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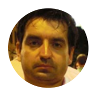

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Systems Requirements For a Small Autonomous Tractor

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ABSTRACT

This paper proposes some system requirements for a small autonomous tractor that includes some physical attributes as well as behavioural traits in certain conditions or contexts. The tractor should be physically small, lightweight, reliable, have good real-time communication facilities and be managed easily, especially under fleet management. Five internal and thirteen external contexts have been identified that can be used to trigger different behaviours. Four operational modes for the tractor have been identified. Field scouting and mechanical weeding have been identified and described as the first two niche tasks likely to become autonomous.

Keywords: autonomous tractor, agricultural robots, behaviour, systems requirements

INTRODUCTION

The advances in information and telecommunication technologies have produced significant changes in almost all disciplines, as well as agriculture. Moore's law proposes that computer-processing power, delivered by the information technology industry, will double every 18 months for the same price. What do we do with this computing power now? Effectively, the more computing power we have, the more complex problems we can solve. Most computer programmes are still highly deterministic (finite state machines) that reflect the views and values of the programmers, but with this power we should be able to have more sophisticated self-modifying software that can adapt itself to the individual needs of the users as well as improved modelling of, and interaction with, the real world. To be able to utilize these advances in the agricultural mechanization, more intelligent machines are inevitable.

As world prices for food products fall and production subsidies are phased out, many farmers today are under increasing financial pressure to remain a viable business. Farmers are trying different ways to reduce the cost of production. Many farmers are taking advantage of economies of scale in their farms such as increased farm size, larger fields and bigger tractors that minimise the labour required per hectare. This is leading to a more industrialised type of agriculture, which is at odds with many environmental considerations.

To further improve the efficiency of developed agriculture, horticulture and forestry found in northern Europe a concept is being developed to investigate if 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 should 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, this system 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 better matched to stochastic requirements. Additionally, it will have smaller incremental investment and lower labour costs. Finally, it may have very low soil compaction that would lead to a more sustainable production system. Some aspects of this concept appear in a US patent (Keller et al., 2001). Auernhammer *et al*. (1995) also supported that the development of driverless, small tractors in agriculture is “entirely possible”.

The 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 field down to 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, but these processes lend themselves to different forms of automation, especially in high value crops. 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 could be seen in the future. These autonomous platforms would be used for cultivation and seeding, weeding, scouting, application of fertilizers and chemicals, irrigation and harvesting. Two good examples of this process are field scouting and mechanical weeding.

Field scouting

There are many sensing techniques that can ascertain crop and soil conditions. A number of them could be used now in existing production systems, apart from the fact that they take a long time to process the data. Examples are weed recognition using machine vision, multi-spectral response from the plant canopy that can indicate stress (whatever the cause) and chlorophyll content that is associated with crop vigour. Carbon dioxide (CO_2) has been associated with soil health; Ethylene can be associated with pest attack and soil 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 in real time (Shibusawa, et al., 2000). Ion Selective Field Effect Transistors (ISFETs) can be modified to be sensitive to nitrates, pH and other factors from soil solution (Birrell, S.J., Hummel, J.W., 1993). Some 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.

The reason some of these systems are not used now is that the associated cost of an operator's time does not justify the information benefit. If these systems were automated and mounted on an autonomous vehicle then the operator cost would be significantly reduced, thus also reducing the cost of data capture. A prototype automatic steered vehicle has been described by Pedersen (Pedersen et al., 2002), which provides such a platform, for a range of sensing systems. A new vehicle is currently under construction.

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. Recent developments have led 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 the early nineties (Hoffman, 1991; Steinhauser, 1993) and has more recently been developed by Tillett (Tillett and Hague, 1999) and commercialised by the Danish Institute of Agricultural Sciences and Eco-Dan (Sogaard and Olsen, 2000).

Small automatically steered weeding vehicles have been developed by a number of research teams recently. Tillett reports having developed a small reactive horticultural toolbar that can recognise and spray each plant individually (Tillett et al., 1998). A student project team at the Danish Technical University built a four-wheel drive, four-wheel steering weeding platform (Madsen and Jakobsen, 2001). Research teams from France and Spain report a high mobility robotic weeding mechanism (Blasco et al., 2002). In Sweden an automatic steered weeding vehicle using machine vision has been developed at Halmsted University (Astrand and Baerveldt, 2002).

SYSTEMS REQUIREMENTS

Both field scouting and mechanical weeding equipment as well as many more devices, could be mounted on a small autonomous vehicle that could roam the field carrying out its task over prolonged periods of time. To be able to achieve this, the vehicle must have certain attributes and behaviours.

The main systems requirements for this proposed vehicle are that it is:

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

Small size

A small vehicle size implies higher precision of operation, lower incremental investment and is relatively safe during system failures. The vehicles will probably be 1-2 metres long, large enough for stability but small enough to address safety factors. The power will be in the 10-30 hp range to achieve the necessary energy density requirements, as they will require an internal combustion engine (until fuel cells will become realistic). Smaller vehicles of less than a metre in length and around five hp could be developed for highly specialised tasks with low energy requirements such as non-contact sensing. 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 their inherent size and 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. 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, such as thinning, pruning, selective harvesting.

Light weight

The lightweight design parameter is important as it implies reduced soil compaction. Chamen et al. (1994) 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 caused by traditional practices using 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 may 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 to compact the soil by heavy machinery and then introducing energy to recreate a good soil structure. As the vehicle is inherently light, it should also require lower energy inputs although this may be offset by the higher efficiencies of the larger engines. If the vehicle is also more weather independent, then field operations could be carried out better in accordance with agronomic needs, instead of during small weather dependant windows of opportunity that allow large machines on the soil.

Safety

Any autonomous vehicle should always operate in a safe state even during partial systems failure. Catastrophic failure is unacceptable. Safety is expressed in terms of safety to others, safety of self and safety of the crop. An assessment of internal and external safety issues has been described by (Reid 2002). These safety issues are addressed in terms of sensible behaviour during normal operation as well as when parts of the system fail. Knowledge is needed about which system has failed and the only way to achieve this is by including redundant systems. These redundant systems do not necessarily duplicate each other but offer an alternative method of assessment. An example of redundant systems being used to improve the reliability of sensing is described later as an expert sensing agent.

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 with a reduced capability. This generally involves only part of the task being fulfilled, which is arguably better than a complete shutdown. Functionality is gradually reduced as faults increase. Only systems with redundant sub-systems and the ability to self-diagnose faults can allow this type of behaviour.

The primary safety modes for the vehicle and implement task will have been identified as:

1. Nominal safe operation
   All vehicle and implement systems are operating within normal parameter values
2. Safe operation with warnings
   Operating safely, but there are some warnings about abnormalities (e.g. low fuel)
3. Partial system shut down – mobile
   Partially shut down, although it remains mobile (e.g. camera lens obscured)
4. Partial system shut down – immobile
   Partially shut down, the vehicle is immobile (e.g. transmission fault)
5. Stopped – still communicating
   Fully stopped but still communicating with the co-ordinator (e.g. internal fault)
6. Dead
   The system has fully shut down or 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 should be an early diagnosis (detection, isolation and identification) of faults, whilst they are incipient and hard to detect and isolate. Another goal will be to ensure that the process can tolerate faults through control system reconfiguration or by a graceful degradation to 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.

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 should 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 to the coordinating PC. If the vehicle was seen to move without powering the drive motors, then a theft alarm could be triggered.

Even with all these precautions in place it is inevitable that computers fail from time to time into unknown states that can allow random behaviours. To this end a smaller, slower vehicle is seen as safer than a larger faster one.

Fleet management

A computer at the farm office, operated by the manager, will have a Management Information System (MIS) that gives the overall assessment and control of the autonomous vehicles and their functions. It is likely to be a set of information screens and optimisation routines that can be used by the farm manager. High-level requests can be made, such as monitor the crop for nitrogen stress in field 10 or carry out intra-row weeding in field 5 with implement number 2. The coordinating program can then allocate resources, (e.g. which tractors to use) prepare an initial route plan based on the GIS and develop a suggested instruction set for the autonomous vehicles. The manager can then review the proposed itinerary and make adjustments to it before it is then downloaded to 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 radio link. The coordinating PC will also hold the master GIS that can be synchronised with the vehicle GIS (which is continuously updated) from time to time. The coordinating PC will also prepare all the required operational and application maps (based on the managers input) as well as storing the actual treatments carried out by the vehicles. Other functions will keep records of the logistics in a similar way to current agricultural software.

The MIS should also have an independent 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 through tele-presence. This can be combined with a mimic status display of all the functional parameters of the vehicles. An example of such a mimic display is shown in Figure 1.

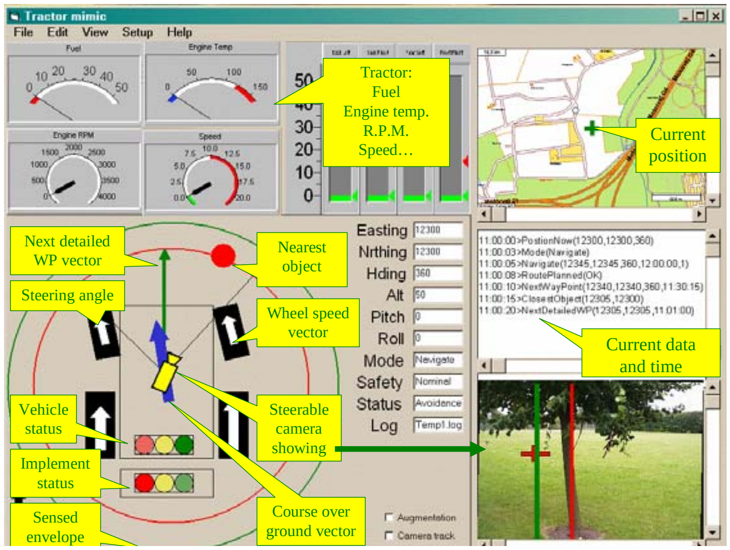

Figure 1. Prototype mimic display of vehicle status

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.

As part of the overall design philosophy, these small vehicles must be capable of coordination, cooperation and collaboration in different tasks. This would help to improve the work rates and allow the time critical tasks to meet their deadlines by scaling up the number of operational machines.

Coordination

Coordination of multiple vehicles must be carried out centrally within the MIS. Each vehicle is working independently and does not necessarily know about other vehicles but has its own task to carry out. An example would be where each vehicle would be carrying out a different task in different fields.

Cooperation

Cooperation is where multiple vehicles are working in the same field and are aware of each other and of what others are doing. If three vehicles were carrying out the same task, such as mechanical weeding in the same field, then each vehicle should know which rows other vehicles are working in before it selects a new row to start in. It would not make sense for two vehicles to come head-to-head in the same row. Real time communications between vehicles on a peer-to-peer basis would be needed.

Collaboration

Collaboration is where multiple vehicles could share the same task at the same time. An example would be for multiple vehicles to pull a large trailer that one vehicle could not pull on its own. This is a very difficult situation to manage effectively.

Autonomous, purposeful behaviour

When attempting to analyse a situation for appropriate response, human behaviour often refers to the current context of the situation as well as the event that triggers the response. This factor is so strong in humans, that the implicit, subliminal or contextual information can override explicit communication but is often ignored in automation although it is essential for sensible autonomous behaviours.

Contextual information and operational modes

There appear to be two classes of finite states for the context: internal and external. Both can be assessed by the use of expert systems. The internal context can be assessed by analysing the internal states of the vehicle including fault finding techniques. Internal contexts that have been identified are: nominal, agent failure, unrecognised message, corrupt message, and parameters outside limits. External states are much more complex and are assessed by considering combinations of internal and external factors. Current examples are shown in Table 1.

Table 1. Showing examples of external contextual situations

Name	**Description**
Nominal stationary	Tractor stationary, in one of the predefined processes/modes (Route planning, Self Check etc)
Nominal Task	Tractor and implement carrying out predefined task
Navigating	Tractor moving freely, implement stowed
Avoiding	Following obstacle boundary
Threat	Shutting down while tracking approaching object
Assessing	Object sensed within threshold, tractor stopped and watching behaviour of object
Skid	Tractor moving faster than the wheels
Slip	Wheels moving faster than the tractor
Stuck	Wheels moving, stationary tractor
Sink	Reduced clearance under tractor
Tilt	Tractor beyond attitude limits
Weather	Tractor experiencing weather beyond set limits
Theft	Tractor shut down but moving after Threat (!)

Operational modes

A number of operational modes have been initiated. These are navigational, exploratory, self-awareness and implement task modes.

Navigational mode

A basic task for the tractor is to be able to navigate safely to a desired position. We estimate that the vehicle will be navigating around 80-90% of its active time, as positioning itself and its working tool will be the tractor'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 deterministic route planning subsumes other lower level reactive behaviours such as 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) and will be an important part of the vehicle's information system (Earl et al., 2000). 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 to given tolerances. To go through the centre of a gateway, the positional tolerance for a small tractor could be +/- 0.5 m. but when inspecting an individual plant the tolerance will be more like 1-2 cm.

During autonomous navigation the local proximity must be continually monitored for objects that may become obstacles. A three concentric ring system is envisaged that will supply appropriate contextual information about the distances to local objects or *localization*. See Figure 2. A multiple object tracking system is also needed that can prioritise importance. If a wide implement such as a spray boom is used then an appropriate shaped polygon could be used instead.

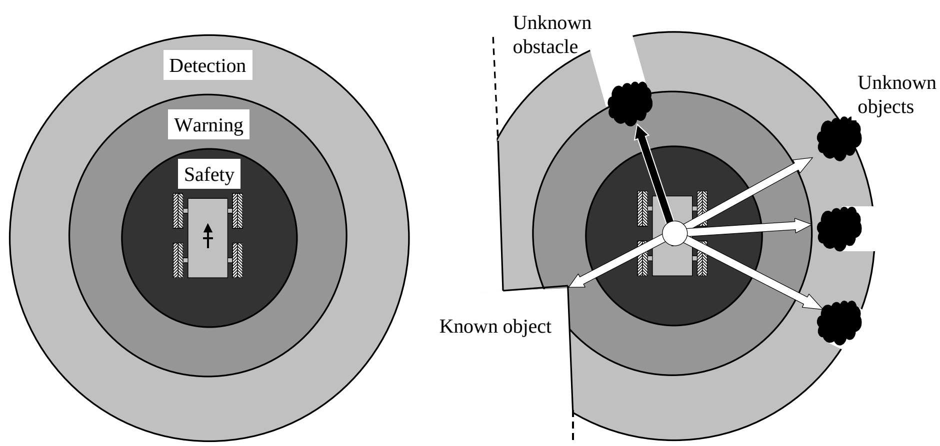

Figure 2. a) Detection, warning and safety distances. b) Prioritised multiple object tracking

When objects are detected, a Reactive Object Tracking agent (an agent is a dedicated processor that is part of the overall system architecture) 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 until the threat goes away.

A specialised navigation mode is refuelling. When the tractor 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.

Exploratory mode

The tractor should 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 rely on a Reactive Navigation agent to find a clear path ahead and record data from all the sensors at the current position. If it assesses that it is safe to move ahead it will then move slowly recording relevant data into an occupancy grid as it moves. Once the boundary of an area has been explored and surveyed, more optimal deterministic route plans can be made to complete the survey. Alternatively, a self-adaptive survey based on the position and the results from the spatial sensor could be used. Fewer readings could be taken from seemingly homogenous areas, while more intensive sampling can occur in areas of heterogeneity.

Self-awareness mode

The tractor 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. 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 behaviour is not mutually exclusive to any of the other modes so may be run entirely in parallel as a separate process or agent.

Implement task mode

The tractor should have mechanical, electrical 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. The tractor will supply the motive power and positioning for the specialist implement but another controlled degree of freedom may be introduced between the tractor and implement to achieve higher levels of accuracy than controlling the tractor position alone. Common data, such as positioning and attitude is more closely linked with the vehicle as it is likely to be required by all implement tasks. The Implement Task agent should have access to the tractor data as well as its own dedicated implement database. Each implement will have at least one agent (job computer) to control the implement tasks and send requests to move to the vehicle. Whilst the implement task is active, the implement controller should control the actions of the tractor. The implement will have at least one ‘focus area’. That is, the active area near the implement 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 (in the case of the 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 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 agent 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, request assistance or return to base for servicing.

CONCLUSIONS

In conclusion, we have tried to set out a framework of specifications that should be able to assist with the design of an autonomous tractor. Issues relating to both the way the machine should be designed as well as the way in which the machine should behave have been discussed. The two key issues are size and reliability. These machines should be small enough not to cause significant compaction and they should behave sensibly and reliably in the agricultural context. Truly intelligent machines are a long way off, but the design of machine behaviours that are sensible in certain contexts are very real today. With this framework in mind we are another step closer to achieving our goal of building an autonomous tractor.

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