Agricultural robots: an economic feasibility study

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Abstract

This paper focuses on the economic feasibility of applying autonomous robotic vehicles compared to conventional systems in three different applications: robotic weeding in high value crops (particularly sugar beet), crop scouting in cereals and cutting grass on golf courses. The comparison is based on a systems analysis and an individual economic feasibility study for each of the three applications. The results showed that in all three scenarios, the robotic applications are more economically feasible than the conventional systems. The high cost of RTK-GPS and the small capacity of the vehicles are the main parameters that increase the cost of the robotic systems.

Keywords: agricultural robots, grass cutter, economics, feasibility study, robotic weeding, crop scouting

Introduction

In recent years, the development of autonomous vehicles in agriculture has experienced increased interest. This development has led many researchers to start developing more rational and adaptable vehicles. In the field of agricultural autonomous vehicles, a concept is being developed to investigate if multiple small autonomous machines would be more efficient than traditional large tractors (Blackmore *et al*., 2004). These vehicles should be capable of working 24 hours a day all year round, in most weather conditions and have the intelligence embedded within them to behave sensibly in a semi-natural environment over long periods of time, unattended, while carrying out a useful task. Moreover, such a system may have less environmental impact if it can reduce over-application of chemicals and high usage of energy, such as diesel and fertiliser, by control that is better matched to stochastic requirements. There are a number of field operations that can be executed by autonomous vehicles, giving more benefits than conventional machines. Blackmore and Griepentrog (2002) referred to a number of autonomous platforms that may be available in the future. These autonomous platforms would be used for cultivation and seeding, weeding, scouting, application of fertilizers and chemicals, irrigation and harvesting.
So far, only a few studies of the economic consequences of introducing autonomous field machinery have been published. Goense (2003) compared autonomous equipment with conventional equipment in widths from 0.5 to 12 m, and showed that when the autonomous equipment can be utilised 23 hours a day, it would be economically feasible with slight reductions in prices of navigation systems or with slight increases in labour costs. He also discussed a number of possible associated changes that will affect the final result: the fraction of labour time needed out of the total machine time depends on the number of elements that need attention; the machine tracking system provides better utilisation of machine working width and there is no need for operators rest allowance. On the other hand, there may be negative effects in the form of shorter mean time between failures and associated travel by service personnel. Have (2004) analysed the effects of automation on machinery sizes and costs for soil tillage and crop establishment in a case study. The analysis, which included all direct machinery costs and timeliness costs, showed that the shift to automatic control would decrease the tractor size, implement sizes and implement

investments to about half, decrease the tractor investment to about 60% and decrease the sum of annual tractor and machinery costs to approximately 65%.
This paper focuses on the feasibility of replacing conventional vehicles with autonomous for three scenarios. In two scenarios (field scouting in cereals and robotic weeding in sugar beet), we used an autonomous research platform (API) from the Danish Institute of Agricultural Sciences (DIAS), Bygholm, Denmark (Bak and Jakobsen, 2004). For the third scenario (autonomous grass cutting in golf courses) the analysis was based on real data from the operational costs for grass cutting on golf courses. We therefore have estimated the cost of building an autonomous grass cutting vehicle to replace the existing human-driven vehicles.

Materials and methods

In all three scenarios, we compared the production costs and benefits of the potential commercial use of autonomous vehicles with conventional operations and management practices. We based the calculations on partial budgeting, where the revenue change and cost change is compared to conventional practices. In this model frame, we included changes in initial investments, labour costs, change in speed, daily working hours, energy consumption, control and surveillance costs. All scenarios are hypothetical and none of the systems have been tested and validates in full scale. For crop scouting and robotic weeding, the model was based on a hypothetical application in a conventional farm with average field size and crop rotation in Denmark. For the grass cutting though, we model a conventional golf course in Denmark with 18 holes. For the grass cutting, data about conventional grass cutting was provided by the green keeper at Skjoldenæsholm Golf Course, a medium sized golf course (18 holes on 65 ha) near Copenhagen. For field scouting and robotic weeding, we have received data from researchers at DIAS, Bygholm in Denmark and general economic statistics regarding specific costs for contracting. For all three scenarios, we assumed that the period of depreciation was 10 years with linear depreciation. The real interest rate was 5 percent and we assumed that it would be necessary to add some additional time (two weeks) for testing and making the necessary calibrations for the systems. The main assumptions of the three scenarios that are examined in this study were as follows:

Autonomous grass cutting on golf courses

It is assumed that it is possible to replace a conventional grass cutter with a robotic grass cutter on those areas that require medium to low cutting skills. This means on the fairway (16 ha) and the semi-rough area (20 ha), which adds up to 36 ha. The yearly amount of time spent on these procedures is 784 h. The fairway lawn is cut about 2-3 times per week and the semi-rough area has to be cut once a week. This procedure takes place about 24 weeks per year implying that we have to make about 24 movements from the fairway to the semi-rough areas each year. In addition, time is needed for refuelling the robot every day, which is the same as for the conventional mower.
For the robotic grass cutter, the electronic equipment is mounted on a conventional grass cutter with RTK-GPS for position, laser scanner and an ultrasonic range finder to avoid obstacles, job computer, actuators and linkages. The system can be linked to a control unit, where any breaks or obstacles would activate an alarm signal on a mobile phone. This is a similar approach to the development of an autonomous Christmas Tree Weeder at KVL, where a conventional grass cutter was transformed into an autonomous one (Have *et al.*, 2005).

Crop scouting in cereals

In this system, we compared autonomous field scouting for weeds in cereals with the manual detection of weeds. The system requires an Autonomous Platform and Information system (API) vehicle and cameras for weed detection and mapping. The Danish Institute of Agricultural Sciences has performed tests using such a vehicle for weed recognition and data provided by the researchers have been used for our calculations.

The API platform, (Figure1) was initially developed by Madsen and Jacobsen (2001). The third generation of API vehicle was further developed by Aalborg University in Denmark (Bak and Jacobsen 2004). The new prototype is a four wheel-drive and four-wheel steering system with two motors per wheel providing higher resistance to slippery terrains and more mobility (Bisgaard *et al.*, 2004). The vehicle has a height clearance of 60 cm and track width of 1 m. It is equipped with a RTK-GPS system. On the top of the frame, there is an operating console and an implement for the agricultural operation, e.g. spraying or weeding tools. The vehicle communicates with the farm management PC for global planning navigating according to the computed route planning, as well as collision avoidance (Bak and Jakobsen, 2004).

Robotic weeding in sugar beet

In this scenario, we compared an autonomous vehicle equipped with a micro spraying system with a conventional sprayer for sugar beet. The micro spraying system would be mounted on the same API platform as the one described above for field scouting. The micro system has been developed at University of California, at Davis and has been tested at both UC Davis and at DIAS. The micro sprayer consists of a set of eight micro valves with a driver circuit for each nozzle. Each nozzle consists of five micro tubes. The total spraying width can be varied from 1.27 cm to 10.16 cm to cover the seed line (Lee *et al.*, 1999). The inter-row weeding (between the rows) is supposed to be carried out conventionally. The data used for the calculations were from the tests made by the Danish Institute of Agricultural Sciences and personal communication with the scientist in charge. The autonomous system consists of an API platform with optical sensors, an RTK-GPS and a micro spraying system (Lund and Sogaard, 2002). It is assumed, according to personal communications with I. Lund from DJF, that this system can reduce the application of herbicides by 90 % compared with standard doses in sugar beet. The working speed is expected to be 1.8 km/h with recharging of batteries every 5 h. The working width is 2 m with capacity to treat 4 rows in one traverse.

Figure 1. The API platform.

Results

Table 1 shows the technical assumptions for the 3 systems. The total area to be treated is 36 ha for the fairway and semi-rough area at the golf course, 500 ha for field scouting in cereals, and 80 ha for robotic weeding in sugar beet. The area capacity for the robotic weeding is adapted according to the limited time for spraying during the year. The area for field scouting could be larger but is limited to 500 ha in order to match large production units with the necessary flexibility. The shorter the time for carrying out the activity, the lower the overall capacity required.
For the grass cutter, the driver is replaced with a robotic system equipped with an RTK-GPS. The grass cutter, in this example a 5200-D from TORO, www.toro.com with cylinder cutters, is applied to the fairway area (grass length: 17-20 mm) and semi-rough area (grass length: 40 mm) at the golf course. Usually, a TORO 455 with rotor cutters is used for the semi-rough area but we assume that the same system can be applied to both areas in order to improve the yearly capacity and reduce investment. The width is 2.41 m with 5 cutting units and a tank capacity of 38 l diesel fuel. In this comparison, we assume that the same grass cutter is used for manual grass cutting and that time for cutting, fuel application and maintenance costs are similar for both the manual and autonomous system.
In field scouting, the robotic system is compared with manual detection of weeds. Manual weed scouting is assumed to require about 0,7 man h/yr/ha (Pedersen, 2003). Most of the time for manual weed scouting will take place in the first year, which is followed by shorter update scouting in the following years. The weed patches are registered by using GPS and GIS systems to create weed maps of the individual fields. Autonomous field scouting using the API platform has a speed of 3.6 km/h and a capacity of 4.32 ha/h, which adds up to 116 h/y for autonomous weed scouting on a 500 ha area.
The robotic weeding is a more time consuming task than field scouting. The robotic system is compared with the costs of conventional weeding in sugar beet. The costs for these operations are

Table 1. Technical assumptions for the system analysis.

	Autonomous grass cutter	Autonomous field scouting in cereals	Robotic weeding in sugar beet
Platform	TORO 5200-D	API system	API system
GPS-system	RTK-GPS	RTK-GPS	RTK-GPS
Total area, ha	36	500	80
Field size, ha	Fairway: 16 Semi-rough: 20	8	8
Speed, km/h	10	3.6	1.8
Width, m	2.4 5 cutting units	12	2 4 rows
Capacity, ha/h	2.4	4.32	0.4
Number of treatments, treatment/yr	96	1	3
Time for testing, weeks	2	2	2
Operation time per day, h/day	8-16	16	16
Operation hours, h/yr	784	116	667
Days for operation, days	24*	7	42
Season for operation	April-October	April-July	April-July

*Similar to a manually driven grass cutter based on average prices for contracting (Dansk Landbrugsrådgivning, 2004). With a *micro spraying system,* it should be possible to reduce the herbicide applications by 90% (I. Lund, 2004) in sugar beets. The API platform, as designed for this scenario, is equipped with 4 micro spraying systems, which cost 6.73 € each. The autonomous platform is able to cover 4 rows at a time. The speed is 1.8 km/h and the capacity is 0.4 ha/h, which adds up to 667 h/yr for autonomous weeding on a total are of 80 ha.

Based on the various systems and technical assumptions above, we give the potential economic viability of operating these systems compared to a similar treatment with conventional practices. The total investment for the three systems varies between 38000 € and 65000 € (see Table 2). The RTK-GPS system is still fairly expensive for these practices, although the price is expected reduce as the technology becomes more widespread. The cost of receiving a GPS reference signal accounts for a significant share of the yearly costs for all 3 autonomous systems. All systems seem to be economically viable given the technical and economic assumptions above. Especially, there seems to be significant benefits by using robotic grass cutters. For this system, it is possible to reduce the costs by more than 296 €/ha, which is equivalent to about 10902 €/y on the fairway (16 ha) and semi-rough (20 ha) area.

Table 2. Investments in autonomous systems, €.

€	Robotic grass cutter	Autonomous field scouting in cereals	Robotic weeding in sugar beet*
API-system		15141	15141
RTK-GPS	20188	20188	20188
Micro-spraying system, 4 rows			26918
Electronic system	20188		
Testing	2692	2692	2692
Total	43069	38022	64939

*Inter-row hoeing is not included here

Table 3. Cost structure for the various autonomous systems, €/year.

€/year	Robotic grass cutter	Autonomous field scouting	Robotic weeding
Capital costs	1077	951	1624
Depreciations	4307	3802	6494
Maintenance	1292	1141	1984
GPS-RTK-signal, yearly fee	1615	1615	1615
GPS-RTK signal costs, variable costs	1055	156	897
Data processing for seed map			150
Herbicide costs			1731
Inter-row hoeing			5599
Additional costs for fuel loading etc.	844	135	776
Total costs	10190	7799	20834

The autonomous field scouting system in cereals reduces the costs by about 20 % but it should be possible to increase the capacity to 1000-2000 ha since the system is only applied 116 h/y in the scenario presented above. For all systems, we assume a depreciation period of 10 years. However, given the intensive utilisation of the grass cutter and the robotic weeding system, it may be necessary to reduce the period of depreciation to about 5-8 y. In contrast, the autonomous field scouting system might have a longer lifetime than outlined above. For all investments, we assumed that maintenance is an additional 3 % of investment costs (see Table 3)

The yearly costs per hectare for the three autonomous systems compared with conventional system are presented in Table 4. For both the conventional and autonomous grass cutting systems, it will be necessary to invest in a TORO-5200D grass cutter (60,565 €) as indicated in Table 1. The actual fuel consumption is expected to be similar for both systems. However, in practice, it might be the case that by using an autonomous system, fuel consumption will be reduced due to fewer overlaps. The labour time spent on the conventional system includes grass cutting and additional relaxation breaks which is based on an average Danish salary (27 €/h). We assume that the tank capacity is about 5 h for the lawn mower, implying that the tank has to be refuelled every 5 h. Each refuelling is expected to take about 10-15 minutes. These costs have to be included for the autonomous grass cutting system. It is assumed that the yearly fee for a reference GPS signal is 1,615 €/yr. In addition, it is necessary to pay 1.3 €/h for using a RTK reference signal.

Field scouting is, to some extent, a hypothetical case in the sense that most farmers do not conduct systematic field scouting in their cereal fields. They either practice conventional farming with conventional spraying or they conduct organic farming with mechanical weeding. In this example, we assume that the alternative to autonomous field scouting is manual field scouting, which implies that the farmer has to count and register the weeds in the field manually.

The *autonomous micro sprayer weeding* is compared with conventional spraying in sugar beets. For the autonomous micro spray system, we assume that inter-row hoeing has to be conducted twice whereas, for conventional spraying, we assume one treatment. For comparison, it might be relevant to inter-row hoe 3 times when conducting band spraying. The primary savings are related to the reduced application of herbicides and the additional costs are primarily related to investments in the micro-spraying system. With this system, it is possible to handle 4 rows with the API platform. In the future, it might be possible to handle 6 or 8 rows at a time. Moreover, the costs of each spraying system are likely to be reduced with larger systems.

All systems seem to be financially viable compared to conventional practices. For the basic scenario, the costs of using autonomous systems for grass cutting will reduce costs by nearly 52 %. However, if it is necessary to apply both a TORO 455 and a TORO 5200 for the fairway and the semi-rough area then the costs are reduced by only 22 % compared to manual grass cutting.

Based on the assumptions above and calculations, it should be possible to reduce field scouting costs by nearly 20 % in cereals and for the autonomous weeding in sugar beet, it might be possible to reduce costs by 12 %. For the latter however, it might be possible to reduce costs by 24 % compared to conventional treatment if inter-row hoeing could be reduced to only one treatment as for conventional weeding. In these calculations, we have used fairly conservative economic figures

Table 4. Differential costs between autonomous and conventional systems, €/ha

€/ha	Autonomous	Conventional
Grass cutting	283.0	586.3
Field scouting	15.6	19.4
Robotic weeding	260.4	296.6

based on current prices. However, we may expect a further reduction in the price of RTK-systems and other electronic systems in line with increased supply of these systems. Software costs are not explicitly included in this study, apart from the RTK software system. In this matter, some additional costs should be expected depending on the diffusion of the systems.

Discussion

In this paper, we have analysed the economic viability of three autonomous robotic systems. In all scenarios, we have replaced trivial labour-intensive tasks for specific areas with autonomous systems based on highly accurate GPS-systems. These concepts and applications could be expanded to other field cultivation systems, tillage systems and grass cutting tasks at sport facilities and at public recreation areas. The autonomous grass cutting is the most economically viable as the labour use in this operation is very intensive. However, there seem to be several other external factors and benefits that may improve the overall economic surplus for the other systems. The autonomous weeding system with micro spraying in sugar beet may reduce the overall herbicide application by 90% and thereby improve the socio-economic benefit. The autonomous field scouting system allows reduced cost weed mapping, which again may give an incentive to conduct patch spraying in cereals and other crops. In addition, these robotic systems may further improve flexibility and allow night operations in the field, thereby improving crop production efficiency.

Conclusions

An initial outcome from this study indicates that most of these autonomous systems are more flexible than conventional systems and may reduce labour costs and restrictions on the number of daily working hours significantly. Moreover, it is possible to substitute the most trivial working routines with autonomous systems although some routines are nearly impossible to automate due to the required accuracy of the specific tasks. In addition, at this stage of development, the initial and annual costs for expensive GPS systems are still relatively high but it seems possible to design economically viable robotic systems for grass cutting, crop scouting and autonomous weeding.

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