

Robotics in horticulture

Flemmer, C^{1*}, Flemmer, R¹ and Scarfe, A¹

¹ School of Engineering and Advanced Technology (SEAT), Massey University, Palmerston North, New Zealand.

* Presenting author, e-mail address: c.l.flemmer@massey.ac.nz

Abstract good to make this look different

The application of robotics in horticulture has been considered primarily in the academic environment and industrial application has been meagre. The main research programs and their achievements are reviewed. We then discuss our autonomous fruit picker from a functional point of view, covering the aspects of autonomous navigation, three dimensional vision to identify and then place the fruit accurately in three-space, robotic arm design, breaking the fruit off the stem and then getting the fruit to fill a bin evenly and without bruising or scuffing. This machine was developed to pick kiwifruit and has enjoyed its first excursion into an orchard during the 2009 picking season. We discuss the issues of using autonomous robots to pick fruit, with particular reference to picking avocados in their normal orchard configuration

Keywords: autonomous, agricultural, robotic, kiwifruit, picker, picking robot, end effector, navigation, vision system, pick-rate, pollination, New Zealand

Introduction good if you could change the text a little to look different

Many of the tasks associated with horticulture, such as picking, pruning, pest and weed control, are repetitive and arduous and there is a problem in getting and retaining labour to do them. Such tasks seem ideally suited to robots and, in countries where labour costs are high, there is an economic incentive to use automation as a solution to the problem. However, while robots are commonly used for repetitive tasks in industry they have not been successful in horticulture. The industrial environment is clean, well-lit, dry and uniform while the horticultural environment is extremely variable in terms of weather, terrain and light. The components which are manipulated in industrial settings are uniform, unobscured, stationary and robust whilst those in horticulture are generally very variable in terms of shape, colour and size, hidden amongst foliage, moving (for example, in the wind) and are soft and easily damaged during handling.

The key problem areas associated with horticultural robotics are:

- Path finding; navigation both within the rows of an orchard and in order to get to the orchard.
- Mapping; keeping track of where the robotic task has already been completed and where it remains to be done
- Robotic vision; computer vision recognition of the target such as the trunk, the fruit/produce, the bud, the flower, etc.
- The design of the mechanical agent or arm of the robot which will perform the task of picking, spraying, pruning, pollinating, etc.
- Building a chassis which is cost effective, can handle rough terrain, sloping ground, muddy soil and rain.
- Intelligent inspection to decide which targets are appropriate for robotic manipulation. For example, robotic picking is vastly more efficient if only produce of the correct size and colour is picked. Similarly, robotic pollination is most efficient when only female flowers with a suitable spacing are selected for pollination.
- Produce handling; many fruits need to be handled very gently once they have been picked as a drop over even a small distance will cause bruising. The produce must be placed gently in the bin and the slope of the bin due to sloping ground has to be taken into account during bin-filling.
- Obstacle avoidance: computer vision recognition of obstacles such as people, poles, wires, stumps and rocks so that the robot can navigate safely around these.
- Swarm behaviour management: to allow multiple robots to function together in one area under remote control - without interfering with each other.

- Overall cost; most of the horticultural tasks, such as fruit picking, only last for a few months of the year and it is not cost effective to use a robot for such a short period. Ideally, robots should be capable of performing many different operations, such as picking followed by bud count followed by pollination followed by fruit count, in order to extend the useful work period of the robot and ensure a reasonable payback time on the robot.

The following section reviews the progress which has been made in these key areas. Thereafter, the desirable attributes for a horticultural robot operating on kiwifruit are discussed and progress made by the authors in the development of this robot is reported. The paper concludes with a discussion on the extension of the current research to other produce such as avocados.

Literature Review [more](#)

Research into the automated processing of horticultural products began in greenhouses because the high plant density and high product value justified the expense of automation and the structured environment was more suitable for automation than the outdoor environment. Research focussed on the harvesting of crops such as cucumbers, mushrooms, lettuce and strawberries and is reviewed by Van Henten et al., 2002 and Belforte et al., 2006. However, none of the work led to commercial automation with the possible exception of a strawberry picker robot, with a pick rate (time to recognise fruit and pick it) of 10 seconds per fruit which Japanese venture firm, Romobility Youto claim may be commercially available in 2010. Belforte et al., 2006 note that greenhouse robots are not commercially viable because they are too specific in their purpose which means that they are only used for a small fraction of the plant lifecycle.

The history of research in automated outdoor fruit picking is given by Muscato et al., 2005 and a review of the progress made in robotic manipulators and robot navigation in horticultural environments is provided by Scarfe et al., 2009. Despite massive effort and investment there are only two outdoor robotic fruit pickers¹. The first is an orange-picking robot being developed in Catania, Italy (Muscato, et al., 2005). Work on the picking hand or end effector began in the late 1980's and progressed to the robotic picker in the 1990's. This has two telescopic picking arms fitted with mechanical end effectors and a camera housed inside the pincers. The arms are mounted on a tracked vehicle which weighs over 2 tonnes and must be manually driven to the start point of the grove. It then navigates along the grove using GPS (global positioning system) way points which must be preprogrammed and has a pick time of 8.7 seconds. The percentage of the total crop picked is not stated.

The second system is an automated fruit-picking machine (AFPM) being developed in Belgium by the Automation Centre for Research and Education (ARCO) to pick apples (Hardin, 2007). The project began in 2004 and the AFPM comprises a Panasonic anthropomorphic robot with a soft silicone cup-shaped end effector with a camera at its centre which can identify and pick apples using suction. The system detects and harvests about 85% of the apples (in non-windy conditions) with a pick rate of 8-10 seconds per apple. The engineers aim to reduce the pick time to 5 seconds and to pick other fruits such as pears. Currently the robot is mounted on a tractor trailer. A human operator drives it to the tree, stabilizes the robot platform by activating hydraulic legs, positions a shroud over the tree to control the lighting and receives, in the human hand, the picked fruit. Hardin, 2007 reports that although one person is needed to operate the system, it "can handle the workload of 6 workers" but this figure seems unfeasible since a human picker would have a pick rate of 1 to 2 seconds and would not have the time overhead of stabilizing the robot platform or shrouding the tree. Further, there are two potential disadvantages to ripping the apple off the tree using suction. Firstly, there is likely to be damage if the stem pulls out of the apple and secondly, any foliage which breaks off with the apple will need to be removed prior to the packing process. In practice, when apples are picked manually, the stems are bent as they are pulled so that the break occurs in the stem, leaving the fruit undamaged and the foliage on the tree.

In spite of the somewhat poor progress in developing a commercially viable horticultural robot, there is significant funding in the area. In 2008, the US Department of Agriculture awarded Carnegie Mellon

¹ A third system is under development by Vision Robotics, a San Diego company. They are working on a two-robot system; a scout robot to form a 3D map of the location and size of the fruit and a second robot to pick using 8 arms. \$ (US) 1 million has been invested in the design concept and another \$ 5 million will be needed to get to the finished product. Neither robot has been built but a description may be found in Strickland, 2007.

University (CMU) \$ (US) 10 million for a four year project researching automated farming robotic systems, with \$ (US) 6 million for research into apples and \$ (US) 4 million for oranges (Piquepaille, 2008). CMU's objectives are "to develop and test technologies including navigation and augmented harvesting of fruit and to assess the economic feasibility of these technologies"².

Design of an autonomous robot operating on kiwifruit

A chassis was designed to be the vehicle from which several different agents such as picking devices, pruning devices, bud-count and fruit-count devices, pollinating devices and liquid application devices can function. It is 4WD with intelligent anti-skidding control and fairly aggressive tyres in order to handle all types of terrain and it must be autonomous with the capability to traverse orchards and identify individual plants and portions of plants. It is linked by radio to a base-station from where it can talk to the internet so that control of a swarm of such robots is possible from anywhere on earth. Software resides on the internet and can be encrypted (as a security measure) and downloaded as required.

The unit is powered hydraulically and has a 7 kW generator. The prototype top speed is 5 kph but this can be increased at need. Navigation is by GPS for gross moves outside the orchard. This is appropriate for the unit to drive along the road up to a set entry point for the orchard. Within the orchard, the unit will navigate by looking at the plants and recognizing the rows between the plants. It will recognize headlands or boundaries and be capable of finding the next row. The strategy for picking/counting/pollinating/pruning will be that the unit is introduced to a row and then told how many rows to service. For many operations, the unit will need to break its activities to unload a full bin and acquire an empty one or to refill its diesel tanks. It must have this level of autonomous navigational ability.

Commercially available robot arms are too expensive and too heavy to be integrated into the kiwifruit robot. Therefore, the unit has four picking robot arms which are custom-designed and built to be light, inexpensive and energy efficient. In picking they will operate asynchronously and will each pick at better than 60 fruit per minute. Picking hands, pneumatically operated, were designed using a four-bar-linkage to mimic the operation of human picker, i.e. to grasp the fruit and bend the stem as the fruit is picked. Dedicated software has been written to optimize the picking cycle wherein the robot grasps and picks as it moves downwards and then moves across and up for the next fruit.

The unit has two cameras looking forward, two cameras looking back, two cameras monitoring bin level and eight cameras looking upwards (two for each robot arm) at the kiwifruit canopy. The forward and rearward cameras manage navigation and bin-finding. The unit has lighting to illuminate the canopy as well as headlights. Navigation is sufficiently accurate and reliable to position the unit so that the picking cameras can direct the arms. The two cameras and software which service each picking arm are capable of placing the kiwifruit horizontally to an accuracy of +/-1mm and vertically to an accuracy of +/-6mm. This is done by stereoscopic vision. The software processes all four fields which the robot arms can reach for any station and then schedules the picking to distribute the task optimally between the four arms and to avoid any 'head clashes' between arms.

Picked fruit roll from the hand down soft concertina tubes, attached to each picking arm, and onto a conveyor. The conveyor transports the fruit to a robotic bin-filling device called an 'ovipositer', which places the fruit in the bin without ever allowing it to fall more than 75mm, even though all surfaces are soft. This robotic device gets feedback from 'whiskers' and visual feedback from stereoscopic vision looking down into the bin. The vision system will flag a full bin at which point the filling robot will retract, the picking robots will go to a safe stance and the unit will drive to the headland to unload the full bin, locate and pick up an empty bin and return to its last picking position.

² CMU's funded brief is available at <http://cris.csrees.usda.gov/cgi-bin/starfinder/0?path=fastlink1.txt&id=anon&pass=&search=R=15699&format=WEBLINK>

Current Status of the Kiwifruit Robot

The project has been running for 18 months.

The chassis has been built and tested and is shown in Figure 1. It is driven by a hydraulic motor at each wheel and is capable of carrying a payload of one tonne. It weighs about one tonne and is 1.8m wide by 2m long. It has forks on the rear to load empty bins and unload full bins (weighing approximately 450kg). It has GPS, compass and wireless communication capability. The GPS permits crude navigation (to an accuracy of about 1 metre) around the extremities of the kiwifruit orchard.



Figure 1 Autonomous chassis configured for picking with four robot arms but only one picking hand

The unit is capable of autonomously traversing a kiwifruit orchard and managing its stop-start trajectory in order to pick. It does a three-point turn at the end of a row and finds the next, adjacent, row. Intelligent computer vision controls all navigation within the orchard and the recognition of fruit within the canopy. Typical views of the canopy are shown in Figures 2 and 3.



Figure 2 Typical view of a lane in an orchard – from the position of the poles and vines, the avenue is mathematically defined



Figure 3 Image of the canopy taken with up-looking camera

The four customised robot arms have been designed, built, tested and have their software drivers. They work according to the design specifications and use stepper motors. They cost about 5% of the cost of an 'off-the-shelf' anthropomorphic robot and are extremely light and strong. They have adequate reach, both vertically and horizontally with a mechanism to keep the picking hand vertical. The arm follows a U-shaped trajectory moving the hand (with its picked fruit) down, across and up (to pick the next fruit). A portion of the trajectory of the robot arm is shown in Figure 4.



Figure 4 Robot arm

The design of the picking hands went through three generations and Figure 5 shows the final hand and the four bar linkage motion which picks kiwifruit satisfactorily. It shows five sequential conditions from grasping the fruit to ingesting it. During the twisting motion the picking head lowers to pull on the stalk and induce combined bending and tension.



Figure 5 Picking hand

Each robot arm is serviced by two webcams directed at the canopy above and operating stereoscopically to determine the position of each fruit. Sophisticated software dictates which fruit is to be picked by each of the four arms and manages the interaction between the arms so that they do not interfere with each other. Clusters of fruit are picked from the outermost inward.

The picked fruit drops into a soft concertina tube attached to the picking hand and rolls down to a conveyor which moves it to the ovipositor, a dedicated bin-filling robot. The ovipositor is complete and distributes fruit to the bin (see Figure 6). Two cameras and stereoscopic analysis provide an accurate map of the height of fruit at each position in the bin, so that the ovipositor can fill the bin evenly, even when the chassis is on sloping ground.



Figure 6 The ovipositor shown in the raised position

The structures for intelligent control are in place and the machine has speech and voice recognition. It gives verbal warning when it is about to move and it responds to both verbal and wireless commands.

The kiwifruit robot has spent the past 6 months in an orchard, learning to navigate and to recognise and pick fruit. We are confident that it is mechanically robust. Fruit picking and handling are still in the experimental phase and will wait upon the 2010 harvest before further development. A video showing the unit operating one of the four robot arms is available at the link:

<http://www.massey.ac.nz/~rcflemme/current%20projects.html>

Advanced Features

When the robot is fully developed, it will have the following additional features; it will recognise whether the kiwifruit is wet and whether it is raining. It will not pick wet fruit and it will pull a tarpaulin over the fruit in the bin to keep it dry. It will automatically check light level and activate lighting so that it can pick at night. It will have the capability to recognize misshapen fruit and not pick it and will examine the fruit as it passes along the conveyors, discarding blemished fruit. Currently New Zealand packhouses reject about 30% of the kiwifruit because of poor size and quality and the growers are charged for handling the rejects.

In addition, there is the possibility of integrating the picking operation with the packing operation. Because the robot is on the internet, it can feed forward information to the packhouse on what it is picking in terms of quantity, size and quality. The packhouse can also feed back information to the picker, for example, instructing it to select certain fruit. It is feasible to send the machine through the orchard for several picks.

These techniques will, of course, be applied to apples in due time.

Conclusion

Table 1 summarises the current status of the main achievements in global fruit picking robots. The development of the autonomous kiwifruit robot (the last entry on the table) represents a major advance in the field of horticultural robotics. However, in order to become economically viable, the kiwifruit robot has to be able to turn its hand to other tasks as well as picking. In the kiwifruit orchard, we envisage that it will do, bud-count, intelligent pollination (to ensure an even spread of fruit) and fruit-count, several times. The main difficulties with all these tasks have already been overcome in that we have a machine which can navigate and operate intelligently. The vision tasks required for these other operations are essentially the same as those for the navigation. It will therefore take some time during the first season to get each additional task right.

Table 1 Status of Global Fruit Picking Robots

Country	Fruit Type	Start Date	Budget (\$ US)	Status
Italy	Orange	1980's	2 – 5 million	Uses GPS way points to navigate in the grove, 8.7 second cycle (windless conditions), fills bin, manual drive to/from orchard and to change bins. Very heavy (over 2 tonnes), very expensive, not commercially viable.
Belgium	Apple	2004	1-2 million	Picks 85% of the crop, at 9 second cycle. Proof of concept only; needs human operator to drive robot to orchard, stabilize platform, shroud tree and handle picked apples. Not commercially viable.
Japan	Strawberry?	?	?	Operates in greenhouse, 10 second cycle providing fruit is trained to grow over the edge of the container. "May be commercially available in 2010"
USA Vision Robotics	Orange	2005	6 million	Design concept only; a scout robot forms a 3D map of the location of fruit and an 8-arm picker robot gathers fruit. Neither robot has been built.
USA Carnegie Mellon University	Apple	2008	6 million	Objective, over four years: "to develop and test technologies including navigation and augmented harvesting of fruit and to assess their economic feasibility".
	Orange	2008	4 million	
New Zealand Massey University	Kiwifruit	2008	0.25 million	Autonomous visual navigation of orchard and rows, pick rate 0.25 seconds (1 fruit per second for each of 4 hands), gentle fruit handling and bin-filling, automated bin replacement, "commercialized in 2010". This unit has demonstrated, in the orchard, the steps of navigation with 3-point turn in the headland and entering the next row, identifying and picking fruit, automated, even bin-filling (even on a slope). The unit must still demonstrate autonomous placing of filled bins on the headland and acquiring and loading empty bins.

Estimated

The first robot was developed, somewhat serendipitously, for kiwifruit. Kiwifruit are more ordered than apples but the vision problem – looking up into the sky – is considerably more difficult. The mechanics of picking apples are harder because the technique for breaking the stem of apples is more sophisticated in that the apple has to be broken away from the branch. This is not unattainable; it merely requires a little more development and more visual intelligence. Apples are more fragile than green kiwifruit but are similar to the more modern varieties, some of which have not yet reached the supermarkets. On the other hand, both apples and kiwifruit presently suffer levels of damage which are defined by the tender mercies of the pickers and this clearly can and must be improved.

There is a range of ways in which apples are grown, from the traditional trees up to four metres tall, to two-dimensional trellis structures which might only grow two and a half metres high and have the apples presented over a depth of 500 mm. This latter arrangement is identical to a kiwifruit orchard except that it is vertical rather than horizontal. On the whole, it seems that trellised apples will be

slightly easier to pick than kiwifruit. Since it can be expected that the uptake of robotic picking will take place over some years, it is comfortable to target trellised orchards first. This will provide an added incentive to move away from traditional orchards. However, if robot uptake overtakes the number of trellised orchards, then market forces will mandate the development of the technology to handle the unfriendly orchards. Moreover, it must be born in mind that from the point of view of deploying robots for picking and orchard management, the average household, worldwide, spends much more on apples than on kiwifruit so it is a much more attractive market for which to develop specialized machines where the development cost is significant.

Southern Cross Robotics, the company which has developed the robot will complete its development of the kiwifruit robot and will then consider moving into cherishing apples.

Acknowledgement

The authors acknowledge the financial support provided by Steve Saunders, Managing Director of GroPlus, Tauranga, New Zealand and Garth Atkinson, Agribusiness Consultant of Fielding, which has made this research work possible.

Intellectual Property

The intellectual property contained herein is protected by New Zealand provisional patents.

References

Belforte, G, Deboli, R, Gay, P, Piccarolo, P & Ricauda Aimonino, D 2006, 'Robot design and testing for greenhouse applications', *Biosystems Engineering*, vol. 95, no. 3, pp. 309-321.

Muscato, G, Prestifilippo, M, Abbate, N & Rizzuto, I 2005, 'A prototype of an orange picking robot: past history and experimental results', *Industrial Robot*, vol. 32, no. 2, pp. 128-138.

Hardin, W 2007, 'Vision system simplifies robotic fruit picking', *Vision System Design*, Retrieved: July 7, 2009, from http://www.vision-systems.com/articles/print.html?id=303062&bPool=VSD.pennnet.com%2farticle_tool_bar

Piquepaille, R 2008, 'Picking apples with a robot', *ZDNet, News & Blogs*, Retrieved: July 7, 2009, from <http://blogs.zdnet.com/emergingtech/?p=1115>

Romobility Youto 2008, 'Strawberry picking robot in Japan', *Technovelgy.com*, Retrieved: July 7, 2009, from <http://www.technovelgy.com/ct/Science-Fiction-News.asp?NewsNum=1608>

Scarfe, A, Flemmer, R, Bakker, H & Flemmer, C 2009, 'Development of an autonomous kiwifruit picking robot', *Proceedings of the 4th International Conference on Autonomous Robots and Agents*, ICARA 2009, Wellington, pp. 380-384.

Strickland, E 2007, 'Farms fund robots to replace migrant fruit pickers', *Wired*, Retrieved: July 7, 2009, from http://www.wired.com/print/science/discoveries/news/2007/06/robo_picker

Van Henten, E, Hemming, J, Van Tuijl, B, Kornet, J, Meuleman, J, Bontsema, J & Van Os, E 2002, 'An autonomous robot for harvesting cucumbers in greenhouses', *Autonomous Robots*, vol. 13, no. 2, pp 241-258.