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CONFERENCE PAPER

ROBOTICS AND SMART ENGINEERING

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Developments in robotic engineering and computer based technologies offer huge opportunities for agriculture. Robots have the potential to undertake a wide variety of operations on the farm including some of the mundane tasks such as manual harvesting. This paper explores the way in which the good robotics engineer is capable of thinking 'outside the box' and how he has to have a good grasp of the economics of the problem he is seeking to solve. The various components available to the engineer are considered including sensing systems, power units and control systems as well as the mechanical machine that does the work. Case studies include an asparagus harvester, robotic weeding, fruit harvesting and movement sensors for use with dairy cows.

Keywords Robotics, technology, sensing systems, machine learning, harvesting, milking, condition scoring.

Introduction

Developments in engineering and computer-based technologies offer huge opportunities for agriculture. Many tasks in farming are dull and routine and involve huge gangs of labour performing repetitive tasks. These mundane tasks can potentially be replaced by robots. Farmers also require information about their operations in order to manage them effectively and developments in new sensing technologies offer opportunities to produce more timely data and information that has to date been uneconomic to collect.

Robots have the potential to undertake a wide variety of operations on the farm including cultivating, seeding, spraying, nutrient application and harvesting. The drivers for introducing robots on to the farm are economics and the poor availability of manual labour. There is the potential for robots to complete tasks at lower cost and possibly to higher standards. Robots don't get tired and will complete the one thousandth task as effectively as the first. The farming industry has suffered with a lack of available labour. In recent years the UK industry has relied on willing workers from Eastern Europe but they probably won't be available for ever. However for many years the USDA had a moratorium on funding research into robotics because of the threat to employment. That moratorium was only lifted 3 years ago.

The development and use of robots in agriculture is still in its infancy. The robotic milker is becoming established with numerous installations across the UK. Lely believes that 20% of all new installations in the UK are now robots (Dunn, 2009). The robotic milker has been developed over the last 30 years and is a sophisticated machine. The accurate placement of the cups on the teat was a significant challenge but the machine also had to rise to the challenge of mastitis detection and to maintaining milk hygiene standards. All these issues were overcome and a small group of pioneer farmers then brought the machines into commercial use.

The good robotic engineer has to be capable of thinking outside the box to solve problems. The starting point in developing suitable robotic technology is


Columnar trees make harvesting easier for robots

understanding the problem. What is it that has to be done? And are there opportunities to adapt what is done to make the robotic solution easier? For example growing strawberries on table tops presents fruit to a robot in a much more acceptable way than growing strawberries on the ground. Can fruit trees be grown to present fruit to a robot in a way that will make picking much easier? Apple breeders at Cornell University are using genetics to develop 'columnar' trees that will present a 'fruiting wall' to robots for harvesting – an easier environment than searching for fruit in the canopy. 'Re-positioning' the problem is often a significant part of the solution for the robotics engineer.

The engineer also has to understand the economic environment that the machine is going to work in. Indeed this is a fundamental issue in technical development; does the engineer solve the problem and then try to reduce costs or does he work at low cost and then work his way up to solve the problem?

As in most fields of research and development (R&D), robotic engineers work at different levels. Some engineers work at a theoretical level developing novel sensors, control systems and tools for which they do not have an immediate need. They create the 'new science' that is then used by those engineers who are closer to the market place to develop marketable machines (the military are a key driver in the development of robotics and smart engineering: they do not have the same cost constraints as the commercial world and can develop concepts that are then used by commercial engineers). Once the technical problems are overcome bringing down the cost usually follows. Global Positioning Systems (GPS) provide a good example of this process; once they were developed both the physical size of the GPS units and their cost came down quickly. This model works over and over again.

Robotics

Robots consist of a number of key components –

- Sensing systems – to see, locate and feel;
- Control systems including a CPU (Central Processing Unit);
- Power units – to provide the power;
- The mechanical apparatus that actually does the work.

Sensing systems

Robots make use of a number of different sensing systems including machine vision. Machine vision is used to help robots locate where they are working and also for a wide variety of other applications including locating produce for harvesting, plants for spraying and animals for condition scoring. Machine vision is based on a number of different sensors that can include:

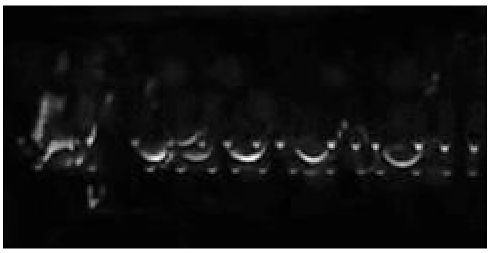
- Colour cameras
- Infra-red cameras
- Cameras tuned to specific light frequencies
- Radar
- Lasers
- Ultra sound

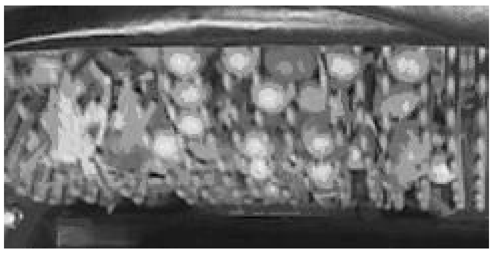
Often stereo cameras are used to help create a 3 dimensional image and sensors can also be fitted with motors so that they nod and scan a field of vision. In some cases a number of different sensors is used to create reliable images. These images are then combined using complex algorithms to create an image of the surrounding area. It is important that the sensing system can detect the floor and any vertical surfaces so it can place objects into that space. Sensors on a vehicle that is travelling on bumpy ground represent a particular problem. They have the potential to produce 'noisy' images. The CPU has to be capable of taking these images and producing clear images. It also has to be capable of synchronising images coming from different sensors.

These cameras can take thousands of pictures a second and the processing units must be capable of processing that data in real time to produce an image of the working environment. One of the challenges of vision systems is coping with shadow – areas of dark and light. This can be overcome by using double exposures that the CPU then processes in real time to produce a single image but it is costly. This helps to 'see' objects in the shade. The human eye and brain is particularly good at doing this.

Work done by the National Centre for Engineering in Agriculture at the University of South Queensland demonstrates how lighting can be used to aid computer vision. The research team wished to develop a computer aided system for assessing the yield of macadamia nuts. The pictures below show how working in an environment of structured light can make the target easier for the computer to identify in comparison to uniform light.

Robots also use sensors other than machine vision to locate where they are.





Pictures Courtesy of Cheryl McCarthy-NCEA

The disadvantage with machine vision is that it can only locate position relative to a feature and it doesn't work in an unstructured environment. Alternatives include:

GPS (Global Positioning Systems), with which most farmers will now be familiar. GPS signals are used to pin-point exactly where the machine is. Systems associated with the very high levels of accuracy required for field operations are still expensive and the signal can be lost, particularly under tree canopies.

Wheel encoders, which can be used to track vehicle position. They are electro-mechanical devices that measure the rotation of an axle and calculate how far the vehicle has moved from a known starting point.

IMU (inertial measurement units), which are electronic devices that measure and report on a vehicle's velocity, orientation, and gravitational forces, using a combination of accelerometers and gyroscopes. They are commonly used in aircraft. These measurements are likewise used to calculate how the vehicle has moved from a known starting point.

Both wheel encoders and IMU use a process known as dead reckoning to calculate vehicle position. Position is calculated from a known starting position based on speed over a period of time. A disadvantage of dead reckoning is that since new positions are calculated solely from previous positions, the errors of the process are cumulative, so the error in the calculated position grows over time. In a fixed environment such as an orchard these errors can be corrected using 'high precision way points' that the vehicle uses to adjust its calculated location.

Arial photo graphs can also be used to help a machine locate its position and some research has been done into using cameras positioned high above working areas to help locate position. (Zhang: 2009)

Sound is not widely used on robots for sensing. It has been used by the military to 'listen' for gunfire but has limited value in an agricultural setting.

Touch is a particularly challenging sense to imitate. Force feed back can be used where the electrical current required to pick something up can be measured. Tactile sensors are useful in unstructured and changing environments and play a major role in grasping objects. Imitating the human hand is particularly difficult in terms of robotic development – it is very expensive. Humans use vision and touch to handle objects – we locate the object with vision but then use touch to actually handle it.

Other sensors that are used in robots include tilt and stability sensors.

Control systems

Robots require effective control systems based around a CPU. These include:

High Level Controllers – for mission decisions, path planning, safeguarding, specialty sensors and user interfaces that handle large amounts of information;

Low level controllers – for steering, engine and implement control.

The two systems must effectively communicate in a timely and fail-safe manner. An architecture is required for this (Cameron, 2009). Cooling the CPU can be a problem.

Power units

A number of different power options are available to the robotics engineer. These include:

Many types of batteries, such as:

Lithium Ion batteries that offer good power density and can be shaped to fit into any space. They require recharging and if mishandled they can explode;

Wet Lead Acid Batteries that are heavy, lack power density and also require recharging.

Electricity through a power lead which is low cost and light weight but lacks freedom of movement;

Petrol and diesel engines that work for a long time on a tank of fuel but produce vibration, noise and heat.;

Hybrid power where engines are used to recharge batteries. Electricity has good power characteristics and the engine smoothes the power requirement.

Cooling the power units can be a potential problem

The mechanical apparatus

The machine uses a variety of solutions to solve 'doing' the task including:

Hub electric motors that offer great torque and are easy to design into a machine. They have no direct drives and very little loss of energy.

Hydraulics which results in a loss of power if used to drive the vehicle. However they are easy to design in. Hydraulics can also be used to move components like mechanical arms.

Pneumatics that are 'soft' in their operation. Gases can compress and take shocks which can be very useful in controlling some mechanical operations. They are also easy to design in.

The movement of the robot is usually accomplished using wheels but tracks can be used, and some robotic engineers have worked with 'walking' machines in certain applications. When wheels are used a wheel can be put on to each corner of the robot with the possibility of using four-wheel steer and four-wheel drive. Turning circles can be made tighter using braking control.

(Idia, 2009)

Machine learning

'Safeguarding' is an important feature of any robot. Invariably this involves creating images to detect dangers. Safeguarding needs to be conservative in its operation and should detect false positives, that is the robot should stop on suspicion of a problem at the risk that there eventually proves to be no obstacle actually present. Typical obstacles in a farm environment include telegraph poles, trees, people, animals, other vehicles, irrigation pipes and pumping stations. When a machine stops it can send an image that highlights the obstacle back to a supervisor who decides if he should override it. (Moorehead, 2009)

Machine learning is a key component of robot development. The robot adjusts its own software based on previous experience. The algorithm learns patterns from the data sets and then uses them in a predictive manner. The robot's perception is thus improved. For example if the robot is fitted with long distance vision sensors and short distance vision sensors it may ' see' something in the distance but may not know what it is. The short distance sensors may then recognise that object as a tree when it gets close to it. Next time the machine 'sees' a similar object in the distance it will recognise it as a tree. Or when it hits an obstacle it remembers what it saw and then next time it recognises it as an obstacle. Robots can use this process to reset their own parameters in a new environment, saving programmers huge amounts of time and cost.

Machine learning was used in the development of an oestrus detection aid that the Livestock Improvement Corporation (LIC) in New Zealand has developed. The system that is commercially available is designed for large herds. It uses a camera to 'read' Kamar heat detectors. Creating an algorithm that could read the Kamars was difficult and eventually a blue Kamar was produced to overcome the problem, but machine learning was used to refine the software during the development of this product.

LIC are also investigating using machine learning to analyse data for individual cows. For example each milk cluster could be adjusted based on the machine's previous experience.


BRAIN in Japan - The driverless machine is a reality

Most robotic engineers currently envisage a future based on groups of small robots under the control of a single operator. Such a system will require a supervisory system with a communications infrastructure. In the future the operator might be a 'mothership' controller with sophisticated systems to control the smaller machines, along with an infrastructure to refuel and replenish them. The driverless machine is a technical reality and its uptake appears to be limited by legal issues rather than technical ones: for instance who will be responsible if the machine drives through someone's living room? Smaller machines will limit the potential damage that might occur and could also be more easily retained by a series of 'tank trap' ditches around the working area.

Developments in sensor technology are creating a revolution in the information that is available to farmers (Singh, 2009). A plethora of sensors and communication systems is being developed that can be used for applications as diverse as:

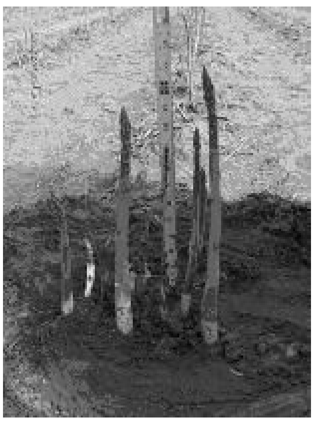
- Identifying crop stress
- Identifying crop disease
- Measuring the nutrient content of plant leaves in situ
- Estimating crop yields
- Identifying internal defects in produce
- Measuring body condition score in livestock
- Measuring livestock activity

These will help farmers react more quickly and to make more informed decisions.

Case studies
Asparagus Harvesting

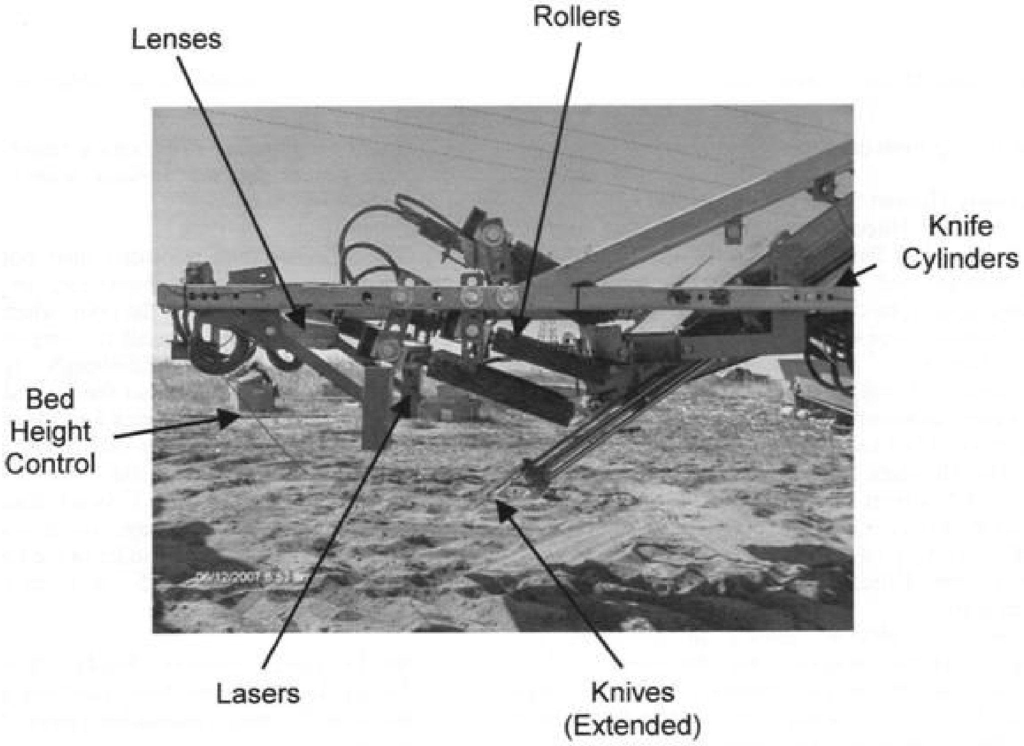
Geiger-Lund Engineering in California has successfully developed a robotic asparagus harvester that is now ready for the market (www.asparagusharvester.com).

Harvesting asparagus with a robot is not easy. The crop is selectively harvested and cut below ground. Any automatic harvester has to be capable of identifying the spears that are ready to harvest and then cleanly cut and collect them without damaging the spears that are developing. The machine has to be quick and reliable because during the peak harvesting season the crop is cut on a daily basis.



Bill Lund first started building prototype harvesters in the very early 70s and persevered throughout most of the 1980s before putting the project aside. He returned to developing the machine in 2000 as a result of renewed interest in automated harvesting and technical developments that offered the potential to overcome the obstacles that had been encountered over a decade earlier. The development of the machine has been slowed because there is only one short season each year in the Western United States to develop and test it.

The machine uses two laser beams along with a series of sensors to identify where the spears to harvest are; it then uses pneumatically fired knives to cut the spears and finally uses rollers to collect the spears and deliver them onto a conveyor. The cut spears are then manually packed into trays.



A variety of sensors was tried over the years. An early video camera was tried, as were small flappers that touched the spears. It quickly became clear that any sensor that touched the spears was unacceptable. Spears that leaned over also represented a problem in terms of detecting exactly where to cut them. The chosen sensing system uses two laser beams. The higher beam is used to determine if the spear is ready to harvest. If the spear is lower than the beam then it doesn't get cut. The lower beam is used to determine where to cut. The beams create a red spot on the spears that is 'seen' by optical sensors that sit behind a series of lenses. There are two sensors behind each lens; one focused on the top laser beam and one on the lower laser. Each sensor then has its own micro controller with its own programme running. The laser is modulated and the sensors detect a rapid change in intensity. The sun does not interfere with the system.

The header is constantly kept at just the right height above the bed using a simple rod that moves and activates a pair of proximity switches. Earlier versions had mechanical switches, ultrasonics and laser distance detection but they proved to be unreliable or unsatisfactory. Where a harvester has more than one header they will all move independently. Farmers grow asparagus on differing widths and heights of bed and machines will be custom built to suit the farmer's requirements.

Cutting the asparagus is a real challenge. The machine has to calculate just the right spot to cut. If the machine is moving at one mile per hour it moves almost two inches in a tenth of a second. The knives have to be very accurately targeted to cut the spears. The harvester has a shaft encoder on the axle that calculates the machines speed every tenth of a second. The CPU then calculates when to 'fire' the knives to cut in the right spot.

The knives are two inches wide and fitted to the end of 20 inch stroke pneumatic cylinder that can fire five times each second. The knife has 100lbs of force and reaches full velocity within an inch of starting to move. It takes just 0.07 of a second to go down. The cylinders had to be custom built to provide ports that were big enough to allow enough airflow to meet the performance requirements. Its movement is cushioned by a small pneumatic cylinder that ensures the cylinder rod does not strike the cylinder case at the top of its stroke. On the down stroke the cylinder reverses direction before it bottoms out. Early versions of the cylinders shook themselves to pieces: rods that held the cylinders together stretched and fittings shook themselves apart. Lock nuts and lock tight were tried without success. Cylinders that are welded together with tapered fittings provided a reliable solution. The current cylinders have a one inch bore with a centre-to-centre spacing of one and three quarter inches.

The width of the knives and cylinders has been reduced as the machine has been developed. The knives were originally five inches wide. They cut the asparagus well but did far too much damage to spears that were developing around the spear that was harvested. They were having a negative impact on the overall yield across the season. As targeting was refined their width was progressively reduced. Sometimes two knives are fired at once if the sensors detect that a spear sits in the margin between the two knives.

There are three sets of rollers that pick the spears up and carry them into the conveyer. The first set starts to grip the spear before it is cut. The rollers then 'pass' the spears from set to set and lift the spears well out of the way of the knives before putting them onto the conveyor. The rollers have been developed so they don't damage the spears.

Images courtesy of Bill Lund

The machine is finally ready for the market place and Geiger-Lund expects to sell one into Australia in 2010. The cost is expected to be in the region of £150,000 for a machine with three headers. In a commercial environment the machine should be able to work at two miles per hour.

To date no study has been done comparing the machine in its current form with a manual team cutting the crop but it is envisaged there will be a small yield penalty associated with its use.

Weed Control

Weed control is an area where alternatives to conventional spraying are being pursued by a number of research groups. Our existing spraying techniques result in potential risks to the environment and the possibility of product contamination. In Europe many agrochemicals are being removed from the market and in some cases alternatives are urgently required. Possible solutions are robotic weeding and targeted spot spraying.

Dr Nick Tillett of Tillett and Hague Technology has been working on alternatives to conventional spraying for over twenty years, and his success in this area demonstrates how frontier technology develops over a period of time. As long ago as the late 1990s he and his colleagues had developed a tool carrier that could steer itself through a field of row crops using machine vision. This developed into the first Robotic weeder, the Robocrop, which was launched in 2001. A number of different techniques were tried to differentiate between the crop and the weeds. Colour differences between the crop and the weed were found to change constantly and were insufficient to differentiate successfully. Leaf shape was tried but it required very high definition cameras and too much computational capacity. The solution was found by using the planting geometry to identify where the crop rows were. Colour cameras were able to quite easily distinguish between the green crop and the background soil. A band pass filter tuned to the known row spacing was then used to create an image of the rows that the hoes could follow.

Unfiltered image

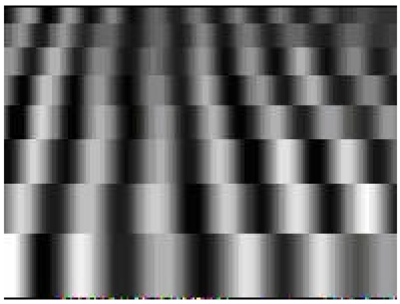


Image after filtering

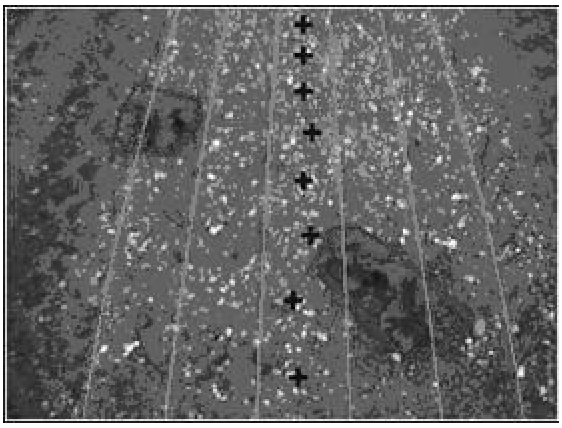
The machine tracks crop rows from image to image and uses knowledge of the tractors forward motion to ensure reliability. This solution was found to very robust in terms of identifying the rows and even worked reliably when the tractor was deliberately driven badly. The Robocrop found a market with vegetable farmers and organic cereal farmers and sales have risen to about 50 machines each year. The research team continued to refine the machine over the next few years but their attention moved on to the next challenge.

Weeding in between vegetable plants within the row as well as between the rows was the next problem to be addressed and overcome. This required both vision innovation and mechanical innovation. Once again knowledge of the geometry of the crop is the basis on which the machine works. The camera produces 30 images each second and the machine predicts when a plant will appear at the top of the image. It then refines the location of the plant as it moves across the image and rotating hoes are then run around each plant as the weeder passes over them. When an unusually large gap exists between two plants the hoe can be clearly seen to hesitate before it sweeps through the gap.

The Robocrop in row – hoes weed around each individual plant

The Robocrop InRow was successfully launched in 2007 and offers a real alternative to spraying in precision drilled or transplanted vegetable crops where large gaps exist between individual plants. Once again the research team moved on to a fresh challenge.

Using the technology to identify individual weeds and spot spray them is the current focus at Tillett and Hague Technology. The particular challenge that they are addressing in a collaborative


Potatoes identified for spraying

HortLINK project is volunteer potatoes in onions and carrots. The current agrochemicals used for this task may well be withdrawn in the near future and they have a reputation for checking the crop. On the prototype machine the camera looks forward and down across a 1.8 metre wide bed. Once again it differentiates between plant material and the background soil on the basis of greenness. The potatoes are identified based on a weighted combination of their distance from the crop row, their size and their shape; that is their aspect ratio (width divided by height) rather than the leaf shape. The algorithm then identifies spots to be sprayed.

Control plot alongside a crop that has been spot sprayed. Between 75% and 95% of potatoes have been removed in one pass in trials with very low levels of crop damage

This project has involved solving the problem of spot spraying the weeds as the machine passes. The sprayer has to turn on and off very sharply with no drift at very low flow rates. This has been achieved with Glyphosate where quite large droplets have been used to give good drift control and targeting. However these may not be suitable for all other chemicals. The machine is now an advanced prototype and is probably 2 years from becoming commercially available. One of the problems to overcome is a legislative one; there is no approval for using Glyphosate in onions and carrots.

A research team at the National Centre for Engineering in Agriculture in Australia has successfully used colour differences to identify different weeds. They managed to identify weed grasses in sugar cane using the 'blueness' of the leaf. Accuracy of detection was over 90%. Although this is not directly applicable to the UK it does demonstrate that there are potentially alternative ways of identifying weeds to the one outlined above. Indeed it may well be that individual solutions have to be found for particular weeds in particular crops.

A really futuristic approach to chemical application is being researched at Washington State University. The programme is seeking to use cold plasma to accurately apply chemicals to fruit crops. The long term aim is to apply pesticides to just the part of the crop that requires treating – so when the apples need spraying they will get coated in pesticide but not the leaves. Once again vision technology is used and cold plasma is used to apply an even film across the target. It may be many years before this technology is available to use in the orchard but it could be available much sooner for applying materials to harvested crops in the store or pack house.

Smart engineering for livestock farmers

Progressive dairy farmers have been aware for many years that locomotion scores and body condition scores for their cows are valuable data that can improve management, but obtaining this information through manual assessment is laborious and interpreting it to produce meaningful trends has not been easy. IceRobotics in Edinburgh have developed technical solutions to gathering and interpreting this information and are due to launch an animal activity recorder onto the dairy farm market that will not only produce locomotion scores but a variety of additional management information in relation to both individual cows and the whole herd. IceRobotics' expertise is in sensing technology. They have already developed an activity recorder that monitors, records and reports detailed animal activity. Called the IceTag3D it is based on an accelerometer that picks up the forces of gravity in three dimensions – up/down, forward/backwards and left/right.

It records information 16 times each second and transmits the data wirelessly. This is a progression from the pedometers that have been on the market for some time that record just stepping activity. Software interprets the raw data into the animal's activity patterns rather than just recording step count. The IceTag3D is currently used by animal scientists to support research into animal health and welfare. Typically, devices are attached to animals for the experiment period and then removed and the data downloaded wirelessly to the researchers' computers.

A new system is being launched at the Precision Dairy Management Conference in Toronto in March 2010 to enable much larger longitudinal datasets to be collected to support research. Called the CattleGrid, the device combines the IceTag3D with automated data download on the farm and internet connectivity. This will allow devices to stay on animals for several years and the researcher to access the data remotely. Oestrus detection will be available to participating farms through the system. A system is also being launched in Autumn 2010 that is being designed specifically for commercial dairy farmers. This will be based upon a localised system but will be internet enabled to allow for downloading updates and to benchmark with other herds. Initially this will provide monitoring and alerting for oestrus and lameness. IceRobotics have been holding farmer focus groups to develop an understanding of exactly what information farmers want from a commercial system.

The accuracy of the information generated is currently being validated to ensure that the system is accurate whilst minimising the detection of false positives. In addition to individual cow monitoring, the system will also produce whole herd information; how long cows are spending lying down, how long do they spend just standing. This will allow farmers to assess the impact of management changes on the behaviour of the herd. Has a ration change resulted in the cows spending more time standing at the feed face? This should lead to the development of 'time budgets' that the farmer can use to maximise the time his cows spending eating and lying rather than waiting to be milked. It should allow good management practices to be scaled up.

IceTag3D on grazing cow

The IceTag3D incorporates battery saving technology that gives its batteries a prolonged life and it sits within a tough plastic housing that can tolerate life on a cow's ankle.

The concept of gathering information from sensors on the animal can be further developed. Researchers in Japan have collected data automatically on the number of bites an animal takes when feeding. It should be possible to put a bolus into the animal that would take temperature readings. All this information could be linked back into sensors in the milking system and in the future it should be possible to gather a wide variety of data that will give us new insights into individual cows and whole herds.

IceRobotics have also been involved in the development of automatic body condition scoring. They have developed a system demonstrator that uses a thermal imaging camera to assess the shape of a cow. At present body condition scoring is manual and subjective. It is time consuming and requires trained labour. Very few farmers consistently measure body condition scores although many recognise the value of the information associated with the practice.

The system developed by IceRobotics works by determining the presence of the animal and then taking an image of the back of the cow from above. The data is then analysed to identify certain points on the animal's back. The angles associated with these are then calculated and the appropriate resulting body condition score generated.

Thermal image of cow's back from above

Studies to date with the system have demonstrated its effectiveness, although it still requires some refining before full commercialisation. Automatic body condition scoring could also be used to select animals for slaughter in beef feedlots.

At present the cost of thermal imaging cameras is prohibiting the commercialisation of this approach to automated body condition scoring, but technology is constantly coming down in cost and there is every prospect that this technology will be available on the farm in the future.

Fruit Harvesting – a significant challenge for the robotics engineer

A number of research groups around the world are working on this difficult issue. A consortium from Washington State University and Pittsburgh University is working on an orange and apple harvester, Washington State University (WSU) is working on a cherry harvester and BRAIN (Bio-oriented Technology Research Advancement Institution) in Japan is working on a strawberry harvester. The challenges associated with harvesting fruit are considerable but the most significant was probably summed up by Marvin Pitts of WSU: 'If I touch a fruit, I bruise a fruit'.

The robotic fruit harvester has to navigate and power itself around the orchard; it has to see the fruit to be harvested, differentiate between fruit that is ripe to pick and fruit that is still immature, restrain it to grab it, remove it from the tree or plant and then put it into a tray or bin. It has to do all that economically, and a large part of doing it economically means doing it quickly. Locating the fruit is made difficult because it grows on a plant that is not uniform. Fruit can be hidden behind branches and leaves. To locate red fruit a colour camera is probably the lowest-cost option, but green fruit against green leaves creates problems. In this case neo-infra-red, ultrasonic or laser scanners may be the best option. The machine will have to reach and grab the fruit. As the fruit gets further away from the robot this becomes more difficult. The machine has to be able to judge distance and to grab fruit that is moving in the wind. Of course one possible solution to this is that the trees are trained. As discussed above columnar trees may have a big role to play in this respect if they are used to create a 'fruiting wall'.

Having located the fruit the next challenge is to handle it. Robots are often built to mimic humans. When we reach out to pick an apple we use vision to guide us to the point of grabbing the apple but then touch takes over. Touch is a very difficult sense to mimic. Indeed it would appear that nobody has yet produced an effective robotic finger tip. That finger tip would require a number of sensors – 3, 20 or 100? It would then require very rapid feedback loops from the sensor to the mechanical actuators to stop the 'finger' bruising the fruit before it had stopped moving. Progress is being made here. Until recently the fastest actuator took one tenth of a second to respond; too slow to prevent damage. This has been reduced to a two-hundredth of a second – twenty times quicker.

The 'hand' that grabs the fruit has to be soft but not so soft it won't work. If it grabs too firmly it will bruise but if it isn't firm enough the fruit will slip within its grasp and scratch. The 'hand' that grasps the apple could consist of 3 fingers, or 4 fingers or may make use of suction. Will one device handle all sizes and shapes of fruit?

The fruit will then have to be moved back to the tray or box. Will that be done with the picking arm? If so can it be quick enough? Can it be done through a vacuum tube? Without bruising the fruit?

Any harvester will have to be reasonably straightforward to operate and calibrate.

Power options include electrics through a cable, batteries and engines.

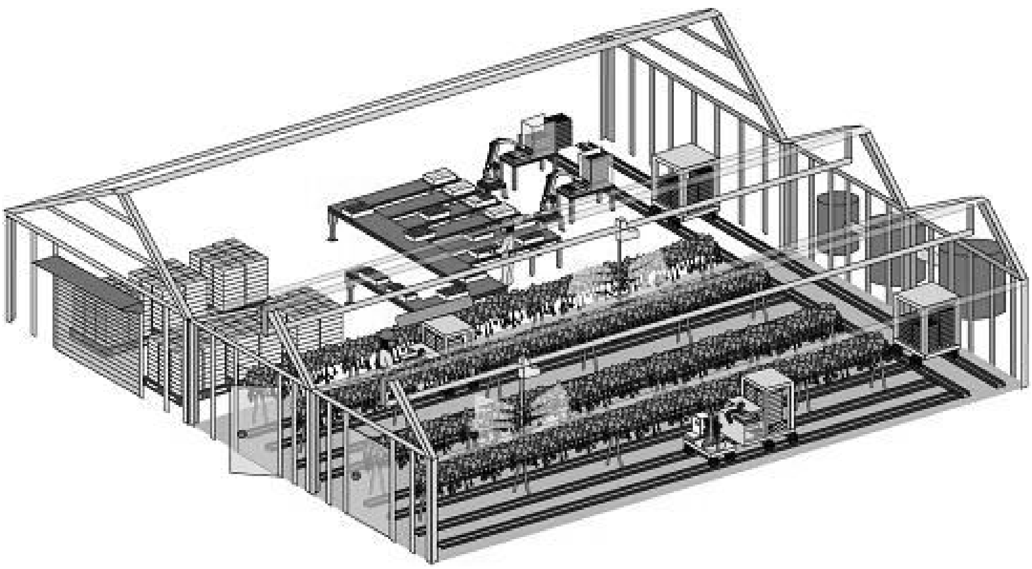
Traction systems could include rails, wheels or tracks. On a slow machine working in a confined space an umbilical system on rails may well be the preferred option.

GPS could be used to guide the machine around the orchard but trees interfere with the signal. A portion of the signal bounces back.

In developing a robotic harvester the design parameters are important. What is the specification? What is the tolerance level in terms of bruising? However technological breakthroughs could make a huge impact. If someone develops an effective 'touch sensor' next week development could be much faster than we might expect.

Strawberry Harvesting

Research engineers at BRAIN in Japan have produced two prototype robots that will harvest strawberries. The eventual goal is to develop a complete automated harvesting and packing operation based around strawberries grown on table tops in either greenhouses or poly tunnels.

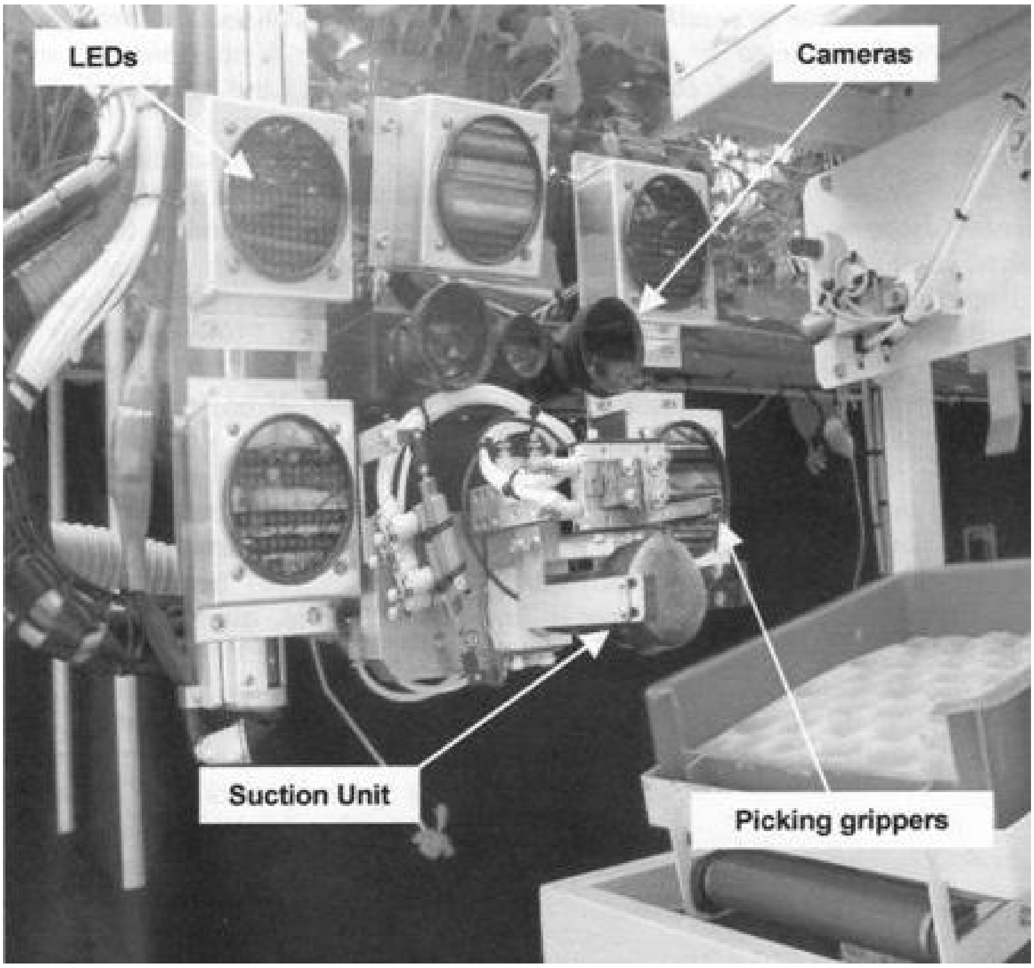


The robots are designed to work at night when shadow does not interfere with the machine vision. The robots travel on rails, are battery powered and work under LED lights. Cameras are used to identify the fruit and an algorithm calculates the proportion of the fruit that is white at the top to determine if the fruit should be picked.

The team have developed two prototypes -

A cylindrical type robot that picks just from the aisle side of the plant;

An articulated type robot that picks from both the aisle and the bed side of the plant.



The cylindrical machine uses machine vision based around five LEDs and three cameras. The centre camera is used to detect the peduncle and the two

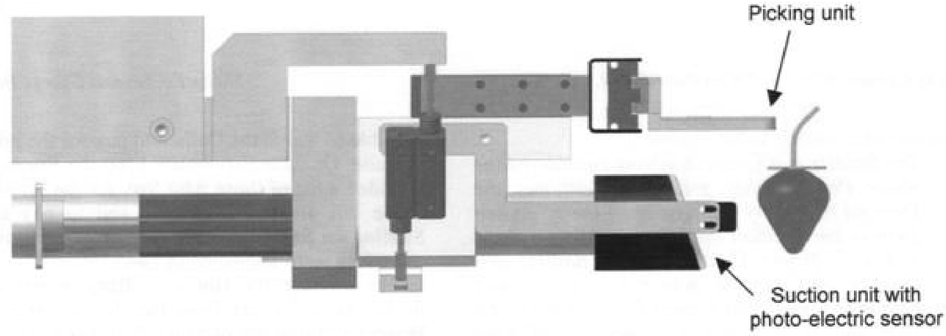


Diagram of the picking arm

side cameras are used to create a three-dimensional image.

The picking arm reaches out and picks the strawberry at the peduncle. The fruit itself is not actually touched. This has overcome the problem of damaging the fruit when it is touched. The machine has been fitted with a small suction system to hold the fruit stable as it is picked and has been tested with and without this in operation. The articulated machine uses machine vision based on two cameras and one LED. It also handles the fruit by the peduncle but can approach the fruit from both the aisle side and the bed side.

The machines have been tested. They do not pick all the fruit, and do pick some fruit that isn't ripe. Indeed it seems likely that for the foreseeable future

Working from the aisle side

Working from the bedside

a feature on robotic fruit harvesting will be that a manual picking team will have to follow the robots to pick what has been missed. Results are shown in the following table:

	Success rate (%)	Execution time (s/fruit	Mature fruit left (fruit/10a)	Immature fruit harvested (fruit/10a)	Damaged (%)	Test length (m)
Target	60>	<10 [1)]	<1440-2880 [2)]	<216-432 [3)]	0	-
Cylindrical (Suction)	41.3 (7.7-75.8)	11.5	1491	558	0	684
Cylindrical (Non-suction)	34.9 (18.0-61.5)	11.5	1188	500	0	360
Articulated	49.1	11.6	136	1443	0	23

1) Theoretical working hours per 10a

10[s]x7200[fruit/10a] x 0.6 = 43200[s/10a] = 12[h]

10[s]x3600[fruit/10a] x 0.6 = 21600[s/10a] = 6[h]

2) Mature fruit: 3600~7200 fruit/10a

3) 10% of harvested fruits

The results show that the robot has created no damage, which is a significant improvement on manual picking where finger bruising is a problem. The machines do not quite meet the target execution time and at present pick too much immature fruit. Improvements to either the vision systems or fine tuning the algorithms will be required to solve the latter problem. The team also have not yet solved the problem of automatically moving the machine around the greenhouse from the rails in one row to the rails in the next row. They are going on to produce a third prototype and believe that a commercial strawberry harvesting robot is still about five years away from the market.

Conclusions

Developments in engineering and computer-based technologies are set to make a huge impact on agriculture. A number of complex robots are already on the market and more are set to follow. Driverless machines fitted with GPS and machine vision are a technical reality and legal issues appear to be the greatest obstacle to their commercialisation. Harvesting fruit is a particular challenge to the robotic engineer. Locating it and handling it without bruising is difficult but a research team in Japan have created a prototype strawberry harvester and teams elsewhere are working on apple and cherry harvesters. An important feature of robotic development is to rethink the problem to make the task easier for the robot. In this respect plant breeders and geneticists have a role to play in changing the structure of the crop to improve the presentation of the fruit.

Sensing and communication technologies are creating a revolution in the information that is being made available to farmers to improve their decision making processes. Information that was historically difficult to collect can be created automatically and analysed to help fine-tune management and spread best practice.

About the author

David Gardner (David.Gardner@co-operative.coop) is Head of Fruit Operations for the Co-operative Farms and is responsible for developing the fruit business to supply the 'Grown By Us' brand into Co-operative stores. During his career with the Co-operative Farms he has held a variety of roles in several different industry sectors. Since 2002 he has been part of the Senior Management Team. Prior to this date he held management roles on farms and spent 10 years at Stoughton Estate in Leicestershire managing combinable crops and dairies.

He has recently completed the Nuffield Frank Arden Memorial Study on New Technologies. This study took him to leading research institutes in the UK, USA, New Zealand, Australia and Japan. His study focused on gene technology, functional foods, non-food uses for agricultural produce and robotics.

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