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Development of An Autonomous Kiwifruit Picking Robot

A. J. Scarfe, R. C. Flemmer, H. H. Bakker and C. L. Flemmer
School of Engineering and Advanced Technology
Massey University
Palmerston North, New Zealand
R.C.Flemmer@massey.ac.nz

Abstract-**The design concept and development status of an autonomous kiwifruit-picking robot is presented. The robot has an intelligent vision system that ensures that only 'good' fruit is picked. The robot receives instruction by radio link and operates autonomously as it navigates through the orchard, picking fruit, unloading full bins of fruit, fetching empty bins and protecting the picked fruit from rain. The robot has four picking arms, each of which will pick one fruit per second. To extend the useful annual work period of the robot, it is envisaged that it will also be used to pollinate kiwifruit flowers.**

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

I. Introduction

There is widespread use of robots in industry but much less success in using robots in agriculture. The industrial environment is relatively clean, dry, predictable and well-lit while the agricultural arena is extremely variable in terms of light, weather and terrain. Industrial automation involves uniform components which are robust enough for robotic manipulation, while agricultural automation must deal with crops which vary enormously in terms of colour, size and shape, are frequently partially obscured by foliage and are vulnerable to damage during handling.

There is an economic incentive to use automation in agriculture, particularly in countries with relatively high labour costs (the USA, Italy, Israel, Australia and New Zealand). Manual harvesting of crops is an arduous task and there is a continuing problem with getting and retaining labour to do it.

In this paper we describe the progress made in the development of an autonomous kiwifruit picking robot which is currently being developed in New Zealand. Similar 'agrobotic' systems include a prototype orange picking robot being developed in Italy and an apple-picker being developed in Belgium. Neither of these is currently commercially viable and both use human operators to position the picking robot.

II. LITERATURE REVIEW

In agriculture, the only successfully commercialized semi-robotic system is the automatic field harvester [1]. However, Murakami et al. [2] describe a manure spreader with GPS guidance which is capable of spreading manure on a field under remote control by an operator 1 km away from the field. Much work has been done on autonomous robotic weed control systems (for example, [3]). This area of research is reviewed by Slaughter, Giles and Downey [4] who note that while three of the contributing core technologies, namely guidance, precision in-row weed control and mapping, are well advanced and are used commercially in non-robotic agricultural applications, the remaining core technology, namely weed detection and identification is the weakest area and the main limitation to commercial development of robotic weed control systems.

Research into the automated harvesting of discrete crops (as opposed to bulk grains and grasses) initially began in greenhouses where the structured environment, high plant density and high product value justified the expense of robotic picking. Van Henten et al. [5] describe an autonomous robot for harvesting cucumbers but only 80% of the cucumbers are picked and the average pick-rate is 45 seconds per cucumber. Belforte et al. [6] review robotic harvesting of mushrooms, lettuce and strawberries in greenhouses and note that these are not commercially viable because they are too specific in their purpose (picking is typically a very short period in the life of the crop) and have an unattractively slow pick-rate. They developed a proof-of-concept stationary robot capable of under-leaf spraying and precision fertilization of potted plants which were moved on a conveyor past the stationary robot with a cycle time of 7 to 8 pots per minute. Although the dual functions of the robot mean that it can be used for a greater portion of the plant life, the cycle time is too slow for commercialization and the problems associated with moving the plants rather than the robot are large.

The history of research into the area of automated outdoor fruit picking is given by Muscato, Prestifilippo, Abbate, and Rizzuto [7] who note that the two main problems with robotic fruit picking are having a vision system capable of recognising the fruit and having a grasping device which doesn't damage the fruit. They review the research in both of these areas. A more detailed review of robotic manipulators (called 'end effectors') in horticulture is provided by Tillett [8]. Another problem with autonomous robotic picking is the navigation of the robot through the orchard. Guidance systems use either

Global Positioning System (GPS) technology or computer vision and Durrant-Whyte [9] reviews these in autonomous land vehicles.

In practical terms, there are currently only two robotic fruit pickers[1]. The first is an orange-picking robot being developed in Catania, Italy [7]. 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 navigation and has a pick time (time to recognise fruit and pick it) of 8.7 seconds. The percentage of the total crop picked is not stated.

The second system is an apple picking robot being developed in Belgium [11]. Research has focused on 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. It detects and harvests about 80% of the apples (in non-windy conditions) with a pick rate of 8-10 seconds per apple. Currently the robot is mounted on a tractor trailer. A human operator drives it to the tree, stabilizes the robot platform, positions a shroud over the tree to control the lighting and stores the picked fruit. It should be noted that, generally, it is not desirable to simply rip the apple off the plant because there is likely to be damage where the stem pulls out of the apple. In practice, the stems are bent as they are pulled so that the break occurs in the stem.

III. Design Concept for the Autonomous Kiwifruit Picker

The kiwifruit picker being developed in New Zealand[2] is an autonomous four-wheel drive vehicle with the following design attributes.

It is powered by a 7 kW petrol generator, coupled with an hydraulic pump. The robots are electrically driven, while steering and motion are hydraulic. The vehicle is about 2.3 m long by 2 m wide and, with a full bin of kiwifruit, weighs 1.5 tonnes. The system runs on two commercial dual-processor motherboards which handle all aspects, including vision.

A robot was custom designed and built for this application. Four of them are deployed on the picker. This step was necessary because the use of anthropomorphic commercial robots would be prohibitively expensive and also excessively heavy. Secondly, the interface with a commercial robot is not flexible and we required it to be able to produce customized movement trajectories. The robots use an advanced technology so that they can be driven by stepper motors without the need for encoder feedback or trapezoidal profile stepper controllers. The technology (discussed below) leads to a performance increment of about 100% over the standard stepper control technology. Using stepper motors without motion control boards and harmonic gearboxes leads to a massive cost saving – each axis costs about 10% of the cost of a standard brushless servo motor and harmonic gearbox design.

The vehicle uses a combination of GPS and intelligent computer vision to navigate the kiwifruit orchards; manoeuvring around obstacles such as posts and 'deadmen'[3] and recognising braces. The vision system identifies fruit hanging from the canopy, discriminating for size and gross defects. Each of the four robotic arms picks the 'good' fruit and a robotic system places it gently into the bin at a rate of four fruit per second. The vision system checks the fruit level at each point in the bin and adjusts fruit placement to fill the bin evenly. When the system determines that the bin is full, the vehicle goes to the end of the row and puts the bin down. The vision system then searches for an empty bin and adjusts its approach trajectory so that it can engage its forks into the bin. It picks up the bin and then returns to its last position and resumes picking.

The vehicle operates continuously, sensing when it needs to re-fuel and navigating to the fuel supply point. The vision system checks for light level and operates floodlights if necessary. It also checks for rain or dew and covers the bin with a tarpaulin when this is detected so that picked fruit is protected. The system can go into secure mode (for example when the fruit is wet and should not be picked), moving the robotic arms to a safe position, switching the unnecessary power systems off, and maintaining battery power only to the main (monitoring) computer and radio link. The system 'wakes up' when appropriate and resumes picking. It receives and responds to communications via radio link. It uses a variety of recovery strategies to deal with faults such as getting stuck, vision becoming obscured, etc. Data is collected on the fruit yield from a particular orchard and this is sent to appropriate places such as the packhouse which will be packing the fruit.

In existing New Zealand kiwifruit packhouses, approximately 30% of the fruit is rejected on the basis of size and quality. The fruit growers pay the packhouse a packing fee which is based on the gross tonnage with a fine for rejects. The ability of the vision software to recognise fruit which is undersize, misshapen or marked is consequently enormously economically attractive to the growers.

The kiwifruit picking season extends over a period of about three months in the year and there are strategies to increase the working period of the autonomous picker. The first of these is to use the same vehicle with a different end effector for pollination. This is an expensive and difficult operation in kiwifruit orchards and bee colony collapse disorder is a considerable worry to orchardists. Consequently, some orchardists apply pollen manually so that they are not reliant on bees. Manual applications are very expensive. The vision system on the autonomous kiwifruit robot will be developed to recognise female flowers and apply pollen precisely to the flower in an optimal manner (leaving sufficient room between pollinated flowers for the fruit to

[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. Neither robot has been built but a description may be found at [10].

[2] School of Engineering and Advanced Technology (SEAT), Massey University, Turitea Campus, Palmerston North, New Zealand.

[3] Deadmen are buried posts with cables tied to them for bracing

develop in an unobstructed way) using a customised pollen delivery system attached to the robot hand. Secondly, the vehicle will be used in orchards based in both New Zealand and Italy, to take advantage of the out-of-phase growing seasons.

IV. Current Status of the Autonomous Picker

The project began in December 2007. The vehicle and picking arms have been built and are shown in Figures 1, 2 and 3. The major systems are at the following stages of completion.

A. *The Vehicle*

The chassis is complete and the control system for the hydraulic drive is functional. The main computer provides a slave computer with information on the centre of rotation for the vehicle's turn and tangential speed around this arc. The centre of rotation lies on a line connecting the two back wheels and the vehicle is capable of turning about either of the back wheels. The maximum speed of the prototype is 6 km/hr.

B. *The Robot Arms*

The four robotic picking arms were custom-designed and built. They are complete and have been programmed to do asynchronously two types of move. The first of these is a 'go to' move where the arm proceeds from its current position in 3-space to a specified position. The second is a complex picking move. This move starts from a position where the hand is enveloping a fruit. The hand closes on the fruit and rotates it in such a way that the stem is bent while the hand lowers itself, thus breaking the stem appropriately. Simultaneously, the robot arm moves the hand down, across and up to the next fruit. At the mid portion of the movement, the hand opens and releases the fruit into a recovery chute. This move takes under one second; the control (main) computer sends the slave computer the position of the next fruit and the slave computer executes the next picking cycle. Communication between the two computers means that the main computer knows when the slave has completed the cycle for each of the four arms - which operate asynchronously.

All four picking robots are controlled by one core, on a CPU running at 2.5 GHz. The control runs under DOS, using QuickBasic™. This legacy language (circa 1990) and legacy OS were chosen as the easiest and cheapest way to get 'edit and continue' programming without latency issues. The time-sharing code necessary to provide step and direction, asynchronously, in real time, at 10 kHz for twelve stepper motors was written in QuickBasic™. The code turned out to be economical and friendly.

In order to achieve the required performance, a novel motion trajectory was used. For stepper motors, the characteristic curve of breakout torque versus speed declines smoothly and strongly from a maximum at rest to about 10% of maximum at 1 kHz. This was approximated by a straight line intercepting the vertical axis at C, with a (negative) slope, M. The line was chosen to lie below the curve at every point.

Thus,

$$\mathrm{T} = Mn + C \tag{1}$$

where n is the number of steps per second and T is the pullout torque.

Then, by Newton,

$$\mathrm{T} = \frac{d^2\omega}{dt^2} I \tag{2}$$

where I is the rotational inertia of the system experienced at the motor shaft and ω is the rotational angle of the motor.

Then, in order to operate on our approximating line,

$$\frac{d^2\omega}{dt^2} I = Mn + C \tag{3}$$

or,

$$\frac{d^2\omega}{dt^2} I = M\alpha \frac{d\omega}{dt} + C \tag{4}$$

where α is a constant of proportionality. Integrating twice:

$$\frac{d\omega}{dt} = \frac{\alpha M}{I}\omega + \frac{C}{I}t + A \tag{5}$$

where A is the integration constant and,

$$\omega = \frac{\alpha M}{I}t + \frac{C}{2I}t^2 + At + B \tag{6}$$

where B is the integration constant.

Equation (6) permits a simple and smooth trajectory using the following algorithm:

- Compute the total number of motor steps for the move.
- Accelerate for half of this number and then decelerate.
- At each time increment, compute the desired number of motor steps from (6).
- If the actual number of steps taken is less than this, then take a step.

Figure 1. The autonomous kiwifruit picker

This algorithm provides smooth stepping and strong acceleration at the ends of the move with a progressively smaller acceleration in the middle as the maximum speed of the motor is reached. It is not necessary to limit motor speed because as the control line (1) approaches the speed axis, the torque tends to zero and the motor no longer accelerates. Compared with the permissible (constant) acceleration based on the cruise speed for a trapezoidal move, a tenfold increase in torque at the beginning and end of the move is possible. Overall, the time for the move is improved by better than a factor of two.

C. Navigation

The system has functional differential GPS and a compass which are together used for navigation when the vehicle is not under the kiwifruit canopy. When under the canopy, the picker relies upon two forward facing cameras in order to find its way. This system is functional and permits the picker to drive down the aisles of the orchard, turn when it reaches the end and come back up the aisle, picking the area between the poles in two swathes.

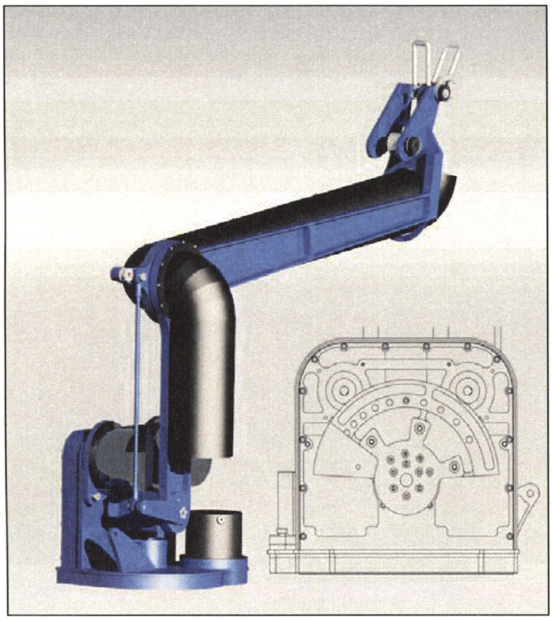

Figure 2. Robotic arm with detail of lower and upper arm drive.

The vision system uses navigational cues provided by the lines of poles which define the lanes. Hough Transforms are very efficacious in defining the pole edges. These provide information from which the edges of the lane, its direction and its extent can be derived.

Commercial colour cameras (640 x 480 pixels) with auto-iris lenses and frame grabbers are used for navigation and bin manipulation. Eight Webcams are used to look up into the canopy, to identify fruit and to perform stereopsis in order to determine the three position coordinates of each fruit. Because the Webcam lenses are very short (3mm), provision has to be made to handle fisheye in the stereopsis. See Flemmer and Flemmer for a simple method [12]. Two Webcams look down into the bin as it is filling and perform stereopsis to provide a map of surface height. All the vision software has been custom-developed, operating at pixel level.

The vision software has enough intelligence to perceive obstacles and the system can take appropriate action. The vision algorithms described by Flemmer and Bakker [13] are used for obstacle recognition and the handling of bins.

V. CONCLUSION

With the exception of the automated kiwifruit picker described in this paper, there is no report of a commercially viable picking robot. The contenders lack adequate vision, adequate navigation, adequate delicacy of fruit picking and handling and adequate speed/commercial payback. The present robot has demonstrated capability in all these areas, particularly the ability to use artificial vision for navigation and bin management, without artificial visual markers.

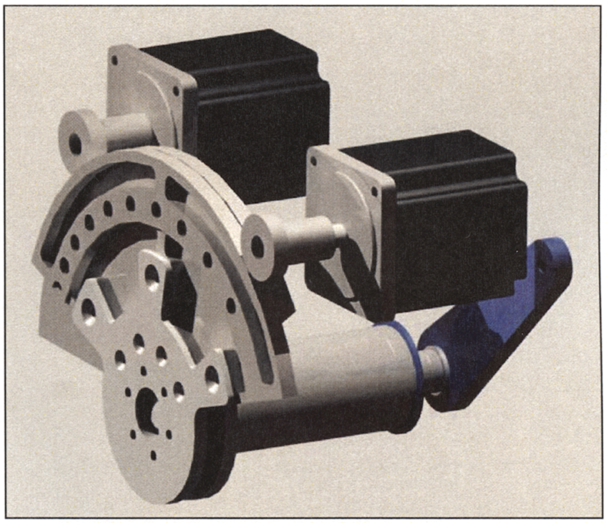

Figure 3. Lower and upper robotic arm drive chain.

REFERENCES

[1] T. Pilarski, M. Happold, P. Henning, M. Ollis, K. Fitzpatrick and A. Stentz, "The Demeter system for automated harvesting", Autonomous Robots, vol. 13, no. 1, 2002, pp. 9-20.

[2] N. Murakami, A. Ito, J. D. Will, M. Steffen, K. Inoue, K. Kita, and S. Miyaura, "Development of teleoperation system for agricultural vehicles", Computers and Electronics in Agriculture, vol. 63, 2008 pp. 81-88.

[3] B. Astrand and A. Baerveldt, "An agricultural mobile robot with vision-based perception for mechanical weed control", Autonomous Robots, vol. 13, no. 1, 2002, pp. 21-35.

[4] D. C. Slaughter, D. K. Giles and D. Downey, "Autonomous robotic weed control systems", Computers and Electronics in Agriculture, vol. 61, 2008, pp. 63-78.

[5] E. J. Van Henten, J. Hemming, B. A. J. Van Tuijl, J. G. Kornet, J. Meuleman, J. Bontsema, and E. A. Van Os, "An autonomous robot for harvesting cucumbers in greenhouses", Autonomous Robots, vol. 13, no. 2, 2002, pp. 241-258.

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

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

[8] N. D. Tillett, "Robotic manipulators in horticulture: a review", Journal of Agricultural Research, vol. 55, 1993, pp. 89-105.

[9] H. Durrant-Whyte, "Autonomous land vehicles", Proceedings of Inst. Of Mechanical Engineers, Part I, Journal of Systems and Control Engineering, vol. 219, 2005, pp. 77-98.

[10] E. Strickland, "Farms fund robots to replace migrant fruit pickers", Wired, http://www.wired.com/print/science/discoveries/news/2007/06/robo_picker , visited on 15/8/2008.

[11] J. Baeten, K. Donne, S. Boedrij, W. Beckers and E. Claesen, "Autonomous fruit picking machine: a robotic apple harvester", 6th International Conference on Field and Service Robotics, Chamonix, France, 2007 published in the Springer Tracts in Advanced Robotics (STAR), vol. 42, C. Laugier and R. Siegwart (Editors), Springer Verlag, Berlin, 2008, pp. 531-539.

[12] C. L. Flemmer and R. C. Flemmer, "A simple and accurate method for lens calibration", Proceedings of the International Conference on Autonomous Robots and Agents (ICARA), Wellington, New Zealand, 2009, in press.

[13] R. C. Flemmer and H. H. C. Bakker, "Generalised object recognition" Proceedings of the International Conference on Autonomous Robots and Agents (ICARA), Wellington, New Zealand, 2009, in press.