New concepts in agricultural automation

Simon Blackmore

Center for Research and Technology of Thessaly, Greece

simon@unibots.com

Summary

Many new agricultural automation technologies are being developed by university researchers that pose questions about the efficiency and effectiveness with which we carry out current agricultural practices. This has given rise to many new opportunities to service the agronomic requirements albeit in radically different ways to those currently used. This paper sets out 41 concepts relating to this work. Some are new and untried; others have been built and tested in research conditions or are traditional concepts that have been revisited in light of new technological opportunities. This paper aims to raise awareness that there are now alternative ways to support the cropping system; it is not meant to give a definitive view. Only time will tell which ones become successful.

Introduction

The development of precision farming technologies in the 1990s opened up a new way of thinking about mechanisation for crop care. It introduced a number of concepts, which although not new, brought about a shift in the thinking and management of variability. With yield mapping and VRT (Variable Rate Treatments) the spatial scale of variability could be practically assessed and treated for the first time since mechanisation was first used. Pre precision farming, managers assumed that spatial and temporal variability existed but did not have the ability or tools to deal with it. Since then we have seen the scale of management and hence treatments reduce from farm-scale, down to field-scale, through to sub-field scale with varying expectations and benefits.

This technology trend has continued to the point where we now have many smart controllers that allow the scale of treatment to be reduced further, down to the plant and even leaf scale. In doing so, these new methods of introducing smart controllers and automation have enabled the development of new concepts of practical crop management that were not feasible before. We now have levels of automation where we can consider the methods people used before large-scale machinery was introduced and see if these same methods can be utilised today using small smart machines.

New concepts

Many new concepts are being developed to allow agricultural automation to flourish and deliver its full potential. In some respects this needs a paradigm shift away from how we have done these tasks in the past to how we could do them using SSM (small smart machines). The current trend of machinery development is incremental where each new machine is a little better than the one before. This is a successful approach but one that ignores radical alternatives and opportunities.

Take size for example. We have seen the continued increase in size and work rates of agricultural machines over the years, which to a large extent, can be highly beneficial as more work can be done by a reduced labour force, hence giving increased economy of scale but it also has a detrimental effect on the ability to deal with spatial and temporal variability. Many machines have been retrofitted with VRT controllers to help deal with this. An alternative approach can be taken by extending the vision to the point where the machine can work by itself, without constant human supervision. But if this radical scenario is to be fully developed it should take into account not only current problems but also identify potential opportunities. By taking this approach we can redefine the basic agronomic plant needs irrespective of the current machinery constraints and develop new SSMs that meet these needs alongside environmental care and economic prudence, health and safety, work directives and societal impacts, i.e. we start with a blank sheet and design the system of machines we need currently and those for the future.

To take full advantage of these technologies, we should not just consider the implication of developing a new single technology but should look at the wider issues of a complete mechanisation system, including appropriate machinery management. To do this we have to consider all the impacts and implications but in doing so we need to define some of the systemic concepts that underlie the designs. This is not intended to be a recipe for developing new system but an explanation of some of the new concepts encountered.

When taking a systematic view of agricultural robotics, we can see there are many factors that will affect the final designs. Figure 1 shows a first attempt to define the numerous interactions.

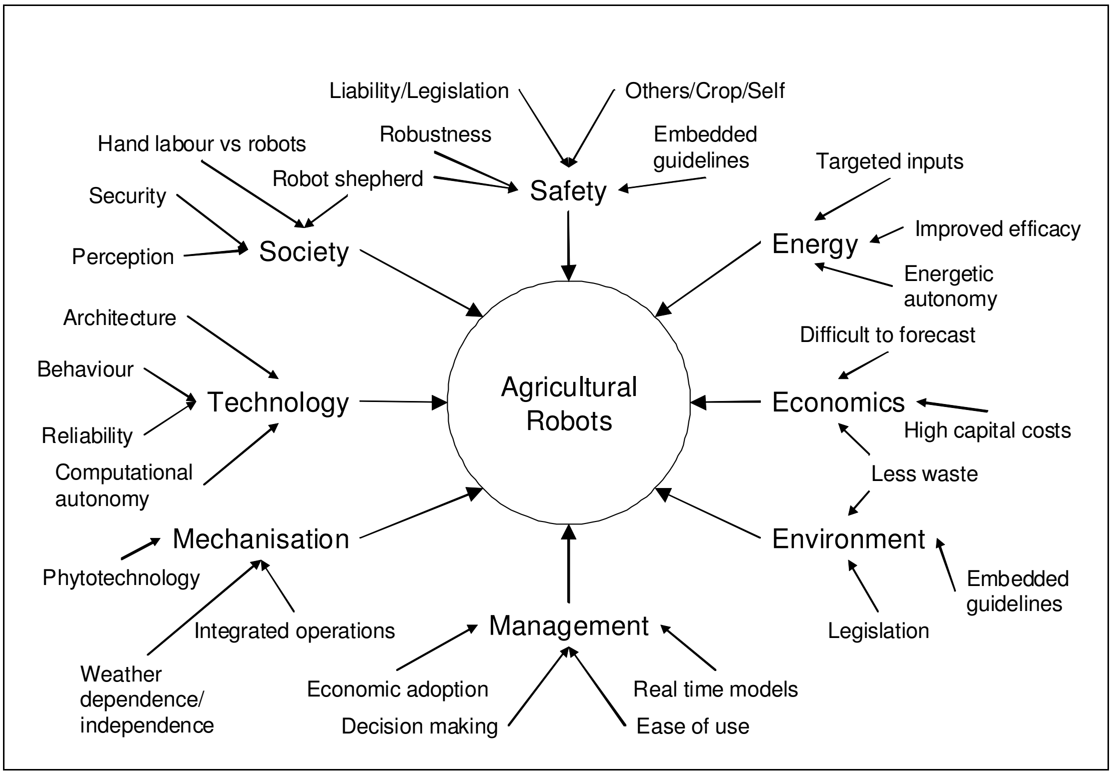

Figure 1. How system environment affects agricultural robotics (from Blackmore, 2007)

The system in question is the mechanised support for growing crops which is increasingly becoming more automated and may lead to a system of agricultural robots. There would appear to be two sets of concepts developing: those that apply to the whole system (systemic) and those that describe the parts of the system (systematic). The next section describes new (and not so new) concepts from both perspectives.

Systemic concepts

These concepts deal with overarching ideas that impact the whole mechanisation sector.

***Phytotechnology**:* This word was first used in this context by Shibusawa (1996) to describe machines that were better suited to dealing with individual plants. Tillett and Hague (1998) developed a similar conceptual approach called plant-scale husbandry in their weed spraying robot. This concept takes the emphasis away from the machine and work rates and focuses directly on plant needs – to develop an autonomous machine that can tend and care for each individual plant according to its needs. When plant requirements are defined independently of the machine that carries out the corresponding operations, this improved specification can be used in conjunction with mechatronic principles to design smarter and more efficient machines.

***Intelligently Targeted Inputs (ITI)**:* Current machines do not usually use sensors or control systems to regulate what happens during field operations. They tend to use blanket treatments and in many cases it is quite difficult to achieve the desired levels of accuracy. Consequently this approach uses more inputs than are necessary. This leads to higher costs as well as environmental pollution. These inputs can be seen as energy inputs and many field operations can be equally categorized in the form of energy, such as the energy requirement to build the tractor, energy to make the chemicals and energy to fuel the machines. From both environmental and economic perspectives, this energy should be limited to a minimum of what is needed both in how it is delivered (there is not much point in having a 10 tonne tractor applying a few grams of chemical) and how it is targeted to the right place at the right time in the right way to make best use of its potential and minimise waste.

In some respects, this is nothing new; if a person were to establish, care for and harvest a number of valuable plants, they would instinctively try to understand the plants' requirements and apply only those inputs which are needed by using perception and rationality. This is the precept of intelligently targeted inputs.

Zero draft force is another strange concept to many. We know that draft force is an important part of the way in which machines, particularly tractors, impart their energy to the soil in a horizontal manner. This is why tractors have large back wheels and heavy front weights. Many soil-engaging operations can be made draft force neutral or have a significantly reduced draft force requirement. Although we could never achieve 'zero' draft force due to the rolling resistance of the soil to the wheel, it can be reduced drastically by reducing overall machine weight. This gives a circular argument: the lower draft needs less weight which causes less compaction and less compaction needs less draft force energy requirement to break it up.

Zero compaction is the ability to carry out field operations without compacting soil, thus negating the requirement for more energy to reinstate soil structure. After lengthy consideration it now seems strange to run machines on top of the growing media and damage the soil that is there to grow plants – not support tractors. Again, this is not new and many techniques have been developed to help minimise soil damage by big tractors, especially controlled traffic. In the SSM system we need to know what maximum size of robot and hence ground pressure can be sustained before damage occurs. Even if some damage occurs self remediation can take place due to natural activity of native soil flora and fauna. If we can carry out field operations below this threshold then we may consider we have zero compaction.

Energetic autonomy is the ability of a machine to get its motive energy from its surroundings rather than from an imported energy source. The concept has been successfully trialled (Leropoulos *et al*., 2003; Kelly *et al.,* 2000) and could be extended to include SSMs running a hybrid system of batteries and an engine run on biofuel grown and processed on-farm. As in the days of using horse power, land could be set aside to give motive energy requirements for the robots, thus giving a closed energy loop on the farm.

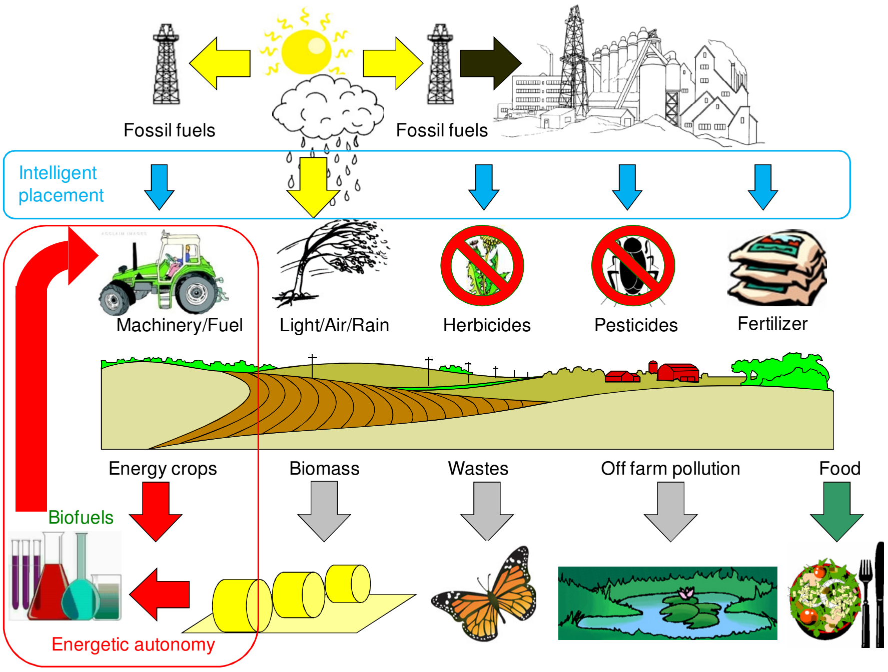

Figure 2. Agricultural energy flows

Usability is an important concept in the design and introduction of any new technology. In Precision Farming we (the scientists and engineers) made agriculture too complex for most farmers by introducing endless maps of differing soil and crop properties, without developing a clear method to use them for their own purposes. Any new technology must be intuitive and simple to use, without having long training courses and thick manuals.

Modularity should be incorporated at all levels of design from system architecture and software, right up to logistics and packaging. Given that a system has been modularised, when one module fails or needs to be changed, it is a simple matter to remove one ‘black box’ and replace it with another. This makes servicing much easier especially if the system is aware of which module needs to be changed. (*q.v.* self aware).

Task oriented Automatic Sub Systems (TASS) are modular end effectors that fit to a mobile platform, much like a traditional implement attaches to a standard tractor. They should be designed specifically to interact with crop or soil using mechatronic principles and the concepts described here. (*qq.v.* ITI, Phytotechnology). An example of a TASS would be an ultra high precision seeder *q.v.*) They should have a common interface for mechanical support, electrical power and machine communications and should be easily exchangeable, possibly even automatically. Each TASS is self contained in terms of functionality but communicates bidirectionaly with the host platform. A single TASS could be used on a SSM or multiple TASSs could be fixed to a standard toolbar behind a manned tractor.

Cropping systems: Given that these SSMs exist, a number of new opportunities open up in terms of how we actually grow crops. At the moment we traditionally (in Europe) grow a single crop once a year which seems a little simplistic. Is that the most suitable scenario for either the varieties we have or for the weather patterns we experience? Do we keep to monocropping because we cannot do it any other way with the existing machinery system?

With a ***phytotechnology*** system where individual plants are treated individually, we can consider ***multi-cropping*** where multiple crops could be grown in the same field at the same time and take advantage of symbiotic relationships between species (ref insects avoiding one species that is planted close to a crop species that the insects normally predate).

Phased-cropping is another concept where the same or multiple crops can be planted in different phases through the year. Instead of planting all the crop at the same time and running the risk of a weather event ruining the whole crop (frost during flowering, rain at harvest) the crop could be planted at three different times: one third planted early, one third planted at the conventional time, one third planted late. If a detrimental weather event does occur then there is less likelihood of catastrophic failure. Another advantage of phased cropping is there is less need for such large machines. Smaller machines could be used over longer periods of time. This system moves us away from the existing ‘all or nothing’ single phase current cropping cycle.

Flexible bioproduction is the concept of changing crop and or treatments according to changing situations. Given we have individual plant operations that can be easily changed by management software, a rolling cropping system of multiple crops being planted and harvested at different times can be envisaged. If we were expecting a dry spring and chose a suitable variety and it became a wet spring where it failed to emerge, those areas could be reseeded (*q.v.*). With a rolling cropping system crop plants could be changed throughout the growing season to take advantage of current prices or weather, or supermarket requirements.

The cropping cycle can be reduced to three types of treatment: establishment, crop care, selective harvesting.

> ***Establishment*** can be where all of the agronomic conditions for the seed and the soil can be met in a reduced number of operations, i.e. do the minimum required to establish the young crop plant. (*qq.v.* micro tillage, microconditioning, precision seeding).
>
> ***Crop care*** is the phase where the crop needs to be monitored and nurtured. If crop scouting is made automatic with suitable sensors and on an organised basis, prophylactic chemical treatments may not be necessary as remedial treatments (e.g. to control fungal attack) could be applied quickly and only when actually needed. Individual treatments such as fertiliser and herbicide can be applied to individual plants. Automated crop scouting could give the manager up-to-date maps of the current situation and even send SMS messages when critical conditions are encountered.
>
> ***Selective harvesting*** mimics the human approach of just choosing those parts of the crop that meet criteria such as ripeness, colour, size, etc. At the moment we harvest the whole crop when it is ready ‘on average’ but we know that there is a lot of spatial and temporal variability that cannot be managed. This mixed product is then sent off the farm for grading and processing where a significant value is added to the product. If only the crop product that is required or saleable is selected through quality or

quantity attributes the grading process stays on the farm as well as the added value. If the selective harvest is repeated then the smaller / unripe produce that was rejected before, may well have grown or developed into something acceptable this time around and the process repeated. This approach could significantly increase the marketable proportion of a harvest as well as increasing its value.

Weather dependence is the concept of a SSM being active only in suitable weather conditions. At present if a manned sprayer is working and the wind becomes too high the operation may be postponed for the day or until perhaps the following morning. If a SSM could monitor wind conditions it could work while they were appropriate, halt while it was windy and wait until the wind dropped before continuing. In this way the task could possibly be accomplished sooner.

Weather independence is where a SSM could continue working when a larger manned tractor is halted by conditions. Most cereals in northern Europe are planted in the autumn both to establish the crop early and because manned tractors cannot go into the fields when soil is wet as it would cause significant damage to soil structure. If a smart machine were small and light enough to work in soft soils it would have the ability to plant seeds into the ground whenever agronomically or economically required, thus giving an example of weather independence.

Safety and ***reliability*** in any technology should be paramount but more so as machines become more autonomous. They should be safe towards the crop, safe to itself and most importantly safe to others. If a person makes a mistake it is seen as an accident; if a machine makes a mistake it is seen as unacceptable. This brings up many issues of philosophical and legal implications. Particularly ‘who is responsible for an autonomous machine?’ Is it just a tool and the responsibility of the user, or is it so automatic that it shares the values of the programmer? Some consider the absence of autonomous machines now results from this single issue. If catastrophic failure is unacceptable then automatic safety needs to be built in to SSMs at all levels. To achieve this, redundant systems must be in place to help understand what has gone wrong.

Self awareness introduces a new level of complexity but gives the ability for automated systems to embed enough knowledge in itself to know whether it is functioning correctly. Self awareness is the prerequisite of graceful degradation (*q.v.*). If a machine has self awareness, it may have redundant sensors that monitor the machine’s functions like engine temperature or fuel level and access to real-time data to make informed assessment that the machine is working within design parameters. This assessment is best suited to be modelled as an expert system and the output status can be utilised by a supervisory function that can take appropriate action.

Graceful degradation is the process where the machine is self aware and knows that parts of the machine are working sub-optimally or have failed. It could then adopt a degraded functionality but keep working until repaired, or navigate itself back to base for attention. An example could be where a hybrid power system (engine and batteries) failed due to the engine not starting; the SSM could return to base on the remainder of the battery power.

Safeware is the word now used to describe combined systems that deal with self awareness, failsafe (shutting down in a safe way) and choosing appropriate internal and external behaviours (*q.v.*) to give increased operational safety. It includes redundant hardware systems, embedded knowledge in software and can instigate appropriate reactive behaviours.

Machine intelligence: “Our definition of intelligence is so anthropocentric as to be next to useless for anything else" (Samuel Butler, 1887)

No machine can ever be really intelligent as 'intelligence' is defined by being an aspect of humanity. Without biology we cannot have emotion and without emotion, we cannot have intelligence. However, machines can appear intelligent by adopting certain behaviours in given contexts. When conditions change and the robot adopts a new sensible behaviour that matches the changed conditions, it would appear to us to be intelligent behaviour.

Central paradox of artificial intelligence: "Systems simple enough to be understandable are not complicated enough to behave intelligently; systems complex enough to behave intelligently are not simple enough to understand (Dyson, 1997)."

A machine can be made more intelligent by defining a set of behavioural modes that make it react in a sensible way, defined by people, to a predefined set of stimuli or triggers within known agricultural contexts. It must be able to carry out its task over prolonged periods, unattended. As the vehicle interacts with the complex semi-natural environment such as horticulture, agriculture, parkland and forestry, it must use sophisticated sensing and control systems to be able to behave correctly in complex situations.

Robotic behaviours*:* An autonomous machine should be able to carry out a range of well defined field operations, such as seeding and weeding, which are made up from tasks that exhibit predefined behaviours. These external behaviours can be made up of a mixture of pre defined deterministic tasks and real-time reactive behaviours. The choice of appropriate behaviour is made by identifying a trigger and the context of the situation.

Deterministic tasks are those concerted actions that can be planned before the operation starts (e.g. route planning). Deterministic tasks can be optimised in terms of best utilising existing resources based on prior knowledge about the vehicle, implement and field conditions.

Reactive behaviours are those actions that are carried out when uncertainty is encountered. These tasks react in real-time to local conditions that were not known before the operation started. Reactive tasks can be defined by their behaviour to certain classes of situations (e.g. stopping when approached, obstacle avoidance).

Systematic concepts

The second part of this paper deals with concepts that are systematic in nature as they deal with issues that cover some specific parts of the mechanisation system.

Traditional tillage uses a lot of energy, much of which is not necessary. **Microtillage** is the concept of reducing energy and soil disturbance to the minimum to give the required structure. Instead of inverting the whole topsoil, as is done with current ploughing, we now have the ability to till soil in a small area to create a suitable interface between seed and soil. Combined with minimising compaction of soil through other methods, the natural flora and fauna in soil can be encouraged to symbiotically keep soil structure in good condition for rooting, thus enhancing the process. Microtillage could well be combined with ultra high precision seeding to reduce the number of operations. Traditional cultivations do a good job of creating a significant weed seed bank, thus extending the longevity of weed seeds in the soil. By stopping incorporation, weed seeds become less viable on the surface and will have much higher predation by birds and reduced viability from frost and cold.

An alternative concept is called **microconditioning**. This is where microtillage can be used followed by adding a hygroscopic gel to improve water availability and hence germination. As germination is often limited by moisture due to low moisture in the surrounding soil or poor contact to the soil, adding a gel to the seeding site could improve the contact between soil and gel and gel and seed. If the gel were hygroscopic, it could enhance soil moisture extraction or even have its own moisture, which would be enough to allow germination. The gel could also have slow release nutrients to ensure the young plant does not suffer from nutrient stress.

During the process of seeding, it is important to place seeds at the required interval to allow each plant to thrive from local resources as well as to limit intra crop competition. It would also be an advantage if the depth of seeding could also be regulated. Current seeding machines are not capable of placing seeds in soil with the desired accuracy. ***Ultra high precision seeding*** (UHPS) is the concept of putting individual seeds specifically where we want them to go – both vertically and horizontally.

Most crops are grown in rows as this is easier to achieve with simple machines. The individual crop plant and hence overall crop does better when each plant has equal access to light, water and nutrients. This concept then leads to the old idea of growing crops not in single rows but in a grid pattern with equal space all around. This idea was semi-automated years ago by using a rope with knots tied in it to trigger the seed placement. Given that crop plants were planted in a grid pattern, intra row weeding can then be replaced by orthogonal inter row weeding.

Vertical precision in seeding depth can also take advantage of placing seeds within the range of soil moisture. Wetter soils can allow shallower depths while drier soils should be planted deeper.

Permanent planting positions are now also a reality. The seeding position could be the same each year especially if microtillage were being used. The same seed application map could be used as well as subsequent treatment maps. Crop residues and non competitive weeds could be tolerated in areas away from the crop plants if they did not cause problems, and residual nutrients are still in the correct place for next year's crop to use.

Reseeding is a new concept where crop seeds or seedlings could be planted in positions where the original seed did not germinate. Given that most seed companies can only guarantee a germination rate of 80%, 20% of the cropped area may be unproductive. As this area is fertilised in the same way as the productive area, this could easily give rise to a significant yield and economic reduction. If the main crop growth has developed beyond the acceptance of new seeds, then seedling could be transplanted into the unpopulated areas. A reseeder would have the ability to insert individual seeds/plants without disturbing the surrounding crop.

Crop scouting is normally the process of where a person walks through the crop assessing health and looking for abnormalities. As the development of sensors (and biosensors) continues this process could be automated by mounting them on an autonomous platform.

Automated Crop Scouting (ACS) can give a significant advantage as firstly it gives the manager access to unparalleled data from the crop and secondly can give real time alerts to unusual conditions and stress. This data can be stored as maps for future review if required. If the crop is continually scanned, say, for fungal attack, prophylactic treatments may be unnecessary if an attack does not take place and the data only used when symptoms actually occur so long as it can be treated quickly. Crop breeding trials could also benefit from this type of system as many, highly repeatable, measurements could be taken daily which would not be cost effective with a manned system.

Microspraying: is the concept of intelligently targeting inputs such as herbicide so that it only comes into contact with the weed leaves. Individual weeds can be identified and the species recognised along with measuring the weed leaf position and size. Microjets can squirt out minute drops of liquid or jets of gel that adhere to the surface of the weed leaf. The efficacy can be drastically increased by such a system as the herbicide is only administered to the leaf of the target weed.

Proximity fertilisation is the concept of applying fertiliser to the soil at a desired distance from the crop plant. As many of the traditional mixes of conventional fertiliser will burn a crop plant if exposed to a too concentrated amount, the same mixture could be applied at a controlled distance from the plant to allow a slow release and hence have a higher utilisation rate.

Biomanipulation is the ability to manipulate individual plants or parts of individual plants. Many expensive operations such as thinning, pruning and picking are carried out currently by hand but could well be automated. This concept complements selective harvesting (*q.v.*).

Advanced Machinery Management System (AMMIS) is the concept of bringing together all the management tools required to manage a fleet of SSMs into one integrated software package. Many of these tools and concepts apply to both manned and unmanned vehicle fleets. ***Fleet management*** is a set of tools that allow the coordination of multiple machines, not only in their current task, but it also deals with their support and coordination in real time. ***Route planning*** is one of the fundamental tools needed to optimise where the SSM should go in relation to field size and shape. ***Real time coordination*** is the concept of integrating movement of multiple machines to make best use of their resources and minimise their down time. A simple example might be where there are two harvesters and three trailers. Which trailer should go to which harvester? Where should it wait?

Coordination of multiple vehicles should be carried out centrally within the AMMIS. 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 is where multiple vehicles working in the same field 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 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.

Discussion

Although many of these ideas are still in the conceptual stage, a number have been trialled within research environments and have proved to work. To be able to take full advantage of these opportunities a complete system needs to be developed so that all can work together. To do this a paradigm shift is needed in the way we think about agricultural mechanisation. We need to break away from defining agronomic tasks by the machines we use now and define them in terms of the plant requirements. Only then can we use appropriate mechatronic principles to design machines to fulfil these requirements.

There is no doubt that agricultural inputs can be significantly reduced by intelligently targeting them. This is no more than attempting to do the right thing, at the right time, in the right way but with smart machines rather than using people in the control loop. This type of development does not reduce the role of the manager as all the traditional management roles are still needed but what it may do allow these smart machines to adapt treatments according to local conditions in the way a person would but without that person being present.

Conclusion

Agricultural automation is a continual development. The current research technologies give rise to the possibility of developing a completely new mechanisation system to support the cropping system based on small smart machines. This system replaces blanket energy over application with intelligently targeted inputs thus reducing the cost of the inputs while increasing the level of care. This can improve the economics of crop production as well as having less environmental impact.

References

Blackmore, S. (2007). A systems view of agricultural robotics. Precision Agriculture conference, Wageningen Academic Publishers, the Netherlands. pp. 23-31

Butler, S. (1887). Luck, or cunning, as the main means of Organic Modification? An attempt to throw additional light upon Darwin’s theory of natural selection. (London: Trübner & Co.) Reprinted as vol 8 of The Shrewsbury Edition of the works of Samuel Butler (London: Jonathan Cape, 1924)

Dyson, G. (1997). Darwin among the machines, The Penguin Press

Kelly, I., Holland, O., and Melhuish, C. (2000). SlugBot: A robotic predator in the natural world. 5th International symposium on artificial life and robotics. Oita, Japan, pp.470-475.

Leropoulos, I., Greenman, J., and Melhuish, C. (2003). Imitating metabolism: Energy autonomy in biologically inspired robots. AISB '03 Second international symposium on imitation in animals and artifacts. Aberystwyth, Wales, pp.191-194.

Shibusawa, S. 1996. PhytoTechnology - An introduction to the concept and topic of a new project. http://phytech.ishikawa-c.ac.jp/WhatIs.html

Tillett, N.D., Hague, T. and Marchant, J.A.(1998) A robotic system for plant scale husbandry. Journal of Agricultural Engineering Research, 69, 169-178.