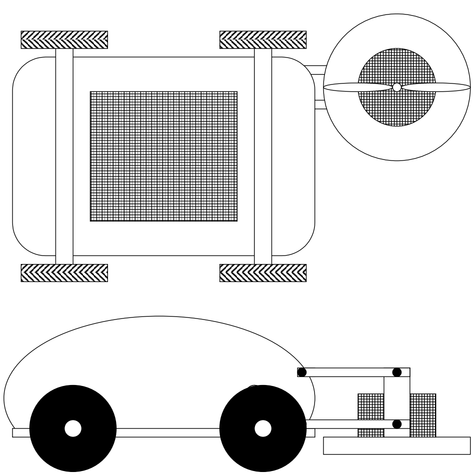

Figure 8.4. Outline of large beetle type weeder with front mounted rotor cutter. A wide design is proposed to place the wheel traffic in the cut lanes only.

8.3.2 The portal type

The portal type (figure 8.5) would be a two-rotor type machine travelling with a set of wheels on either side of a row.

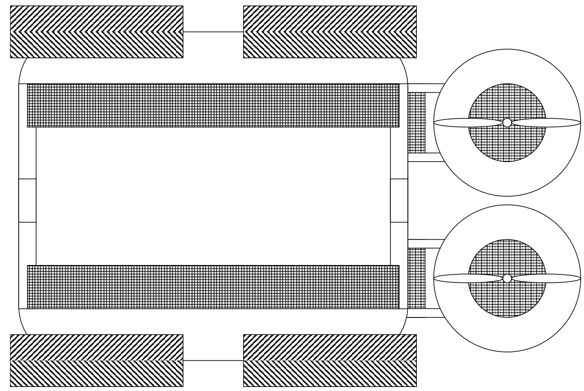

Figure 8.5. Outline of portal type weeder with two rotor cutters seen from the under side.

This type would have limitations regarding the size of the trees, and would also be more complicated to turn on headlands. Another negative point is, that it would be unsuited for operation in most other tree and bush cultures. However the methods of controlling the cutter units into the intra-row area would be similar to those describe above.

8.4 Vehicle operation procedure and transport

It is proposed, that the ACW should work autonomous only within the borders of plantations or a group of plantations having common borders. Before starting the work and eventually at times during the work the operator will input work instructions into the controller by suitable means (e.g. radio or chip card). As part of the work instruction map information (GIS data) for the field borders, occurring obstructions and the tree location has to be provided. The controller will also get information from vehicle-mounted sensors to be used for vehicle guidance, control of the weeding tool and for check up on its own status.

Having been placed in a plantation and given the necessary information the ACW should start to measure its own position and orientation in the field. Then it should work out the best overall operation strategy, i.e. the most efficient order of sub tasks. After that it should start the rotor cutter, move to the first tree and begin to work. Having finished the last tree the ACW should move to the point where it was started up, and report back to the supervisor.

As the production of Christmas trees mostly takes place in small plantations an ACW would in most cases have to serve several plantations to improve utilization and reduce costs. Therefore, the machine would often have to be moved between plantations. This calls for a small, light machine, which is easy to move. One person may move, service and operate many machines simultaneously in one or more plantations at the same time depending on locations.

8.5 System architecture

To achieve the above-described operation of an ACW it must have a controller, which can control machine movements and weeding tool functions. A proposal of a general type of system architecture suitable for this type of controller is provided in appendix B. The information needed for the controller would be a priory information on the positions of plantation borders and trees (GIS database), technical specifications of the vehicle (ACW database and tool database), real time sensor information on the ACW orientation and position absolute and relative to trees and other nearby items of relevance to be able to move and work relative to these, as well as sensor information on the vehicle itself (self awareness and check). Using this data would enable the ACW to work as described in section 8.4. To compensate for inaccuracies of sensor information and positioning of the ACW there seems to be need to sense tree positions relative to the vehicle.

8.6 Sub conclusion

Outlines were proposed of a weeder tool, various vehicle designs, operation patterns as well as vehicle operation procedure and system architecture. The weeder tool suggested is a shielded rotor cutter that can go close to the trees. For the same reason a small vehicle, being able to move beneath the branches, is considered best suited. An operation pattern of linear movement along tree rows was found most efficient. To navigate such a vehicle appropriately would require sensors for measurement of position, orientation and structure of surroundings and others, as well as information on the position of the trees. The system architecture should be adapted to these characteristics.

9 Estimated performance of selected robot concepts

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Having proposed possible outlines of autonomous Christmas tree weeders in the previous chapter the purpose of the following is to estimate the performance characteristics of these outlines.

9.1 Environmental benefits

Compared to the present practice of herbicide application the ACW weeding method has several advantages. Weeds can be controlled without use of herbicides and some natural plant cover may be left over between the rows to improve the biodiversity – an improvement that may help decreasing problems of pests and diseases, and thus the use of pesticides to control these.

Compared to mechanical inter row weeding the method also has the advantages that the soil surface is left nearly untouched and covered by plants, which will reduce problems of nutrient leaching and soil erosion. In addition the energy consumption and CO_2 emission will be much less, because cutting requires less energy than tillage, because only part of the area is treated, and a lightweight vehicle is used. The low weight will also reduce soil compaction.

9.2 Effectiveness of weed control

As described in chapter 4 weeding of 40 cm radius circular areas around each tree is enough to achieve good tree development. Both of the autonomous machine designs outlined in chapter 8 will weed more than this minimum area as they have to mow continuously between the trees. But still they will leave about 33 % (parallel operation pattern) and about 49% (loop operation pattern) of the area untreated. The weeds left in these areas may affect the tree growth positively as they provide shelter and increase biodiversity as already mentioned.

However, problems may occur from large weed plants or trees developing in the untreated areas. This may occasionally require supplementary treatments.

With the precision mechanisms used it is considered possible to weed within a few centimetres of the individual trees, leaving probably less than 1 dm^2 untouched. Weed development in these areas is not likely to cause essential problems because of strong competition from the trees.

9.3 Machine caused losses

Machine caused losses may arise from traffic of vehicles and from injuries caused by weeding tools.

Ignoring any possible negative effects of spray chemicals the only cause of damage associated to spraying may be mechanical injuries along spraying tracks. Also, the damage caused by the present type of mechanical weeding implements is little when they are properly used. It is estimated, that an ACW could reach the same low level.

However when it comes to headlands the present normal size machinery needs a rather broad area for turning, and because of the many turnings required, headlands are often not utilised or suffer from considerable damage. This problem would be solved or would become much less of a problem by use of a small autonomous machine, which can move between the trees at headlands.

9.4 Safety

The methods of achieving safe operation of the suggested ACW in relation to people, animals, trees and the machine itself (described in appendix A and B) are considered sufficient, as the machine is to work in an enclosed environment, is small and is to use screened working tools.

9.5 Estimated area capacity

The term area capacity is defined as the area treated within a unit of time. The area capacity of the beetle type ACW concept was calculated by use of typical or estimated data for the loop type and parallel operation patterns (figure 8.2 and 8.3). It should be noted, that the calculation refers to a design, where the rotor cutter is placed 20 cm off centre.

The parameter values and results are shown in table 9.1. It appears that the effective area capacity (capacity in the defined practical conditions) of the parallel operation pattern is 56% higher than for the loop type. If the off centre distances is reduced to zero the parallel operation pattern is superior by only 4 %, as the vehicle then gets a shorter travelling distance, but this is not considered feasible when the tree becomes some years old, because of the low branches on the trees.

Table 9.1. Anticipated parameter values and corresponding area capacity of the selected types of ACW´s and operation patterns.

Variable	"Beetle", loop	"Beetle", parallel	Unit
Row distance	1,2	1,2	m
Tree distance in row	1,2	1,2	m
ACW minimum distance to tree centre	0,02	0,02	m
Distance from ACW centreline to cutter head centre	0,2	0,2	m
ACW forward speed	0,75	0,75	m/s
ACW cutting width	0,4	0,4	m
Field efficiency	0,8	0,8	h/h
Results			
Time spent on each tree	5,12	3,20	s
Theoretical area capacity	0,28	0,45	m^2/s
Effective area capacity	0,23	0,36	m^2/s
Effective area capacity	0,07	0,16	ha/h

The sensitivity of the results to changes in the assumed parameters values are shown in figure 9.1.

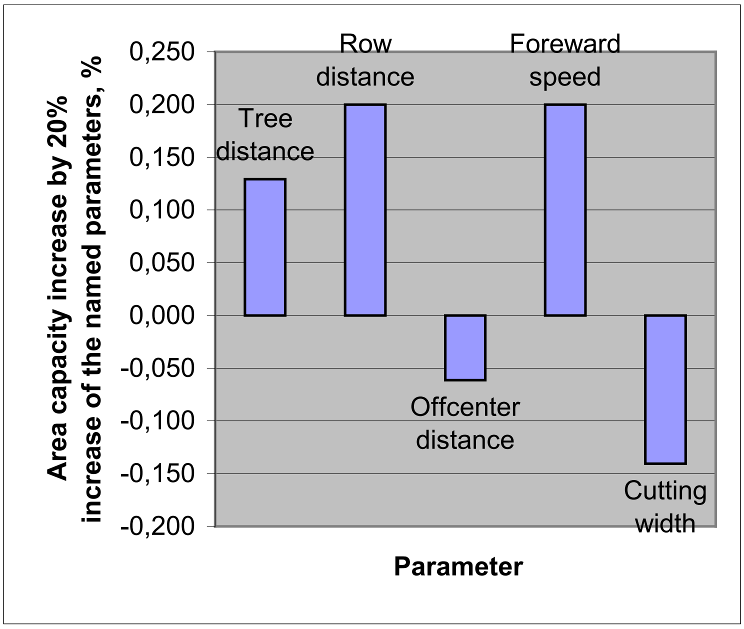

Figure 9.1. Sensitivity of the area capacity of weeding using an ACW in loop operation pattern.

From this it can be seen, that an increase of the forward speed and the row distance have high positive influence on the capacity. The same is the case for the field efficiency, which is not shown. Increases of the off centre distance and the cutting width have less and negative effects.

In case of the parallel operation pattern the field capacity will be proportional to the forward speed, and the field efficiency, while the other parameters have no essential effects.

9.6 Estimated costs

The level of costs associated with operation of an ACW was estimated using a calculation model and best judgement parameter estimates for different operation patterns, (table 9.2). It is of cause not possible to know how realistic these values would be some years a head, but to take an example a conventional self-propelled lawn mower of a suitable size would cost around 25000 to 35000 DKK. Transforming it into an ACW would require sensing systems and controls, which probably will cost considerably more than that, when buying general-purpose equipment. However, prices are expected to drop when the equipment is adapted to the specific purposes, and the electronic processes and software are compressed onto a few computer chips. As an example a general purpose RTK GPS, which now costs about 150000 DKK, is estimated to cost 10000-20000 when adapted to a specific purpose and a general base station. Also the general drop in prices of electronic hardware over time is likely to continue.

The cost estimate in table 9.2 shows an annual cost of around 3300 and 2400 DKK/ha respectively for the two operation modes when weeding 20 ha. This value should be compared to the current contractor rates, which are 1000 – 1500 DKK/ha for spraying of herbicides and 2500 – 3000 for mechanical weeding.

To get an impression of the relative influence on the specific costs of the various parameters a sensitivity analyses was made. For both operation patterns the analysis shows (figure 9.2), that the most important parameters are the area capacity, the parameters of the group of variable costs, and the number of annual weeding operations, while the purchase price and the area allocated to a single ACW are less important.

Table 9.2. Duration and costs associated with the use of an autonomous weeder: A case calculation bases on anticipated parameter values.

Variable	"Beetle", loop	"Beetle", parallel	Unit
Anticipated purchase price	100000	100000	DKK
Fixed cost factor (depreciation + interest)	20	20	%
Annual fixed costs	20000	20000	DKK
Maintenance	15	15	DKK/h
Fuel and oil	10	10	DKK/h
Labour requirement (10 % of operation time)	10	10	DKK/h
Variable costs	35	35	DKK/h
Operational conditions (example)			
Plantation area	20	20	Ha
Working hours each day	16	16	H/day
Number of treatments each season	5	5	1/year
Calculated work duration			
Hours for one treatment	247	154	H
Days for one treatment	15,4	9,6	Days
Hours one season	1234	772	h/season
Days one season	77	48	days/season
Costs			
Fixed costs	15000	20000	DKK/year
Variable costs	43181	27006	DKK/year
Total costs	63183	47006	DKK/year
Specific annual costs	3159	2350	DKK/ha

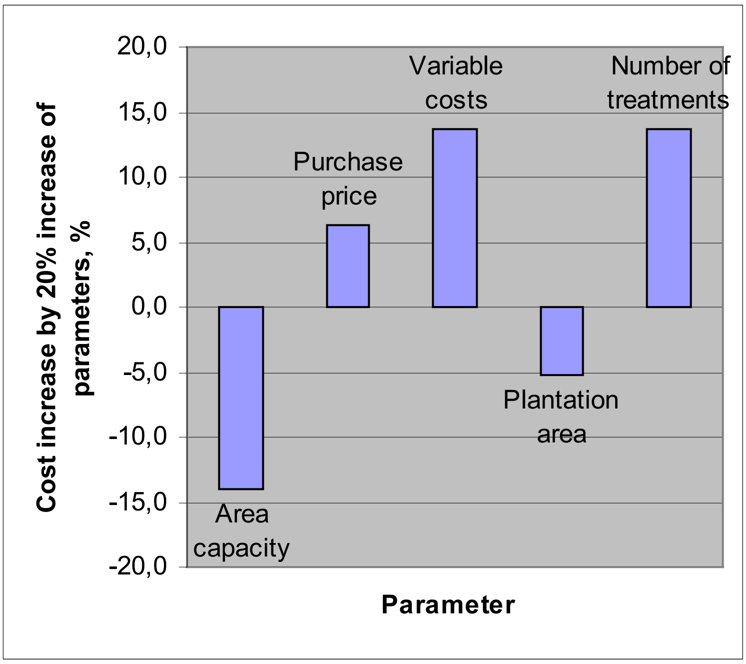

Figure 9.2. Sensitivity of the annual costs of weeding one ha using an ACW in the loop operation pattern.

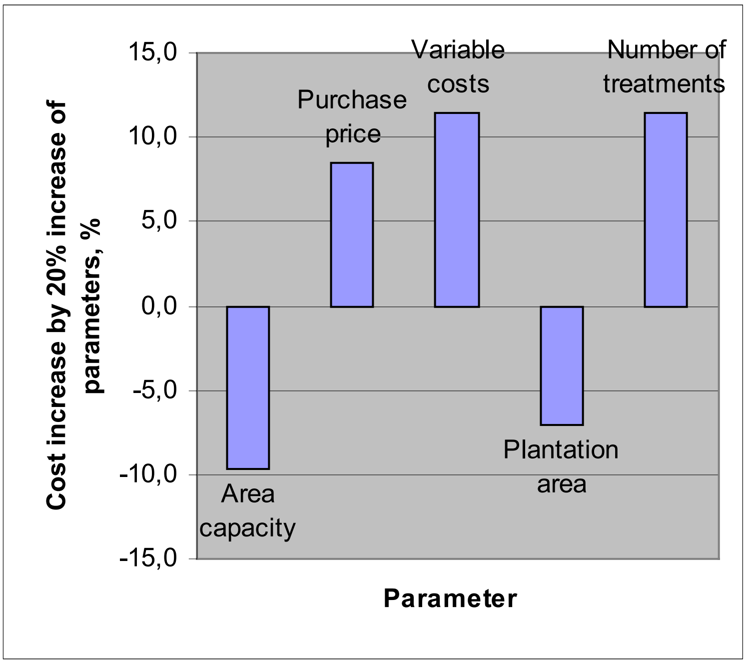

Figure 9.3. Sensitivity of the annual costs of weeding one ha using an ACW in one-sided "strait" operation pattern.

There may be different opinions about whether the chosen parameter values are realistic ore not, but at least the calculations provide an idea about levels and relative significance of the parameters. It appear to be important to find designs and operation patterns that provide high area capacity and low variable costs, while the ACW purchase price is less important. It also seems to show that competitiveness in relation to the present mechanical weeding machinery may be reached within a few years

9.7 Added values

The use of ACW´s in Christmas tree plantations opens possibilities of using the machine sensors and additional sensors to obtain information on individual trees in the plantation. This could for example be size, shape, colour, and occurrence of large weeds near to tree trunks and between the rows. This information could be used for improvement of management decisions like:

- The optimal time of growth regulation (partial debarking or cutting of lower branches), which may vary across the field,
- Supplementary weeding of large weeds,
- Spatial and single tree graduated application of fertilizer and pesticides, Placement of fertilizers and pesticides close to the trees, e.g. carried out by the ACW, to get maximum effect and minimum leaching.

In that way the consumption of auxiliary constituents can be optimised and most likely reduced on plantation basis. At the same time systematic data collection will enable a growth regulation in time and optimise the quality of the plantation.

The value of these opportunities could be quite considerable and would improve the overall economy of the machine.

9.10 Sub conclusions

It is estimated that the proposed ACW system compared to present mechanical weeding may deliver a better quality of work and considerable environmental advantages. On top of that there could be added values in terms of tree specific data for management decisions and costumer information. The costs of the system are estimated to be similar to present contractor rates of mechanical weeding.

10 Conclusions

1. Current Christmas tree production occupies about 31000 ha and has an annual turnover of 500-600 mill. DKK. There are about 4100 producers, of whom the majority have less than 1 ha.

2. Most Christmas trees are produced on farmland. Typically two year old trees are planted on prepared soil. They are cut after 6 to 10 years using selective harvest. Planting patterns are typically square grids with spacing in the range 90 cm to 125 cm.

3. Present weed control measures are mainly chemical (about 70%) and the costs are about 20-25% of the total cultivation costs. Mechanical weeding methods are being developed but are still relatively costly and can mostly only do inter row weeding, which has limited effect and is causing nutrient leaching and soil erosion.

4. The minimum requirement to weed control is found to be an area of about 40 cm radius around each tree corresponding to about 40% of the total area.

5. The requirements of stakeholders are that autonomous Christmas tree weeders should be competitive to present methods and fulfil the minimum requirement of weeding. Stakeholders also want to have several other work tasks, i.e. growth regulation, spot spraying, spatial variable fertilizing, and data collection, done by the autonomous Christmas tree weeder (ACW).

6. The technical requirements to an ACW were defined to cover most plantation scenarios but not extreme cases. Also the workings tasks for the first generation ACW were defined to weeding only, as the development of an appropriate controller system would be the first priority.

7. The general developments within sensing technology, computing technology and robotics has reached a stage where it is considered realistic to develop autonomous machines with appropriate behaviour for regular agricultural and forestry field operations over longer periods.

8. An analysis of different ACW design outlines and operation patterns revealed that the most suitable system was a small machine being able to move in between the trees in a simple operation pattern relative to the location of trees, which are provided in a GIS database.

9. A suitable general type of system architecture was defined using sensor information on position, orientation, surroundings structure, vehicle structure and self-awareness.

10. The environmental benefits of using an autonomous machine in the described way were identified as:

- effective weed control without use of herbicides,
- higher biodiversity because of left over weeds between the rows
- reduction of nutrient leaching and water erosion
- reduction of energy consumption.

11. The overall annual costs of weeding with a future ACW is estimated to be similar to or less than the present costs of mechanical weeding. The costs are more sensitive to changes in the operation costs than to changes in the fixed costs, which means that the purchase price of an autonomous weeder is less important.

12. Added values can be achieved by means of data from the vehicle sensors or additional sensors on tree conditions for management decision purposes, by fitting auxiliary equipment, which can provide individual treatments of the trees.

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A specification of behavioural requirements for an autonomous tractor

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1.1 Abstract

Over the last decade new information technologies, such as GPS and GIS, have been introduced that has allowed the scale of management to be reduced from farm level, down to field level and occasionally to sub field level. With the advent of new information technologies, such as behaviour-based robotics, this process can be continued into the future by looking at an even smaller scale such as plant scale technology or Phytotechnology. (From the Greek phyto, which means plant) These new Phytotechnology units will be small autonomous systems that can behave in a sensible manner for long periods unattended, caring for the individual plant from seeding through to selective harvesting. With this level of sophisticated equipment, it is likely that higher value crops such as in horticulture or forestry will be able to justify such an investment first. Very little new hardware is needed but the challenge is in defining and implementing sensible behaviour and developing the systems architecture to support it. This paper sets out the criteria for the design of such a system.

1.2 Introduction

To further improve the efficiency of developed agriculture, horticulture and forestry found in northern Europe a new concept is being developed that has identified that multiple small autonomous machines would be more efficient than traditional large tractors. In order to meet this hypothesis a *small tractor with intelligent control* is proposed. These vehicles will be able to work longer hours at a slower rate, giving the same, or even greater, overall output as conventional systems. Each vehicle would be capable of working 24 hours a day all year round, in most weather conditions and have the intelligence embedded within it to behave sensibly in a semi-natural environment such as horticulture, agriculture, parks and forestry, whilst carrying out a useful task. Moreover, it may have less environmental impact if it can replace the over-application of chemicals and the high usage of energy, such as diesel and fertiliser, by control that is more intelligent. Additionally, it will require smaller incremental investment and will have lower labour costs. Finally, it may have very low soil compaction that would lead to a more sustainable production system.

Agriculture, horticulture and forestry has benefited in the past from a succession of technological developments that have brought greater productivity and economic efficiency to systems operated in many regions of the globe. Historically, the emphasis of these developments has been on the mechanisation of field operations to increase work rates achievable by individual operators. Today, however, the general trend of increased efficiency through the use of larger, more powerful, machines may be superseded by the adoption of newer information based technologies that may ultimately enable reliable autonomous field operations to be viable (Earl et.al. 2000). A review of possible platforms was carried out by Ellenreider (1996) and a review of automatic steered tractors is given in Wilson 2000.

This scale-reduction process, started by Precision Farming, may lead to the possibility of individual plant care systems called *Phytotechnology*. (Shibusawa 1996) Precision Farming is a set of methodologies that utilise technologies such as the Global Positioning System (GPS), Geographical Information Systems (GIS) and Management Information Systems (MIS) as well as the sensors and controllers in the field, to reduce the area of management from the whole farm down to field level and on occasions sub field level. Due to the increased data processing required to cover a complete field at the individual plant level, only certain operations are carried out with human intervention these processes lend themselves to different forms of automation, especially in high value crops. Two good examples of this process are mechanical weeding and field scouting.

1.3 Mechanical weeding

As most horticultural crops are grown in widely spaced rows, inter-row mechanical weeding (weeding between the rows) has been popular since mechanisation started. The only problem has been in assessing the relative distance between the crop and the weeding tool, as nowadays it is difficult to keep the tractor exactly parallel with the crop row. To overcome this problem, another operator is used to steer the weeding tool relative to the crop row, but this increases the cost. Recent developments have lead to the use of machine vision to recognise the contextual information of the crop rows and steer the tool to within a few centimetres of the plants. This idea was first tested in 1992 (Hoffman 1992, Steinhauser 1994) and has more recently been commercialised by the Danish Institute of Agricultural Sciences and Eco-Dan (Søgaard, 2000).

Intra-row weeding (weeding within the row) has proved to be more difficult due to the problems of discriminating between crop plants and weed plants. A number of techniques have been tried notably categorising plants due to their spectral reflectance characteristics. (Bennedsen 2001) These techniques have worked well in controlled environments, such as the laboratory, but traditionally have not proved so reliable in natural lighting.

An alternative development has been to uniquely identify each individual crop plant by recording the position of each seed as it was planted. (Ehsani 2000) This is not as difficult as it sounds, as technology has developed sufficiently in the form of now standard high-speed PCs and the Real-Time Kinematic Global Positioning System (RTK GPS). Most desktop PCs can easily manage the data rates required during planting as they can also store the 100,000 seed positions in each hectare for Sugar Beet or 10,000

Christmas trees per hectare. The RTK GPS can resolve positions down to 1 cm in stationary mode and 2 cm whilst moving slowly. As the plant positions are now known, a mechanical intra-row weeder can be controlled to move around each plant. Whether this level of accuracy can be maintained in agricultural conditions remains to be seen but a 2 cm systemic shift would result in all the crop plants being removed! (NB Denmark is moving 1 cm to the East each year).

1.4 Field scouting

There are many sensing techniques that that can ascertain crop and soil health. Many of them could be used now in production horticulture, apart from the fact that they take a long time to process the data. Examples are multi-spectral response from the plant canopy that can indicate stress (whatever the cause) and chlorophyll content is associated with crop vigour. Carbon dioxide (CO_2) has been associated with soil health, Ethylene can be associated with pest attack and conductivity has been correlated with soil moisture. (Waine 1999, Waine, et.al. 2000) Soil nitrates, organic matter, Charged-ion Exchange Capacity (CEC), pH and soil moisture have been measured at different depths using Near Infra-Red (NIR) reflectance with a soil photo spectrometer. (Shibusawa 2000) Ion Selective Field Effect Transistors (ISFETs) can be modified to be sensitive to nitrates, pH and other factors from soil solution. (Birrell #) Most of these sensing systems are still in the research phase but they hold great promise to improve our understanding and management of the growing crop and its environment. If these systems were mounted on an autonomous vehicle then they could be used commercially now and not have the associated problems of paying an operator to wait in the field while the processing takes place.

1.5 Autonomous vehicle requirements

Both of these tasks (as well as many more) could be mounted on a small autonomous vehicle that could roam the field carrying out its task over prolonged periods of time but to be able to achieve this the vehicle must have certain attributes and behaviours.

The main design parameters for this proposed vehicle are that it is:

- Small in size (and therefore unmanned)
- Light weight
- Exhibit long-term sensible behaviour
- Capable of receiving instructions and communicating information
- Capable of being co-ordinated with other machines
- Capable of working collaboratively with other machines
- Behave in a safe manner, even when partial system failures occur
- Carry out a range of useful tasks

1.5.1 Small size

A small vehicle size is very meaningful as it ensures higher precision of operation, lower incremental investment and is relatively safe during system failures. The vehicles will probably be 1-2 metres long and in the 10-30 hp range, as they will require an internal combustion engine. An engine is needed due to the energy - density requirement that battery power alone cannot supply. Smaller vehicles of less than a metre and around five hp could be developed for highly specialised tasks with low energy requirements such as non-contact sensing. Much smaller systems could be developed when higher density energy sources become available such as fuel cells. The control systems described here could be applied to any size platform. Incremental investment and replacement of the vehicle and high production runs can be achieved by possibly using standard car components. The farmer's and the public's acceptance will be increased with the launch of small autonomous vehicles rather than bigger ones. These vehicles will have the advantage to be more site-specific than larger machines, due to higher manoeuvrability. Inevitably, the smaller vehicle will have a lower work-rate but as it will be unmanned, it can work for longer hours to compensate. Using site-specific fertilising and spraying, it can achieve a further reduction in inputs, if combined with appropriate sensors These small machines will be able to do selective and more precise treatments and can potentially be developed to sense and care for individual plants or sub plant manipulation, e.g. thinning, pruning, selective harvesting etc.

1.5.2 Light weight

The lightweight design parameter is important as it implies reduced soil compaction. Chamen (1994) has identified that a 70% energy saving can be made in cultivation energy by moving from traditional trafficked systems (255 MJ/ha) to a non-trafficked system (79 MJ/ha). This was for shallow ploughing and did not include any deep loosening. From this we estimate that 80-90% of the energy going into traditional cultivation is there to repair the damage done by large tractors. If we can accept the premise of a light intelligent vehicle replacing the large tractors, there is the possibility to develop a completely new agricultural mechanisation system. As we have the possibility of very low compaction and mechanical weeding, then we do not need to plough, but use micro-tillage and direct drilling, which could play a major role in conservation agriculture. As the natural healthy soil bio-system modifies the soil structure into a near ideal situation for root development, almost zero compaction agriculture could be developed that allows the natural processes to enhance production rather than introducing energy to compact and then recreate a good soil structure. As the vehicle is inherently light, it should also require lower energy inputs although this is offset by the higher efficiencies of the larger engines.

1.5.3 Autonomous behaviour

The main behavioural requirement of this vehicle is that it will have sensible long-term unattended behaviour in a semi-natural environment such as horticulture, agriculture, parkland and forestry. This sensible long-term behaviour is made up of a number of parts. Firstly, sensible behaviour needs to be defined, which at the moment is device independent. Alan Turing defined a simple test (the Turing test) for artificial intelligence, which is, in essence, if a machine's behaviour is indistinguishable from a person then it must be intelligent. We cannot yet develop an intelligent machine but we can make it more intelligent than it is today by defining a set of behaviour modes that make it react in a sensible way, defined by people, to a predefined set of stimuli in the form of an expert system. Secondly, it must be able to carry out its task over prolonged periods, unattended. When it needs to refuel or re supply logistics, it must be capable of returning to base and restocking. Thirdly, safety behaviours are important at a number of levels. The operational modes of the machine must make it safe to others as well as itself, but it must be capable of graceful degradation when sub-systems malfunction. Catastrophic failure must be avoided, so multiple levels of system redundancy must be designed into the vehicle. Fourthly, as the vehicle is interacting with the complex semi-natural environment it must use sophisticated sensing and control systems, probably in an object oriented manner, to be able to behave correctly in complex situations.

Behaviour in general terms is a thematic set of reactions to a stimulus. Behaviour-based systems provide a means for the vehicle to execute a behaviour e.g. navigation, by endowing the vehicle with behaviours that deal with specific goals independently and coordinating them in a purposeful way (Arkin 1998). Four main behaviour modes for this vehicle have been identified.

1.5.3.1 Navigation mode

The vehicle must be able to navigate safely to a desired position. We estimate that the vehicle will be in navigation mode around 80-90% of its time, as positioning itself and its working tool is the vehicle’s main requirement. The vehicle must be able to plan an efficient route to the target point taking into account known objects, tracks, paths, gateways etc., as well as being able to react to unknown objects or situations. This high-level behavioural mode subsumes other lower level behaviours such as route planning and object avoidance.

Deterministic planning of the optimal route for the vehicle between the current position and the desired position requires detailed information about the physical terrain and attributes. This type of spatially related data is best stored and processed in a geographical information system (GIS). Route planning software is currently available but it must take into account the characteristics of the vehicle, such as width, height, turning circle etc., as well as expected time of arrival so that speeds can be calculated. The goal for the vehicle should be to arrive at a predetermined position, attitude and time.

When objects are detected, a sub system will track the range and bearing of the nearest objects until it is clear that the object may become an obstacle, the vehicle will slow its speed to a safe distance and then stop. If the object does not move then the vehicle will perceive it as stationary and give an audible warning to an animal or human to move out of the way. If the obstacle remains stationary then the vehicle will go around it and record the size and position in the GIS. On the other hand, if the object moves, it will then wait for it to move out of the way and then proceed. If finally the object approaches the vehicle, it will perceive the object as threat, and it will close down into a safe mode.

A specialised navigation mode is refuelling. When the vehicle needs to refuel, restock logistical requirements (e.g. replenish chemicals or replace worn tines) or need other attention, it must navigate back to its base and connect with the docking station. Once refuelled and restocked or manually repaired, it can then go back to the field and continue.

1.5.3.2 Exploratory mode

The vehicle will be fitted with local environment sensing systems, which will enable it to explore and record an unknown environment. If the vehicle is initialised in an unknown area with an empty GIS, it can start to populate the GIS with its own data. In the exploratory mode, the vehicle will record data from all its sensors at the current position. If it assesses that it is safe to move ahead it will then move slowly recording relevant data as it moves. Depending on the search pattern required (zigzag across an area, follow boundaries etc.) it could work out a route dependant on conditions. Once an area has been explored and surveyed, more optimal deterministic route plans can be made to carry out surveys. A good example would be a self-adaptive soil survey based on the position and the results from the sensor. Fewer readings could be taken from seemingly homogenous areas, while more intensive sampling can occur in areas of heterogeneity.

1.5.3.3 Self-awareness mode

The vehicle will also be fitted with self-sensing systems built into it to keep a check that all the major parameters are within normal limits. Some of these parameters will be fuel level, engine temperature, tilt angle and outside temperature. (It may be beneficial to add a small weather station as well so that it can return to base or close down if conditions get too bad.) If any of these parameters go outside expected limits, it can give non-critical warnings but if they are seen as critical then the vehicle can move into one of its safe modes. This behavioural mode is not mutually exclusive to any of the other modes so may be run entirely in parallel as a separate process.

1.5.3.4 Implement task mode

The vehicle will have mechanical, electrical power and communication interfaces to allow a range of implements to be fitted so that the vehicle and implement can undertake specific tasks such as mechanical weeding or crop sensing. The mechanical interface is likely to consist primarily of a category zero three-point linkage, which is a recognized standard coupling. Alternative arrangements may be considered if a tighter mechanical coupling is required. The power and the communication interface may well utilize another existing standard such as the control area network (CAN) bus or LBS connector. In this model, we are taking the same roles as existing tractors and implements but scaling them down. The vehicle, like the tractor, will supply the motive power and positioning for the more specialist implement. Common data like positioning, attitude etc. is more closely linked with the vehicle as it is likely to be common to all implement tasks. The data will be available to the implement via the bus. Each implement will have at least one job computer to control the implement tasks and send requests to move to the vehicle. Whilst the implement task is active, the implement controller will control the actions of the vehicle. The implement will have at least one ‘focus area’. That is, the active area on the vehicle such as the view from the camera or weeding area of the tine. This must be matched up to the ‘target area’ by moving the vehicle or the implement may have an extra degree of freedom. In either case, when the implement has finished in one area, it will instruct the vehicle to move to the next area. If a continuous process can be achieved then the vehicle could move along a predefined path and speed while the implement works independently.

Each implement will have its own special requirements for calibration and error checking. It is envisaged that each implement task will have sub-behaviours and that all the processes can be properly calibrated or checked. This will allow the task to periodically carry out a self-check to ensure all functions are working correctly. If an implement task recognises that the weeding tines are worn or that the camera lens is obscured it can carry out remedial action or return to base for servicing.

1.5.4 Communication

Communication between the various processes within the vehicle will be implemented by using a bus system and processor nodes. The bus will be a recognised standard such as CAN or Ethernet but the communication traffic will be kept to a minimum by utilising a high level message passing protocol. All messages will be in text form and a log file will be kept for faultfinding and error checking. All processes will be closely coupled to their respective sensors and actuators directly to avoid any closed loop control systems being adversely affected by time lag over the network. Each vehicle will have a supervisor process (probably in the form of a laptop) that will display the status, keep the log file, and check that the messages are within bounds for a second level of safety.

Communication between a vehicle and the coordinator will be through the vehicle supervisor and a radio Ethernet LAN or other wide bandwidth protocol. Peer-to-peer communication between the vehicles will be implemented in the same way.

1.5.5 Co-ordination

A computer at the farm office, operated by the manager, will hold the overall control of the autonomous vehicles. It should have an independent real time real-time video link to each vehicle with a steerable camera so that the manager can get a quick impression of what the vehicles are doing. This can be combined with a mimic status display of all the functional parameters of the vehicles.

When a new job is planned or a new vehicle is added to the team, an optimisation routine can be invoked to calculate the best strategies, initial routes, placements etc. for the vehicles. This overall plan can then be decomposed into specific tasks for each vehicle and send via a dedicated radio link. The coordinating PC will also hold the master GIS that can be synchronised with the vehicle GIS at the end of each day. The coordinator will also prepare all the required operational and application maps as well as the actual treatments carried out by the vehicles. Other functions will keep records of the logistics.

At times it may be more convenient to have a mobile base station, in the form of a trailer, within a distant field that can serve as a remote docking station for logistics, contain the differential GPS base station, radio repeater, weather station etc. It should have the capacity to allow multiple machines to self dock on the trailer after work to allow the operator to then hook it up to a car or tractor and move the whole system back to the farm for servicing or storage.

1.5.6 Collaboration

As part of the overall design philosophy, these small vehicles must be capable of collaborating on mutual tasks. This will help to improve the works rates and allow the time critical tasks to meet their deadlines by scaling up the number of operational machines. As each machine will still be independent and autonomous, its tasks will be coordinated centrally with the other vehicles to achieve optimal effectiveness. High levels of system integration later may allow the vehicles to work as one entity.

1.5.7 Safety

The autonomous vehicles should always operate in a safe state. Safety is expressed in terms of safety to others, safety of self and safety of the crop. These safety issues are addressed in terms of intelligent sensing and redundant systems. Intelligent sensing involves more than one transducer sensing the same object. Multiple transducers can sense the same measurements for double-checking and contain redundant data to improve reliability. The embedded processor arbitrates between the transducers outputs and chooses the better one. (Blackmore and Steinhauser, 1993) An example of this approach is by using ultrasonic range sensors combined with a laser scanner to track potential obstacles in front of the vehicle.

Redundant systems allow the capability of graceful degradation during partial system failure. Graceful degradation is the process where parts of the system fail but the overall system is capable of functioning even though with a reduced capability. This generally involves only part of the task being fulfilled, which is arguably better than a complete shut down. Functionality is gradually reduced as faults increase. Only systems with redundant sub systems can allow this type of behaviour.

The primary safety modes for the vehicle and implement task will be

1. In a safe operation
2. All vehicle and implement systems are operating within normal parameters
3. Safe operation with warnings
4. Operating safely, but there are some warnings about abnormalities (e.g. low fuel)
5. Partial system shut down – mobile
6. Partially shut down, although it remains mobile (e.g. camera lens obscured)
7. Partial system shut down – immobile
8. Partially shut down, the vehicle is immobile (e.g. transmission fault)
9. Stopped – still communicating
10. Fully shut down, but it still communicates with the co-ordinator (e.g. internal fault)
11. Dead
12. The system has fully shut down and there is no communication with the co-ordinator

To ensure that a controlled process is reliable, always available and safe, it is necessary to perform condition monitoring, predictive maintenance and fault diagnosis, as well as ensuring the quality of the system components (the sensors, the actuators, the process control computers, etc.). One of the main goals is an early diagnosis (detection, isolation and identification) of faults, whilst they are incipient and hard to detect and isolate. Another goal is to ensure that the process can tolerate faults through control system reconfiguration or by a graceful degradation of safe and stable closed-loop performance. Human factors and man-machine interfaces are the final links in the safe operation of technical processes so full data about the vehicle and task should be available in an understandable form.

Blanke et.al. (2001) refer to fault-tolerant control systems that employ redundancy in an automation system to make "intelligent" software that monitors behaviour of components and function blocks. Faults are isolated and appropriate remedial actions taken to prevent that faults develop into critical failures. The overall fault-tolerant control strategy is to keep the automation system's availability and accept reduced performance when critical faults occur.

Control of the vehicle will also be layered. Full automation will occur when the vehicle system has complete autonomy in its own actions after the task has been defined. At the other extreme, an operator can control the vehicle's main control functions. This can be achieved by either using a joystick, or more directly, adjusting each control parameter individually from either the supervisor laptop or the coordinator PC via the radio Ethernet.

As these vehicles are being designed to work for long periods unattended, there is a significant likelihood of theft. If someone approaches the vehicle, it will shut down into a safe mode until the person goes away. A legitimate operator could have access to the vehicle control by using a radio key fob but without it, the machine could go into stasis recording activity and sending this record with its position back the coordinating PC. If the vehicle was seen to move without powering the drive motors, then an alarm could be triggered.

1.6 Vehicle concepts

Although this paper is predominantly focussed on the specification of requirements independent of the hardware, it is useful to consider alternative platforms.

We are considering using three main types of vehicle layout:
1 Conventional small tractor (e.g. 26 hp Hakotrac 3000)
2 Specialised portal tractor (small and medium sized)
3 Highly specialized very small vehicle

1.6.1 Conventional small tractor

This type of vehicle has many advantages in that it is commercially produced, reliable, multi-purpose product supported by the manufacturer. All the mechanical and hydraulic systems conform to recognised standards. The autonomous systems can be retro fitted and the human control interfaces would be modified to include actuators.

Although the vehicle is lighter than most conventional tractors, (see figure 1) it is still heavy enough to cause soil compaction. Another difficulty is to fit the shear bulk of the autonomous systems, as the original tractor design does not allow for this type of addition. Furthermore, as the tractor is of conventional design, (2 rear wheel drive, 2 front wheel drive and steer) it has limited manoeuvrability.

FIGURE 1. The Hakotrak 3000. This tractor is currently being adapted to accept the Agronav automatic steering system from GEO-TEC as part of a collaborative Danish research programme called Autonomous Platform and Information system (API).

TABLE 1. The technical requirements for the small conventional tractor

Power	20 - 30 hp
Engine	Diesel
Speeds	Infinitely variable within 3 ranges, hydrostatic
Controls	Mechanically operated hydrostatic Electrically operated hydrostatic
Wheels	Four wheel drive 2 wheel steering
Chassis	Medium ground clearance
Implement mounting	Front three-point linkage Rear three-point linkage

1.6.2 Portal tractor

The small portal tractor will have to be completely fabricated as no known commercial examples exist. It will be highly manoeuvrable as it will be 4-wheel drive and 4-wheel steer, which will greatly help the control algorithms when accurate positioning is required. It should be capable of carry a range of implements that will be centre mounted within the portal frame of the tractor, such as the mechanical weeding tool. A good example of such a vehicle was designed and built by two Master of Science students (Madsen and Jakobsen) at the Danish Technical University in 2001 and is shown in figure 2.

FIGURE 2. Small portal tractor from the Danish Technical University

The larger portal tractors are produced in great numbers in Japan, for working in paddy fields. They have the advantage of being designed and built for the agricultural environment, light weight, high ground clearance and has standard category zero (or one) rear three-point linkage. The example in Figure 3 has 4WD, 2WS but a 4WS could be easily made by using two front axles.

TABLE 2. The technical requirements for the smaller portal tractor

Power	10 – 15 hp
Engine	Internal combustion engine (Battery at the moment)
Speeds	Infinitely variable wheel motors
Controls	Electronic interface
Wheels	Four wheel drive (4WD) Four wheel steering (4WS)
Chassis	High ground clearance
Implements	Centre mounted

FIGURE 3. A Japanese, larger type, portal tractor.

TABLE 3. The technical requirements for the larger portal type tractor

Power	10 – 20 hp
Engine	Diesel
Speeds	Conventionally geared
Controls	Mechanical
Wheels	Four wheel drive Two wheel steering
Chassis	High ground clearance
Implement mounting	Rear three-point linkage

1.6.3 Very small vehicle. (The 'Beetle')

This type of vehicle is probably as small as an agricultural vehicle can get (~1m), as it needs to carry enough energy for the required tasks as well as being able to remain mobile over cultivated soil and crop residues. Each type of vehicle will be highly specialised and contain an integrated tool such as a grass cutter (figure 4). To achieve such a small size, very high levels of integration will be needed.

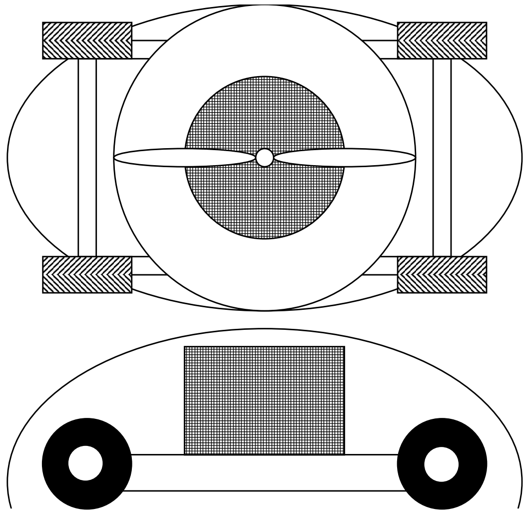

FIGURE 4. Simple schematic drawing of the beetle

Existing grass cutting equipment could be modified to give the required mobility and carry the associated control equipment. This could cause problems due to the bulk of the current equipment. This vehicle is currently being evaluated for suitability of autonomous Christmas tree weeding by the authors.

TABLE 4. The technical requirements for the beetle

Power	~ 5 hp
Engine	Petrol
Speeds	Fixed speeds
Controls	Electro-mechanical
Wheels	Four wheel drive Four wheel steering
Chassis	Very low clearance (dependant on task)
Implement mounting	Integral grass cutter

1.7 Conclusions

This paper has defined a set of requirements that form the basis for a control system that should be capable of behaving sensibly in a semi-natural environment. Behaviours modes have been described as well as the philosophical approaches to the final design from a top-down approach. Graceful degradation through using redundant systems has been identified as a key element in the production of a safe autonomous vehicle. Some alternative vehicle platforms have been considered.

Proposed Systems architecture

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To be able to achieve the behaviours noted in appendix A an inherently complex and sophisticated system architecture is needed. It must have redundant systems to achieve fault tolerance and be object oriented to remain manageable. The objects with the SA will follow the same definitions of object-oriented software in terms of encapsulation, inheritance and polymorphism. Encapsulation is of most use to us as it denotes a rigid sub-system boundary that we only need to define the interface and function at this time. Inheritance and polymorphism is a little more difficult to achieve in hardware but processing units that can fulfil the basic functions can be modified to suit particular applications. Communication between objects will only be as text messages that can be understood by people as well to allow easy analysis of the system.

The system architecture presented here has been developed to accommodate the behavioural requirements.

1.1 Background

We consider the definition of both the behaviour and the system architecture to be of paramount importance before constructing the vehicle itself. In general terms, it is a description of how a system is constructed from basics and how the components fit together to form the whole system (Albus, 1995).

Kortenkamp (1998) states that systems architecture is a set of inter-related components organized to achieve certain goals. Every component of the system has to be fully understood and to the interrelationships among the components has to be defined. Arkin (1998) states that behaviors are actually the answer to the question "What should the autonomous vehicle be able to do?" Rzevski (1995) mentions that behavior of a machine is a particular interaction of the machine with its environment over a period of time, defined by a particular set of inputs from and outputs into the environment over that period.

In general terms, at every point in time, the vehicle is faced with a variety of feasible next states to which the machine could move, and it aims to find the transition that is likely to provide the maximum long-term benefit. The maximum benefit may be expressed in a variety of ways- like the minimum risk of failure, the shortest route to a destination and the maximum utilization factor of a given machine (Rzevski, 1995).

The proposed systems architecture has been designed to accommodate the behaviors already defined. As this behavior-based system consists of a number of different behaviors that the vehicle needs to undertake to accomplish the desired tasks each element within the system must contribute to one of them. A short description of the proposed behaviors can be seen in table B.1.

1.2 Systems Architecture design

In order to achieve these behaviours an object-oriented systems architecture design was developed. To construct this design we followed the Arkin (1998) assumption that robotic architecture designs refer to a software architecture, rather than hardware side of the system.

The benefit with the proposed system architecture is that we can divide the system into elements or objects and we can deal with them independently. Rzevski (1995) also supports this concept. He states that the architecture design usually divides the product into large modules that bring together a set of conceptually related concerns, with relatively narrow interfaces between them. A narrow interface minimizes the interaction between the modules it connects to. The advantage of well-defined interfaces is that if a change has to be made in one module during the design process, no change is needed in other modules unless the interfaces are modified. This interface definition also adheres to the object oriented design philosophy.

Table B.1. Descriptions of behaviour modes.

Behaviours	Description
Navigation	The process of moving safely to a required position at a given time
Refuelling	A SPECIALISED FORM OF NAVIGATION BACK TO A BASE STATION
Idle	The vehicle is doing nothing. It waits for a command to react.
Implement task	A behaviour that is executed by the attached implement whilst carrying out the assigned task.
Self-check	A process that runs all the time in the background. It checks to see if all the parameters of the vehicle are nominal. It keeps a log file and reports abnormalities
Safety	Consists of different layers according to the importance of the existing situation.
Explore	A behaviour that extracts information from the unknown external environment to populate the GIS.
Planning	A behaviour that analyses all the aggregated information to determine the initial waypoints.
Request to start	The behaviour from power up of the vehicle and before it moves into any other mode. All systems are reset and checked before continuing.
Request to stop	This behaviour indicates that the system is ready for power off. It will be a terminal behaviour requiring that the power have to be shut off. During this process, the vehicle may also put all the mechanical components into a safe neutral position.

Each object will only communicate through high level or natural language messages. Each message will have the capability to pass specific parameters that are closely coupled to the particular message. This is the approach taken by a number of other researchers. (Konoglie, 1998 etc) The schematic diagram of the proposed system architecture is shown in Figure B.2.

In the proposed systems architecture design there are two types of objects: processes and databases. Processes execute a coherent set of tasks to achieve an overall goal. This could be pure processing of data, interfaced to sensors or closed loop control. The databases store and retrieve data on demand. Each on-board process could be realized as a processor node, with only messages being passed between them, over a common bus. The current object oriented processes and databases are described here.

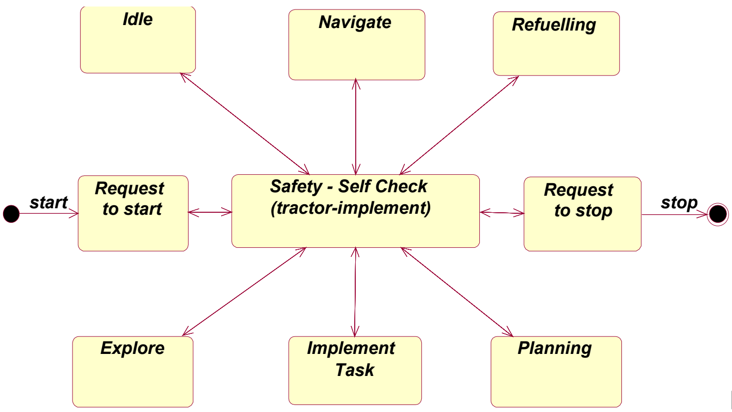

Figure B.1. State diagram showing some of the behaviours and their transitions.

1.2.1 Coordinator

The coordinating process will be carried out in the farm office on a PC. (All other processes will be realised on-board the vehicle) It is likely to be a set of optimisation routines that can be instigated by the farm manager. High-level requests can be made, such as monitor the crop in field 10 for 2 days or carry out intra-row weeding in field 5 with implement number 2. The coordinating program can then allocate resources, (e.g. which vehicles to use) prepare an initial route plan based on the GIS and develop a suggested instruction set for the vehicle(s). The manager can then review the proposed itinerary and make adjustments to it before it is then downloaded to the vehicle(s). The coordination process will also be in on-demand communication with the vehicles and show the manager the current location and status of each machine. A real-time video link to steer able on-board cameras would also allow a better understanding of the vehicle’s environment.

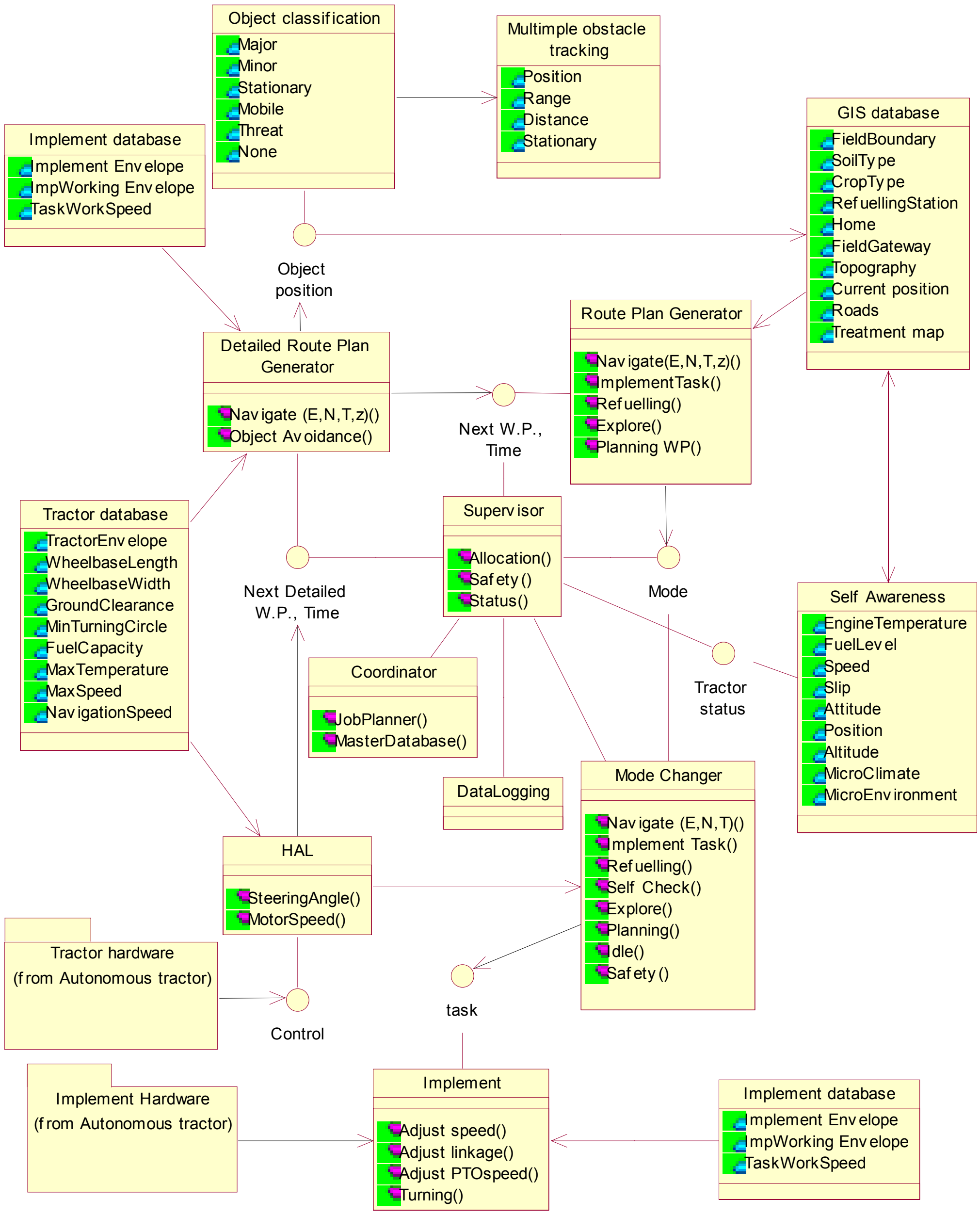

FIGURE B.2. The proposed system architecture.

1.2.2 Supervisor

The supervising process will be hosted on a laptop computer on the vehicle. Firstly, it will relay the appropriate tasks to be executed from the coordinator through a radio modem. Secondly, it will supervise different states of the vehicle and keep a transaction log file of all the messages on the bus. Thirdly, it will present the current status of the vehicle, as a mimic, on the computer's monitor to allow an operator to interact with it directly.

It is not directly used within the control loop but is one of the redundant systems that can supervise the other processes. It will have an expert system that can decide if any of the processes may be malfunctioning, in which case it can then intervene. The expert system can hold a set of sensible parameter values for comparison with what the processes are sending. It can also send simple requests to each process and check that it gets an expected reply. If it receives an unexpected reply then further checks can be made to identify the situation and take suitable actions like reset the process or shut down the whole vehicle into one of the safety modes.

1.2.3 Mode changer

The mode changer is a process that can assess the current situation from other processes and command each process to switch into a particular mode that can allow an appropriate overall behaviour. It may receive an imperative command from the coordinator, through the supervisor, for the vehicle to go to a particular position. It will check all processes to establish it is safe to switch modes and then issue the appropriate command to each process. An example would be where the manager instructed the vehicle to navigate to a particular Easting and Northing near by. If each process responded that it was nominal, capable of accepting a new mode, and that the implement was secured ready for transport, then each process could be configured to allow the vehicle to navigate to the required position.

Identified messages are: Navigate(Easting, Northing, Time of arrival), Implement task(mode), Refuelling(), Self check(), Explore(), Idle(), Safety(mode), Status(), Reset(), Load program(File Name).

1.2.4 Route plan generator (RPG)

The route plan generator can accept a completed route plan from the route planner in the coordinator or generate its own when asked to navigate to a certain position. It will generate a series of waypoints that the vehicle will follow to arrive at its final destination at the desired time. The waypoints will take into account all the prior knowledge in the GIS, such as gateways, preferred paths and tracks, as well as obstacles such as fences, ditches and public roads. At this stage of the planning it is assumed that the vehicle will travel on the straight line between the waypoints, so careful positioning is crucial if the vehicle is to stay on a narrow curving track. These series of points will be optimised for efficiency of the task in hand (minimum distance would be one criteria), such as to provide the best route to start at a gateway, go down every row in a field and come back to the gateway, avoiding the known obstacles. This route plan is predetermined before the vehicle moves and includes the estimated time of arrival at each waypoint, knowing the start time, end time and distance to be travelled. If the arrival time at the target position computes to unrealistic speeds for the vehicle then a warning will be given to the operator. The control processes will not allow the vehicle to be operated outside predefined limits stored in the vehicle database.

1.2.5 Detailed route plan generator (DRPG)

The detailed route plan generator initially calculates a series of detailed waypoints linearly between the waypoints from the RPG at a set distance apart and sends steering and speed messages to the hardware abstraction layer to move towards the next target position. As the vehicle gets to within a certain distance from a detailed waypoint, it switches to the next one in the series. This process will continue until it reaches the next waypoint, unless there is an obstruction in the way.

If an object is sensed within a predefined range and bearing of the vehicle, then the DRPG will stop the vehicle and wait. If the range and bearing of the obstacle changes, then the DRPG will consider it to be a mobile obstacle and wait for it to move outside the safety range and resume its navigation. If the obstacle moves towards the vehicle then it will be seen as a threat and warn the mode changer. If the object appears to be stationary, then its estimated boundary will be entered into the GIS and the vehicle will try to circumnavigate the obstruction.

An obstacle will be deemed an obstruction if it is likely to interfere with the movement of the vehicle or attached implement. If an obstacle is sensed by the obstacle tracking processes to be within the working safety envelope, (derived from the tractor envelope in the tractor database and the implement envelope from the implement database) a new detailed waypoint will be generated to take the vehicle towards the next waypoint but at a safe distance from the obstacle. At this stage, the DRPG does not know the size or the extent of this unforeseen obstacle, so it must rely on the sensors to estimate the distance and plan the next detailed waypoint accordingly and update the GIS for future reference.

1.2.6 Multiple obstacle tracking

This process runs in parallel all the time with the other processes and uses sensors to search the local environment around the vehicle for any obstacles. It can estimate the range and bearing (relative to the vehicle) of a number of obstacles within its sensing range and make a special note of the nearest one and passes this to the DRPG and the safety process. (not shown in the diagram).

1.2.7 Object classification

The navigation process described so far has assumed a two-dimensional world, i.e. all obstacles are of infinite height, as is the tractor and implement. The object classification process may be needed to deal with three-dimensional objects interacting with the three dimensional vehicle. If there is a small obstacle (e.g. a small stone) in the way, can the vehicle go over it, or should it go round? This complex issue would need a separate model of the tractor and implement.

1.2.8 Hardware abstraction layer (HAL)

The hardware abstraction layer object receives the bearing and speed messages from the DRPG and then implements it on the physical platform. It will use an inverse kinematic model to determine the steering angles and wheel speeds before controlling the actuators. Each actuator will also have a transducer to measure the actuator to ensure accuracy. Closed-loop feedback will be used at a number of levels to ensure reliability, but all loops will be within the HAL object (apart from the GPS messages) as the stability of closed loop feedback requires fast responses which cannot be guaranteed over the bus. As the vehicle is encapsulated within the HAL object, no process can get direct access the vehicle control system unless it goes through the HAL.

1.2.9 Self awareness

The self-awareness process also runs parallel and independently all the time. A wide range of sensors on the vehicle supply information about the vehicle and implement hardware components such as position, attitude, engine temperature, fuel capacity and implement logistics. A number of other sensors provide information related to local environment such as altitude, air speed and air temperature from a mobile weather station. All of these data are used to update the GIS database and to send messages to the safety process to decide if there is a need to shut down in adverse weather conditions or unusual situations, like if the vehicle turns over or gets stuck in mud.

1.2.10 Implement task

The implement task process is highly specialised to the particular activities of the implement. It gets data about the implement from the implement database and has control over the whole vehicle whilst active. Examples of a task could be mechanical weeding, selective harvesting etc.

1.2.11 Tractor database

Contains information about tractor dimensions, wheelbase length and width, ground clearance, minimum turning radius, fuel capacity, maximum temperature, maximum speed, navigation speed as well as any other parameters considering important for the autonomous vehicle.

1.2.12 Implement database

Contains information about implement dimensions, implement-working dimensions, task working speed as well as any other parameters considering important for the implement task.

1.2.13 GIS database

The geographic information system (GIS) is the main database to store all the spatially related data. Earl, R., Blackmore, S. et al (2000) state that the GIS is essential for generating the field operations maps for autonomous vehicles. GIS database can contain information from an asset survey, provides all the permanent spatial attributes of the field, pertinent to field operations, transient data, provides attributes of a field that change during the growing season, e.g. crop structure and soil nutrient status and field operations maps.

General motivation of using autonomous vehicle systems

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Agriculture, horticulture and forestry have in the past benefited from a succession of technological developments that have brought greater productivity and economic efficiency. Historically, the emphasis of these developments has been on the mechanisation of operations to increase work rates achievable by individual operators through the use of larger, more powerful, machines. Today, however, the newer information based technologies seems to enable reliable autonomous field operations to be viable (Earl, 2000). This may make small-scale machinery an interesting alternative.

There are many reasons to justify the use of small autonomous vehicles. The main one may be to replace the heavy big tractors and machinery, which may damages the soil, and moreover requires large energy inputs. According to Grath (1997) light machinery compared to the conventional have advantages in:

- Lowered soil compaction
- Lower energy consumption
- Less influence from weather
- Increased yield
- Increased permeability for water
- Less risk for prolonged periods with surface water
- Increased quality of seed bed.

1.1 Vehicle efficiency and costs

Autonomous machines differ from present machinery in many ways. They can work for longer hours than manned machinery, they are less susceptible to weather and soil conditions and may have better utilization, which all together have considerable effects on costs and environmental consequences.

1.1.1 Machinery Utilisation

Operation of common manned machinery is in most cases restricted by labour availability (often only 5-6 hours a day on average), unsuitable weather, soil and crop conditions (up to 60 % of the time) and machinery down time (about 3 %). This means that presently used machinery only can be operated about 10-20 % of the total time.

If the labour restriction to a large extend can be removed this means that machinery utilisation may be increased up to 3-4 times. Additionally, if an autonomous machine is less sensitive to adverse weather conditions we can further increase the machinery utilisation further.

1.1.1.1 Machinery costs

A survey by Poulsen et al. (1997) of 500 full time farms in Denmark showed that on average the largest part of the total labour and machinery costs was the labour costs (31%), followed by machinery depreciation (21%), interest (18%), and maintenance (16%) and energy costs (5%). A shift to autonomous machines would give a major reduction in the labour costs and also a consider reduction because of better machine utilisation. However, high initial investment costs of autonomous systems may work in the other direction.

1.1.1.2 Operator limitations

Often the rate and quality of fieldwork are limited by the skill of the operator, as he has to make steering adjustments continuously while maintaining the attached implement at some level of acceptable performance. Although advances have been made in tractor and cab design to improve operator convenience and comfort, increased speeds, power and machine widths require the operator to be more attentive to the driving function, often at the expense of reduced equipment performance. The need to relieve him is perhaps the most frequently cited reason for the need of a vehicle guidance system (Wilson, 2000).

Kondo and Ting, (1998), states that even though many agricultural operations have been mechanized, there are still many laborious and monotonous tasks that are not suited for human beings, but require some intelligence to perform. Additionally, the availability of the farming workforce is decreasing. Compared with many other sectors, agriculture and forestry are less attractive for the younger generation. This means that the supply of human resources for farming may continue to decrease in the foreseeable future. The development of intelligent vehicles can serve to preserve some farming expertise. As a consequence to labour shortage, labour costs are rising, especially to highly skilled people.

Another aspect is avoidance of operator health problems from dusts and chemicals, which today is limited by various precautions as inconvenient breading filter and skin protecting devices.

1.2 Environmental impact

The most important environmental factors affected by a shift to small autonomous machines are soil compaction, energy savings, emission and leaching of pesticides and nutrients.

1.2.1 Soil compaction

Even though, many tractors are fitted with broad tyres , which producing less compaction in the topsoil, there is always a consequential problem for a severe deep compaction under the topsoil. According to numerous investigations this is beginning to take place when axle loads exceeds 6 ton.

Fear is accelerated if we bear in mind that the latest tractors with attached implements can weigh up to 18 tons.

Schønning et al. (2000) states, that deep soil compaction will in practice be permanent and cannot be repaired by natural processes neither by known growing processes. Permanent yield loss has been measured to 3-5%. In reality yield loss up to 15% may be expected.

According to Håkansson (2000), soil compaction increases the need of tillage as well as the draft of tillage implements. Therefore soil compaction increases the costs, the energy requirement as well as the environmental effects of tillage. Various investigations he refer to has shown, that this increase may be 300 % or more, when heavy machinery is operated with single wheel configuration in wet soil condition, while it may be insignificant when the same machinery is operated with double wheel configuration in dry soil conditions.

Already Nielsen et al., (1977) in their motivation for researching possibilities for development of a master and slave tractor system mentions versatility and avoiding deep soil compaction as reasons for using smaller tractors

1.2.2 Energy savings

Another factor of significant importance is the reduction of energy inputs. It has been stated by many researchers , that up to 80-90% of the energy that goes into traditional tillage, is required for repairing the compaction caused by the large tractors. Another factor is, that the heavy equipment uses a quite large amount to.

1.2.3 Site and plant specific treatment

In agriculture new technology is being developed for site and plant specific treatments. This technology uses many technological improvements in the area of electronics, computers and sensors. Global position system (GPS) provides precise satellite-based information on the location of various soil types, plants and machinery. Remote sensing devices offer the potential of precise mapping of soil and crop conditions. Direct sensing technology can monitor ambient field conditions at fixed location. Electronic control systems facilitate precise placement of measured quantities of seed, fertiliser, herbicides and water (Blackmore, 1994). Additionally, developments in communications and computers provide the basis for rapid transfer of data.

Together with this spatially management strategies are being developed, which attempt to approach the varied agronomic operations that take place, starting with primary tillage and ending with crop harvesting, (Earl, 2000).

The mentioned processes are diverse in type including maps of field operations and final yields, remotely sensed images and records of actual treatment. When agronomic control functions are combined with navigation systems for automatic guidance, large data exchange and processing requirements result such that conventional analogue systems must be exchanged for electronic systems. The majority of the data and information required for autonomous field operations are position and time related. The use of the Geographic Information Systems (GIS) that appears pivotal to the development of an integrated approach that may ultimately provide the basis for implementing autonomous field operations.

Being able to incorporate all of these new technologies in agriculture, leads to a new scale approach. Presently the mostly used strategy is the field scale approach, where each field gets its specific treatment. The next strategy is the sub-field approach, where each sub-field of certain homogeneity gets its specific treatment. The future approach may be the plant scale strategy, which is called “phytotechnology” by the Japanese.

The site or plant specific treatments being possible by this technology means that blanket approach of herbicide and fertilizer applications on the whole field may be replaced by applications adapted to the local requirements and reduce the amounts used considerable. By doing that, we will move a long step towards sustainable and ecological agriculture.

1.2.4 Added value

Apart from the above advantages the data collected by the sensor systems of autonomous or precision machinery or may be used to improve management in other ways, i.e. estimation of crop quality and yield values for sales decisions as well as identification of problem areas or plants of the field.