

Project title Desk Study: A technical review of available and emerging technologies for harvesting of Brassicas and whole head lettuce

Project number: FV 368

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Report: Final report, January 2011

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Location of project: Great Britain

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Date project commenced: 01/03/2010

Date project completed (or expected completion date): 31/01/2011

Key words: Brassica, cauliflower, cabbage, broccoli, lettuce, harvesting, labour saving, automation, robotics, sensor, x-ray, microwave.

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AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

John Reed
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Signature Date

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Grower Summary

Headline

Produce sensing and robotics will be the keys to developing more capable vegetable harvesters.

Background and expected deliverables

The Brassica and leafy salad industries rely heavily on the use of manual labour for most harvesting tasks. In addition, labour costs are increasing and labour is becoming more scarce. Although sophisticated mobile pack houses have been developed for in-field harvesting they mostly rely on selective manual picking of the crop. Automatic picking systems are commercially available for top lifting of some crops e.g. cabbages and whole head lettuce. However, these machines are non-selective, once-over devices with generally higher product damage and wastage levels than manual systems. Selective harvesting of cauliflower has been demonstrated in principle but the technique has yet to be commercialised.

The Brassica and lettuce growers have identified harvesting as a priority target for improvement since the introduction of more automated systems has the potential to alleviate some of their labour problems, reduce costs and potentially improve consistency. This report will include a review of the state of vegetable harvesting automation, recommendations on currently available machinery that could be used or adapted for UK growers use, indications of the gaps in technology that are currently preventing progress and suggestions on where research and development should be concentrated in order to close or reduce those gaps.

Summary of the project

UK vegetable growers have been losing out due to competition from abroad and a dwindling home market for cabbage, cauliflower and lettuce. Labour costs are rising and harvesting labour represents a large proportion of the production costs. If harvesting machinery could be made to be more efficient and less reliant on manual labour the costs of production would be reduced. The report begins with a review of the types of machinery that are currently being used to harvest cabbage, lettuce, broccoli and cauliflowers. At present this means tractor mounted or self propelled harvesting rigs and one-pass, semi-automatic harvesters. Unfortunately, commercial, selective vegetable harvesters do not exist. The review therefore goes on to examine relevant harvesting research that could enhance the performance of current equipment or lead the way to new, fully-automated machines.

The only way, at present, of selectively harvesting vegetables is by hand. In the commercially available harvesters section some images of the types of harvesting rigs that have been developed to maximise the efficiency of hand picking are shown. In addition to the picker-cutters, most of these machines have people on board preparing and packing the produce. The efficiency of these types of rig could be improved if these preparation and packing tasks were automated. Emulating the human's ability to do all these tasks is impossible using traditional agricultural engineering techniques. However, blending mechanical engineering, modern electronics and computing permits the design of highly capable produce handling and packing devices. An almost fully automatic lettuce trimming and packing factory, built in Spain, is evidence of what can be done. More information can be found about this facility in the robotic harvesting section of this review.

One-pass harvesters for cabbage and lettuce have been around for some time. Typical examples of these types of harvester are discussed in the review. Details are given, in particular, of the design philosophy and research that led to the Univerco cabbage puller. This machine pioneered the technique of lifting the cabbage, including its roots, rather than

cutting it off at ground level. The designers of these types of machine claim they cause less damage and permit a more accurate cut, so that produce quality is maximised. Like the picking rigs most of the one-pass harvesters have personnel on-board for trimming and packing etc. The case for automating these tasks is just as applicable to these types of harvester as it is to the picking rigs.



Figure 1. Univerco prototype harvester at work

A commercial, one-pass broccoli harvester is now available from Dobmac Agricultural machinery in Australia. Images and a description of this machine are given in the review. Detail design and development of another Australian broccoli harvester (Matilda Fresh) are also presented. Work with this machine resulted in a further Australian project which aimed to improve the uniformity and number of harvestable quality broccoli heads that would be available to a one-pass harvester. Selective harvesting of broccoli is a step closer. The methodology behind some machine vision research that successfully determined the maturity state from an analysis of broccoli images is explained.



Figure 2. The Dobmac Agricultural Machinery broccoli harvester

One of the main problems preventing the development of selective vegetable harvesters is the non availability of suitable produce maturity sensors. Detecting the maturity of cauliflower curds is particularly difficult because they are usually obscured by leaves. The successful development of a selective cauliflower harvester would, potentially, provide sensing and handling solutions that would be applicable to all the other target crops. A significant part of the selective harvesting section therefore reviews the findings from a UK research project aimed at developing a selective cauliflower harvester (Caulicut). They found that x-rays were very good at detecting curd maturity (size) but the required device would be too heavy and expensive to be practical on a real harvester. They also looked at microwave sensing methods. Although promising, the technique was only able to be refined to the point where 40% of curds were successfully detected. The Caulicut project also investigated cutting,

elevation and trimming (though not on the same rigs). This work is assessed in conjunction with a later patent application.

The final section of the main report assesses the potential for robotics and how adopting this type of technology could result in more capable harvesters. Such machines would be “sensor rich” with individual modules for each harvesting task. The modules would be able to communicate with each other, and a central controller, sharing information to ensure each product was picked, processed and appropriately packed.

Main conclusions

One-pass harvesters and picking rigs rely on humans to inspect, prepare and pack the produce for it to be suitable for the fresh market. Advances in electronics, sensing and computing now make the automation of these tasks entirely possible.

A promising, new, one-pass broccoli harvester has been produced by Dobmac Agricultural Machinery in Australia. Once the first cut has been taken out by hand this machine can harvest the rest in a single pass.

One-pass cabbage harvesters that pull the plant from the soil, then cut the stem separately, give the best chance of producing cabbages suitable for the fresh market

Improved agronomic management using selected varieties and optimised growing locations improved the number of one-pass harvestable broccoli heads by up to 90% in an Australian project. Similar initiatives, relevant to our conditions and varieties, could be undertaken here.

There are no automatic, selective vegetable harvesters currently in production. The key factor currently limiting the development of selective harvesters is the lack of a reliable, affordable, produce maturity sensor. A project to investigate produce sensing and combining inputs from multiple sensors e.g. tactile, visual, microwave is recommended.

X-ray technology can successfully distinguish the size of 90 % of obscured cauliflower curds to within +/- 10 mm. Until the weight, cost and size of x-ray systems comes down the use of one of these detection devices, per row, remains impractical. Microwave sensors could potentially be used to detect maturity but the best results available, 2002, indicate that only 40% of curds were successfully detected.

Automatic detection of broccoli maturity state from images of the heads has been successfully demonstrated. This could potentially lead the way to the development of a selective broccoli harvester.

Robots are now widely used in the food industry for handling variable, delicate products. The cost of robots has fallen and their capabilities have grown to the point where high-speed robotic harvesting of vegetables would be possible. A feasibility study to determine the performance levels required and types of robot that could be used on field harvesters is recommended.

Most of the science and technology needed to develop more capable automatic harvesters already exists. Whether these machines will actually be developed and whether the UK will be involved, will depend on how much commitment the UK growers and manufacturers are prepared to make and what priority is given to the topic.

Financial benefits

The introduction of more automated harvesting systems would reduce labour, reduce waste and could improve quality levels through more consistent handling. The level of financial benefit would depend on the number of operators saved, the value of the crop and wastage reductions that could be achieved. This would vary between crops and would be dependent on the type of harvester and the degree of automation. The benefits could therefore be substantial, however, quantifying such benefits is beyond the scope of this technical review.

Action points for growers

- Engage with the manufacturers of your existing equipment with an aim of persuading them to improve their machines.
- Consider forming consortiums to aid the manufacturer to finance developments that would benefit all parties.

Science Section

Introduction

Making a profit from growing vegetables in the field is becoming increasingly difficult. The combined home production of cabbage, cauliflower and lettuce is now only 40% of what it was back in 1988, Defra (2010). On a brighter note, in the same period, home production of broccoli has grown from 21.4 to 77.1 thousand tonnes, a rise of 360%. If we are to become more competitive we need to reduce our current costs of production. Harvesting is a major cost in the production of vegetables and labour is a major cost in harvesting. The cost and complexity of employing people keeps rising yet attracting suitable labour prepared to work in the field is becoming more difficult. Given this background, the HDC and relevant Crop Associations are keen to reduce the industry's reliance on harvesting labour. They have, therefore, commissioned this review to examine current and future technologies that could potentially be used to further mechanise or automate the harvesting of cauliflower, broccoli, cabbage and whole head lettuce.

The general objectives of the study are:

1. To review and assess current harvesting systems.
2. To review current harvesting research.
3. The investigation of factors limiting the development of automated harvesting.
4. To produce industry recommendations and report on the potential for improving harvesting systems.

Methods

The information needed to carry out the study was gathered using internet and library searches of journals and publications, patent database searches, internet searches of equipment and systems suppliers, e-mail and telephone discussions.

Discussion

This review will first look at the type of equipment typically used for harvesting cabbage, lettuce, broccoli and cauliflowers. For general purpose harvesting the most common type of mechanised picking aid comes in the form of a tractor mounted conveyor-elevator fitted with cups, containers or just a simple belt. Pickers select and cut the produce then orientate and place it onto the moving conveyor. The product is then conveyed back to a processing platform which is either mounted on the tractor or trailed behind it. The platform presents the product to processing operators who further trim, de-leaf, inspect and pack the product into their final containers. Many variations of this general arrangement are used. Some pickers are also responsible for processing the produce e.g. trimming, de-leafing and carrying plastic bags into which they put the prepared product before placing them onto the conveyor. Other systems just elevate the produce before dispensing it into bulk bins or an adjacent trailer. For cabbage, lettuce and, more recently, Brassica, one-pass harvesters have been developed which fully automate the cutting of the stems and transport of the produce up to a preparation and packing area. Fully automatic, selective harvesting of any of the target crops has yet to be realised. One of the primary reasons for this is the difficulty associated with automatically sensing product maturity, (see section on selective harvesting).

Commercially available harvesting equipment

This section looks at the type of harvesting equipment that is currently used and the technical developments that have influenced their design. The first step to automation, after manual picking and carrying out, is to use a tractor mounted cup conveyor system such as the VHS rig (Figures 1 & 2).



Figure 1 (above).
A typical tractor mounted harvesting rig.



Figure 2 (right). The inset shows the pedestrian control unit which connects to the tractor to allow remote controlled stopping-starting and permits driverless field operation.

On the larger farms large, self propelled rigs mounted on tracks or large 4 wheel drive-steer units are equipped with a wide variety of produce elevators and packing stations (Figure 3). These mobile packhouses represent the peak in current practise for selective harvesting of vegetables. Manually cut and trimmed produce is graded and packed into supermarket trays ready for dispatch.



Figure 3. Harvatec self-propelled rigs harvesting lettuce and cabbage

Depending on the crop these machines can be equipped with a wide variety of conveyor elevators and produce handling units e.g. multiple cups, hanging tray carriers. Although the basic drive units and layout remain similar most of these large machines are bespoke designs specifically adapted to each farmer's requirements.

In preparing this report some manufacturers have been helpful and some have not. As with much of agriculture, competition is fierce. So when a new machine is built the farmer and manufacturer often wish to keep their advance a secret to gain a competitive advantage.

Automated cabbage harvesting

From 1999 to 2003, Agri-Food Canada engineers, in collaboration with Univerco Hydraulique, developed a one-pass mechanical cabbage harvester. It is a single row machine mounted on a farm tractor. The picker was the main challenge in the project according to Chagnon et al (2004), (Figure 4). Experiments were done with two types of pickers. In 1999, the first picker tested cut the stalks at ground level using two disc blades, and then lifted the cabbages and leaves onto inclined belts. The cutting height was uneven; this was due to the length of the stalk that varied from one cabbage to the other. This was in agreement with Kepner (1978) who stated that the height at which the stalks are cut is critical and should be measured from a fixed reference point rather than from the ground up. In 2000, a second picker was developed and tested. This design pulls up the cabbages with the stalk, using two belts. The belts were the same type as used on carrot harvesters. Various belt speeds were tested from 35 to 52 m/min, the best results were obtained at 37 m/min.

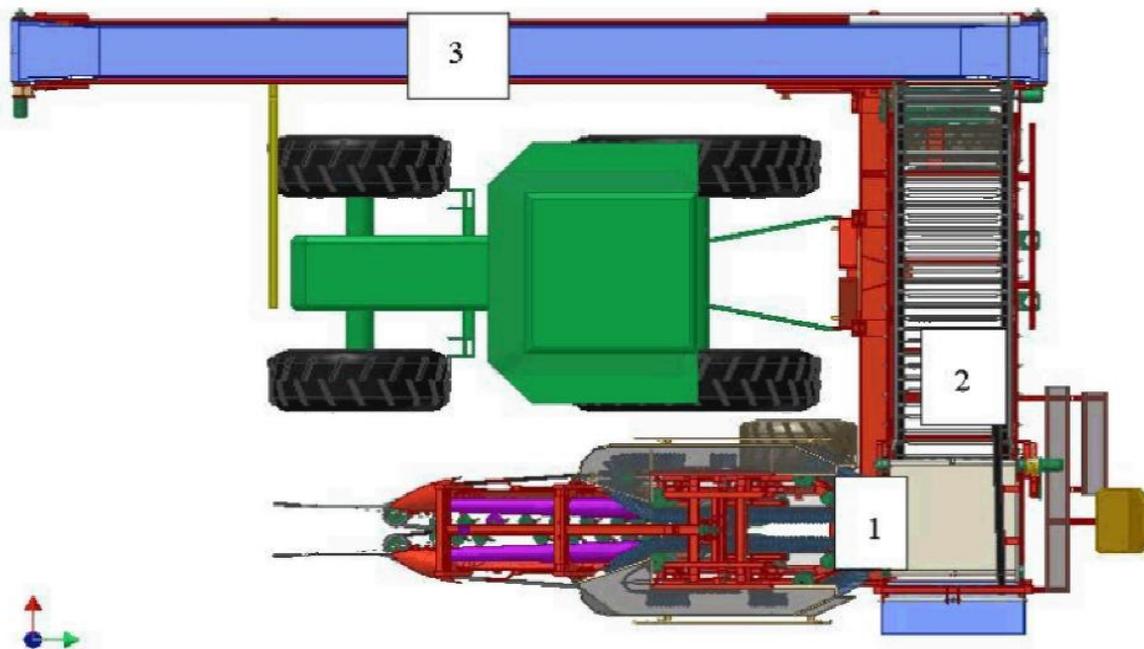


Figure 4. Univerco cabbage harvester schematic

At first, when the cabbages were hard to pull, a digger point was used to loosen the soil and make it easier to extract the cabbages. According to Kanamitsu and Yamamoto (1996), an average force of 110 N is required to pull a cabbage root out of a soft soil but forces up to 250 N were measured in heavy soils. After some improvements to the picker, a digger point was no longer needed. The picker is 350 cm long and 88 cm wide; it lifts cabbages at an angle of 25°. The cabbages are not damaged by the pulling, because they are lifted beneath the bottom leaves, which are subsequently dropped back in the field. The belts lift the cabbages up to a rotating blade which cuts the stalks very cleanly. The height is fairly uniform from one cabbage to the next; however, the height of the blade can be adjusted to keep more or fewer leaves with the cabbage. The roots fall to the ground and two lateral

belts carry the cabbages and their leaves up to an inclined cross conveyor, (Figure 4: see 2 in schematic). This conveyor is 90 cm wide and is made of rubber coated (self cleaning C-Flex cover) metal bars spaced 5 cm apart. Every second bar has been curved downwards to create a cavity in which the cabbages sit while being conveyed upwards. The optimal forward speed was 29 m/min. The inclined conveyor takes the cabbages from the back of the picker and carries them onto a horizontal sorting conveyor, (Figure 4: see 3 in schematic). This carries the cabbages and leaves towards the front of the tractor. Impacts to the cabbages at the transition point are minimised as there is no sheet metal bottom under the belt of the horizontal conveyor at the point where the cabbages fall. The cabbages move forwards along the horizontal conveyor and are picked off and placed into bins by workers travelling on a trailer running adjacent to the harvester and pulled by a second tractor. Best results were obtained working at 2.1 km/h.



Figure 5. Univerco prototype harvester at work

For the 2003 harvest season, tests were performed on two commercial farms, see images above. A team of 8 workers harvested at an average rate of 3277 cabbages per hour. The cabbages were slightly more damaged by mechanical harvesting than by pure hand harvesting. But, when the mechanical harvester was compared to hand harvesting using a field rig elevator the field rig method caused more damage. Long term storage experiments were performed on six different sites and showed that mechanically harvested cabbages could be stored satisfactorily for up to 4 months and even up to 6 months in some cases, Chagnon et. al. (2004). The machine went on to be commercialised and is now available via the Dutch company, Sweere. Sweere also have their own automatic cabbage harvester the Mangnus which can be purchased via VHS Ltd in the UK.



Figure 6. ASA-Lift: TK 2000 trailed two row cabbage harvester



Figure 7. Hortech: Rapid_T single row cabbage harvester

A number of automatic cabbage harvesters are now available, however, when selecting these harvesters, care must be taken to understand each machine's performance and its limitations. Some are more suited to harvesting in bulk for the industrial processing market. This is because the quality standards are not good enough for the majority to go to the fresh market or long term storage. The percentage of high quality cabbages harvested by these machines will depend on the consistency of the crop, the set up of the machine and the number of operators employed to sort the product.



Figure 8. Vanhoucke: single row cabbage puller with torpedo lifters.



Figure 9. Sweere: Magnus cabbage harvester

The cabbage pullers appear to give the best chance of producing quality cabbages suitable for the fresh market. These machines use a variety of passive or rotating shares or torpedoes to gently lift the cabbage, including roots, from the ground. The cabbages are then elevated between opposed belts equipped with a variety of soft elements. These elements are designed to minimise damage yet produce maximum product orientation control to enable under-slung rotating cutters to accurately trim the stem.

Automatic lettuce harvesters

Selective harvesting of lettuce can only presently be done using the picking rigs already described above. However, with good husbandry and the right varieties, lettuce can now be grown such that most plants mature evenly. This means that one-pass automated harvesting has become feasible. The machines use onboard operators to trim or remove leaves, grade and pack the product.



Figure 10. Hortech: Rapid_SL multi-row, auto-steer, lettuce harvester



Figure 11. Tumoba: multi-row lettuce harvester, available through VHS Ltd UK.

Multi-row harvesters such as the types shown below are now commonly used to maximise output and minimise harvesting labour. Lettuce is cut at ground level, usually by pairs of rotating cutters. The lettuce is held during cutting then elevated away from the ground using pairs of opposed belts. As with the cabbage harvesters the belts are designed to softly handle the produce up to point of release onto a flat inspection belt. Operators then stand either side of this belt to prepare and pack the produce for sale. Each manufacturer has their own design for handling the packed produce e.g. bulk bins, plastic or cardboard containers.

Ramsay Highlander in the US produces both tractor mounted and self propelled harvesters equipped with a water jet cutting system, see image below. Their Headraiser harvester is designed to harvest romaine, green leaf, and a version for iceberg. The Headraiser then elevates the lettuce using a flighted, rodded belt. This helps eliminate trash leaves before reaching the sorting/packing belt. The rear of the machine can be configured for totes or bins. Most of the self propelled machines have an automatic steering system, leaving the designated driver free to handle the produce.



Figure 12. Ramsay Highlander: stainless steel, water jet lettuce harvester



Figure 13. Simon: automatically guided multi-row lettuce harvester.

Automatic Broccoli harvesting

Until recently, unlike lettuce and cabbage, the only way to cut broccoli was by hand with or without the aid of a harvesting rig. However, automating the harvesting of broccoli has been the goal of a number of grower-manufacturers in recent years, particularly in Australia and New Zealand. Before describing these machines, the availability of a semi automatic machine from Agrabest that uses manual workers to cut and place the heads into individual floretting units is worthy of note, (see below).



Figure 14. Agrabest: Broccoli heads being cut and placed into field POP a TOP floretting units.



Matilda Fresh applied for a US patent in 2007, US0165433 (2007). The abstract describing the harvester, shown below, was for an apparatus for harvesting broccoli or other standing vegetable plants. The machine would comprise of a mobile frame equipped with a harvesting head (15) for gripping the stems of respective plants and for conveying the gripped stems rearwardly. It would also incorporate a stem severing mechanism (19) and a plant trimming mechanism (20) adjacent to the trailing ends of the conveyor.

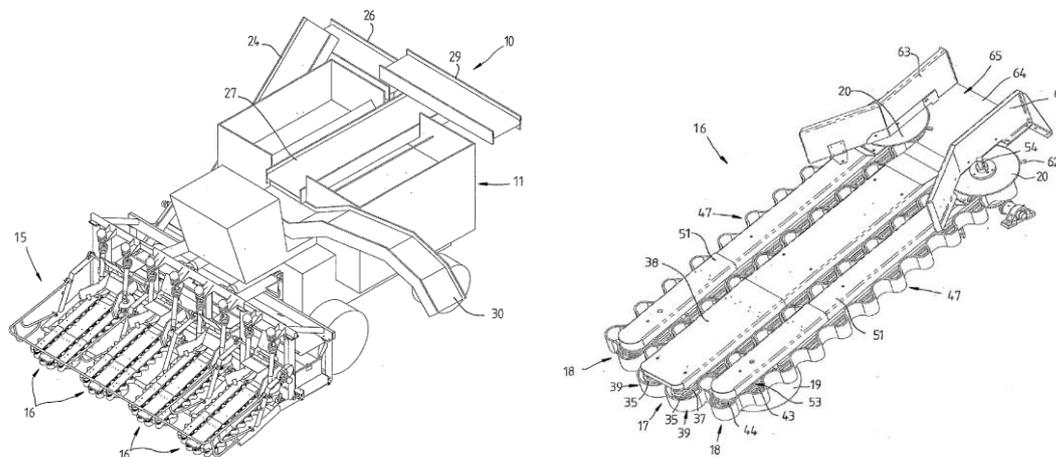


Figure 16. A pair of illustrations from the Matilda Fresh patent application

In order to improve the percentage cut rate, a project was set up by Applied Horticulture Research, Matilda Fresh and some seed companies (Horticulture Australia project no. VG06053). The project aim was to determine the optimum agronomic management of broccoli to ensure uniform crop maturity for once-over mechanical harvesting.

In November 2009 project leader Gordon Rogers reported the findings of the project, Rogers (2009). In their summary they say they were able to improve the potential harvest percentage by up to 90%, by ensuring a uniform plant stand. It was found that by increasing the plant density from 60,000 plants per hectare to 90,000 plants, the higher density improved the head resistance to damage. The reason for this was that it resulted in smaller heads and the heads produced were taller with straighter stems. This would make them better suited to mechanical harvesting. The varieties Gypsy and Atomic consistently produced tall straight stems with small heads when planted at a high density. They reported that the season (autumn or winter) and the district had a greater influence on yield than the individual variety. This result highlights the importance of growing a crop in the correct seasonal and geographic location for optimum yield and quality. They also noted that it was important to have uniform irrigation and nitrogen applications for a uniform plant stand. Variations in these two inputs across a planting will produce variability in plant height and reduce the efficiency of the mechanical harvester.

Having established the agronomic practices to maximise the harvestable heads, the project team recommended that the next stage should be to modify the mechanical harvester to match the geometry of the closer planted, smaller heads. It suggested that the cutting blades needed to better match the resulting plant height and head width. More work was also needed to develop the harvester so that it caused less head damage. In the report it was mentioned that the required developments to the mechanical harvester could not be done in their project due to company constraints. The reason for this is now clear. It was announced in October 2008 that Matilda Fresh, one of Australia's largest fruit and vegetable exporting operations, went into receivership. Although the harvester looked impressive and paved new ground subsequent reports assert that the machine was "a failure and never did as claimed".

This brings us to the second antipodean broccoli harvester, the Dobmac machine.



Figure 17. The Dobmac Agricultural Machinery broccoli harvester

It was reported in Syngenta Brassicas Today, S&G (2010), that Dobmac Agricultural Machinery had developed a mechanised broccoli harvester, the first machine of its kind worldwide! The company says that it will cut harvesting costs and improve productivity. The initial release is a final cut machine and, according to Dobmac, “it will be advanced in time for selective harvests that will enable multiple passes through a crop as the broccoli matures.” The principals of the Dobmac machine are completely different to Matilda’s harvester described above. They can achieve harvest speeds up to 5 to 6 kph. They have options for different row configurations as well as bulk boom or bin cassette delivery. They could also adapt the machine to a packing trailer. The machine shown in the images is all electric and operated by a generator set to ensure they do not get contamination from oil which could potentially occur with a hydraulically powered machine. At present, the broccoli harvester can be found in Tasmania, Australia. There are two, three or four-row models with adjustable row centres for use in different bed configurations.

The broccoli harvester includes full PLC electronic controls. It is fitted with a picking table for final trimming and an air separation system for leaf removal. The harvester is shaft encoded to ground speed to automatically increase and decrease pick up according to the ground speed. It can be equipped with camera monitors and warning alarms to assist operation. Dobmac are keen for the world to see their machine in operation and a video of it working can be found on You Tube; <http://www.yeehee.com/youtube/video/l2Pzc9pNg9g/Dobmac-Broccoli-Harvester-0410.html>

Dobmac’s quote that they expect to develop their harvester to the point of being able to harvest selectively is particularly interesting. If this occurs it will indeed be a breakthrough and represent a quantum leap from existing technology, some of the difficulties of automatically detecting the maturity of Brassicas and broccoli in particular are presented later in the selective harvesting section.



Figure 18. Close view of the Dobmac broccoli harvester.

Clare Shaddick produced a report for Horticulture week on 5 November 2010 regarding the British Seed House's autumn demonstration in Lincolnshire. She reports: *Seminis also had the Tumoba broccoli harvester on display, which could revolutionise broccoli growing - once the company has cracked its concept of "raised head" varieties, where the head is held above the foliage. The idea of a Dutch Seminis breeder more than 20 years ago, machine cutting will not only slash harvesting costs but also improve shelf life if the crop does not have to be cut in the heat of the day, says Hutton*. "The varieties are still at the prototype stage," he points out. "The heads are still too variable."* * John Hutton is a Seminis seed company product sales specialist.

Automatic cauliflower harvesting

There are no automatic cauliflower harvesters available at present. With cauliflowers requiring selective picking it means that the only currently available mechanised harvesting technique is to use humans to detect the maturity, cut and trim the product then place it onto cups or elevators associated with the picking rigs described above.

A number of studies and attempts to automate the harvesting of cauliflower have been done over the years but none have got to the point of going commercial. One of the latest of these, the Caulicut project, is described in some detail in the selective harvesting section.

Selective harvesting

Humans find it relatively easy to use their senses of touch and sight in combination with intelligence and training to determine whether a vegetable is ready for picking or not. Once the decision to pick is made, humans are also well equipped with 3D vision and dextrous limbs and hands to manipulate cutting knives to remove the plant, trim it and place it in a desired orientation onto a cup conveyor. Emulating these actions using mechanical or electronic sensors and appropriate mechanical handling methods has so far eluded the agricultural engineers. For this reason there are no automatic, selective vegetable harvesters currently available for sale. To date, selective harvesting of vegetables relies on humans making the decision whether to pick or not. This is why harvesting rigs, equipped with

covered areas to protect the pickers, have been developed to optimise the ergonomics and maximise the comfort of the pickers to enable them to operate at maximum efficiency for long periods.

Although the crops under consideration, cabbage, whole head lettuce, broccoli and cauliflower have their similarities they all pose different challenges when it comes to selective harvesting. You might think that with modern cameras and image analysis systems it would be easy to remotely assess a vegetable's maturity. However, despite the remarkable advances in technology we have seen over the last 50 years, if you ask an image analysis expert whether they could automatically distinguish one strawberry from another in a punnet, they would wring their hands and say give me a year or two and a lot of money and I may be able to! The problem is that cameras have no conception of what they are looking at, they are just an eye not a brain. They produce 1000's of pixels each with their own brightness levels ranging, typically, from 0 (black) to 255 (white). The image analyst then has to use mathematics to try and interpret these millions of bits of information. They look for level changes and patterns that might relate to edges or known shapes. Unfortunately, organic objects exhibit natural variation in colour, texture, shape and reflectivity and this makes the development of robust algorithms to detect subtle changes in product features extremely difficult. As a result there are only a few simple or specialist applications where vision systems have been used to reliably detect subtle differences in organic objects such as vegetables to determine their maturity.

Selective harvesting and automatic detection of broccoli maturity

In some ways broccoli poses one of the most difficult selective harvesting challenges, due to its delicate nature. However, at least you can usually see the flower so automatic inspection and image analysis by camera is potentially feasible.

Back in 1989 tests were carried with a tractor mounted cut-off saw mechanism for selective harvest of broccoli, Shearer et al (1991). The mechanism consisted of a hydraulic motor and saw blade mounted on an hydraulically actuated swing arm. This combination was attached to the side of a tractor via a vertical prismatic joint to enable adjustment of cutting height, (see diagram below). Preliminary tests during the 1989 growing season indicated that rates of up to 40 heads/min were possible for continuous harvesting. A rate of 23 heads/min was possible when harvesting every other plant. Plants were selected for harvest from the operator's seat with 80% accuracy. There was little visible damage to harvested heads, or immature plants remaining in the field.

This work is included in the review as an example of one mechanical method that was successfully used to selectively cut broccoli, albeit using human guidance. Using humans to indicate which plants are ready then deploying a picking mechanism was put forward as a potential technique a number of times at Silsoe Research Institute for the harvesting of cauliflower. However, it was never adopted because it fails to address the fundamental problem of automatic maturity detection. Other work by Shearer investigated pulling broccoli out by the roots using a comb device, unfortunately, the uprooting forces proved to be too high unless the soil was irrigated prior to pulling.

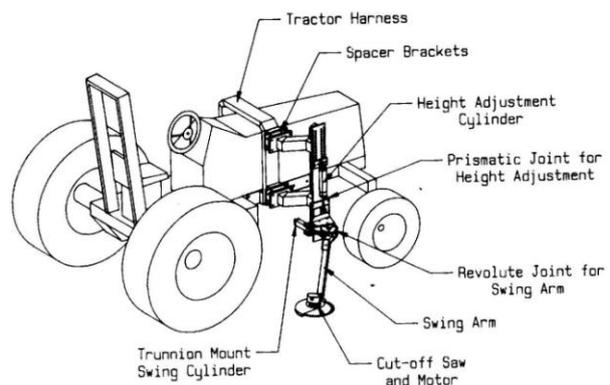


Figure 19. Schematic of prototype broccoli detachment mechanism

In 2006, masters student Rachel Ramirez produced a comprehensive thesis at Virginia Tech on how computer vision based analysis of broccoli might be used in a selective autonomous harvester, Ramirez (2006). The mechanical engineering recommendations made in this thesis re an autonomous harvester were not spectacular. Fortunately, the bulk of the thesis focussed on a range of advanced image analysis techniques which could have considerable potential for the future. The basic methodology on how she locates and assesses the maturity of broccoli is worthy of expansion in this review.

The first step in the process was to identify the location of the broccoli head and estimate its size. Various pattern and colour matching techniques were initially used but were found to be unreliable. It was speculated that the pattern recognition software was being fooled because the pattern of veins on the leaves mimics the bunching patterns of the florets in the broccoli head. Colour matching failed because there was too much colour variation in the broccoli heads from one image to another.



Figure 20. Extended stem lines intersecting over the broccoli head.

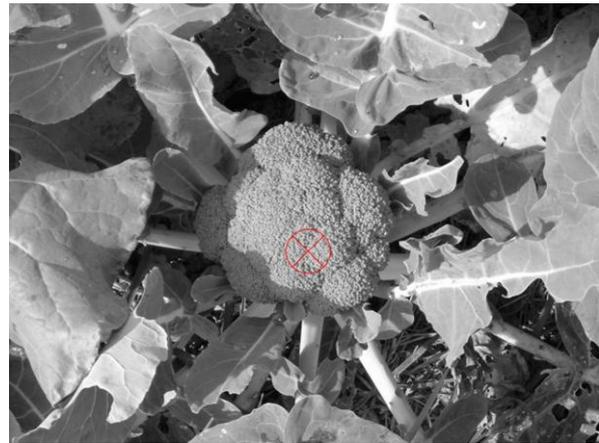


Figure 21. Initial target located using an average stem line intersection algorithm

Using thresholding and filtering of the images followed by a mathematical procedure known as Hough transformation it was possible to produce good images of the convergence of the main stems in the leaves. It was observed that the extended lines representing the stems either pointed at, or surrounded, the head and this could be used to make an initial estimate of the centre, see example images.

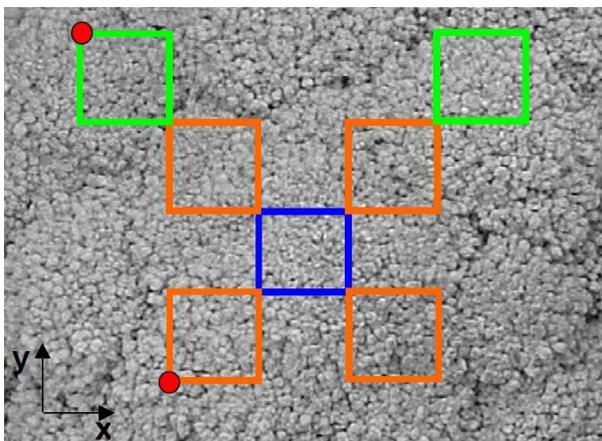


Figure 22. Successive contrast squares expanding from start point to determine head edges

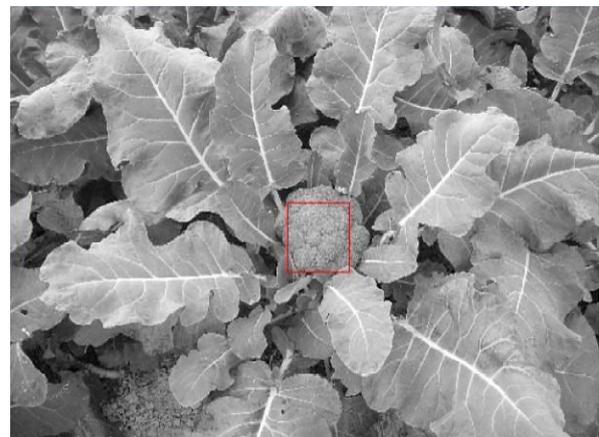


Figure 23. Approximate extent of broccoli head using contrast method

Once an initial estimate of the location of the head was found Ramirez next compared the contrast levels between 4 small squares of interest surrounding the start point, i.e. looking for an edge. If no edge was found then another set of squares were added outside the first and so on until an estimate of the head size could be made, see images above.

Having estimated the head size the next step was to determine the maturity level. Ramirez reports that as the broccoli head matures the size and spacing of the individual florets develop in a relatively predictable way. Line scans across mature heads showed a larger variation in grey level than those of an immature head due to the loosening of the florets that occurs as they mature i.e. the texture of the head becomes coarser. Using a range of imaging techniques to estimate texture or coarseness (that are beyond the scope of this review) she eventually comes up with a maturity equation based on a combination of four texture techniques that results in maturity index for each broccoli image. A maturity value of zero on her scale would define the most mature (over-mature) heads while a value of 30 would define the least mature head of broccoli.

Using advanced image analysis it appears that this researcher may have homed in on a set of techniques that could provide the necessary information needed to enable the development of a selective broccoli harvester. However, the technique is only experimental and only thirteen broccoli images of mature and immature broccoli were analysed in her work i.e. not enough samples (though all sample analyses correctly estimated the maturity level).

Selective harvesting and automatic detection of cabbage and whole head lettuce

The human technique to determine whether to pick a cabbage or lettuce or not relies on sight and feel to determine the size and firmness of the product. The most recent research found which addresses the possibility of automatically selecting these types of vegetable was done in Italy at the Bari Politechnic, Millella (2006) and Foglia (2006). The first of these papers 'Computer Vision Technology for Agricultural Robotics' addresses the image analysis required to detect radicchio and fennel for harvest. The second describes the development of an 'Agricultural Robot for Radicchio Harvesting'.

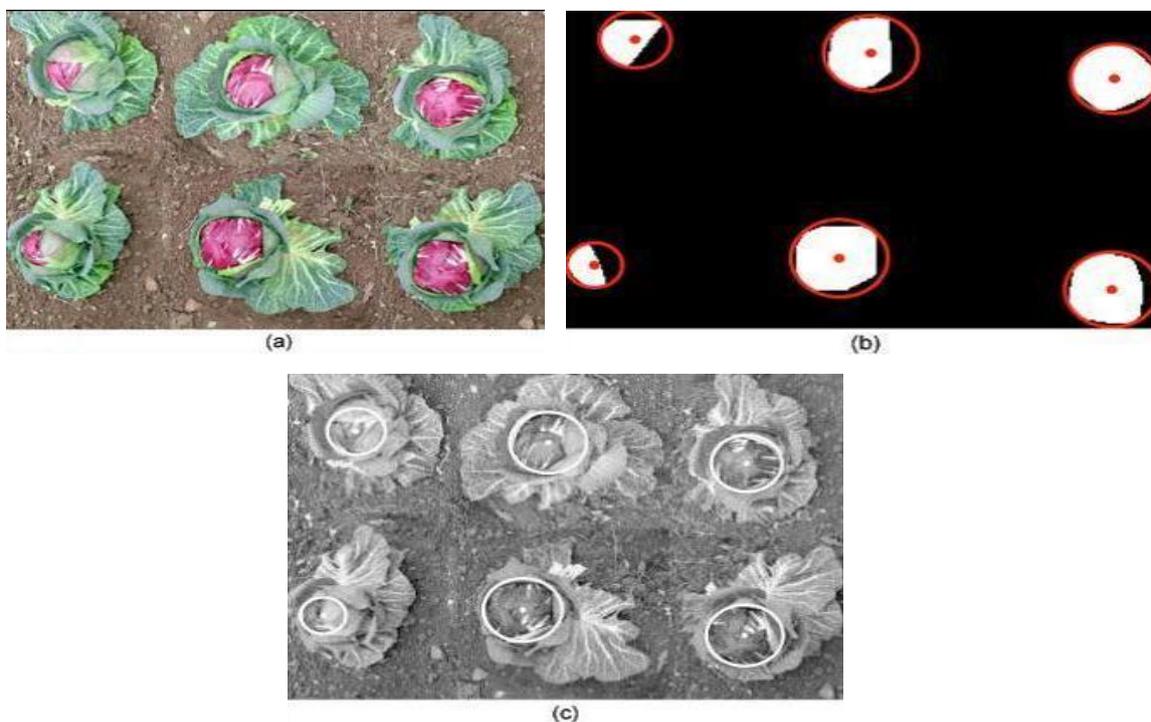


Figure 24. Radicchio detection in the field: (a) acquired image; (b) plant thresholding and (c) localisation

The image analysis associated with red radicchio detection in this work, whilst colour based, does not specifically look to determine maturity. It is designed to locate and size the head so that its position coordinates can be used to accurately deploy a picking mechanism. In a typical field trial with the camera looking at 6 plants the location algorithm correctly detected the location of all the plants with an error less than 5%. Although the first radicchio of the lower row in the images above was partially hidden by leaves its position detection accuracy error was still only 4.2%.

The researchers point out that if the head was totally obscured by leaves their system would not detect the head at all. It should be noted that, in this research, the image analysis relied on the head being a different colour to the outer leaves. More advanced algorithms would be needed to reliably detect the size and location of lettuce and cabbage.

Some of the same researchers then went on to investigate a mechanism for automatically harvesting radicchio. The proposed harvester is composed of a double four-bar linkage manipulator and a special gripper, which fulfills the requirement for the plant to be cut below ground. (see manipulator sketch below).

Both the manipulator and end-effector are pneumatically actuated. The geometry of the manipulator is designed to enable the gripper to initially follow a horizontal path in the harvesting direction before descending rapidly down towards the plants location. The gripper is triggered to close when all 4 limits switches surrounding the gripper touch the soil. At this point it cuts off the plant, 10mm below the soil. The gripper then rapidly ascends with the radicchio back to its start-depositing position. The manipulator was tested with a simple gripper in the laboratory prior to funds running out for the research, see images of their laboratory testbed below. In all experiments, the robotic harvester was consistently and successfully able to pick up the targeted plant.

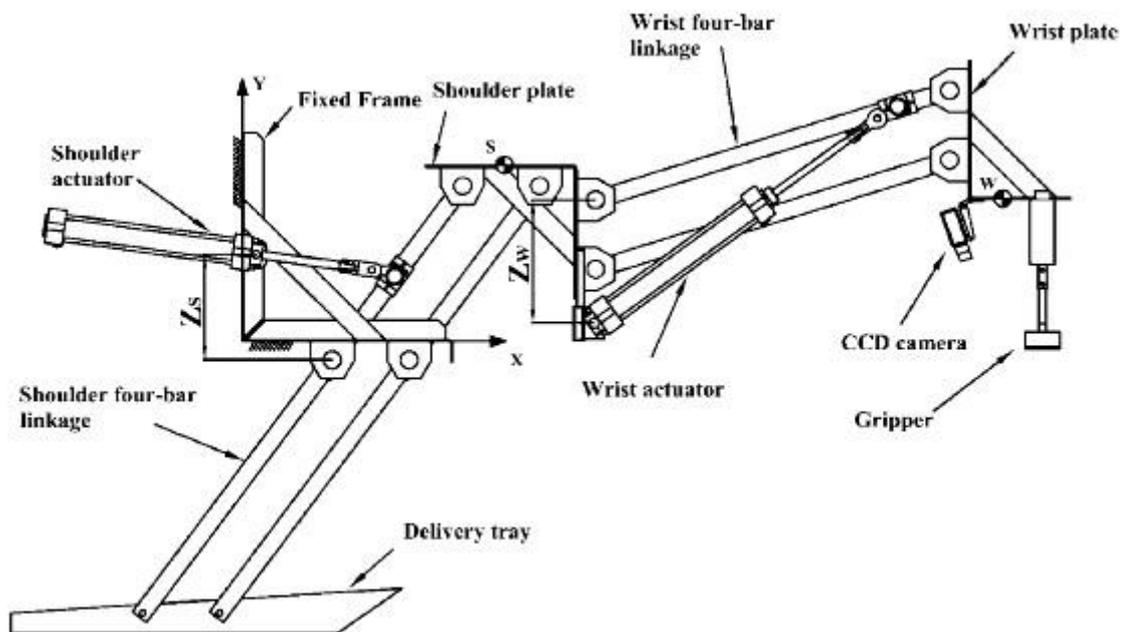


Figure 25. Manipulator for picking radicchio

The average time for a complete harvesting operation was about 6.5 s. Broken down this consisted of 0.2 seconds to locate the radicchio, 4 second approaching and harvesting and 2.5 seconds delivering the plant and reconfiguring. Commercially 6.5s per plant would be too slow and the design looks unnecessarily complicated. Incorporating two servo actuators, one

to move the gripper vertically and the other to transport it horizontally could potentially provide a similar gripper trajectory but at a higher speed. Opportunities for adopting a robotic design approach is further discussed in the robotic harvesting section.

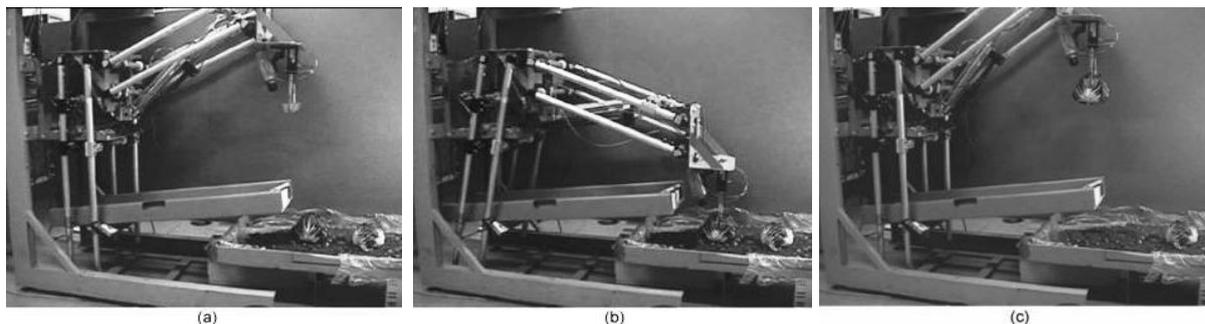


Figure 26. Robot harvesting radicchio in the lab: (a) detection and targeting, (b) harvesting, (c) delivery

Although not perfect, the ideas presented above have been included to give a pointer to the type of approach that could be used in the development of a selective cabbage or lettuce harvester. It remains to be seen whether seeking to selectively harvest is the most sensible approach or whether it might be better to invest in improved crop management and breeding to achieve better uniformity then harvest in one-pass, see limiting factors section.

Selective harvesting and automatic detection of cauliflower

The most successful known attempt to solve the problems associated with selective cauliflower harvesting was made between 2000 and the end of 2002 in the UK. The project was called Caulicut, it was a Horticulture Link project sponsored by Defra, the HDC and a consortium of growers and manufacturers, HDC project FV224, Fawcett (2002). The project addressed the key topics of sensing curd maturity, selective cutting, transport and automatic trimming of the cauliflower. The original goal of building a selective harvester was not achieved. However, the team did make significant progress towards solutions for each of the harvesting tasks.

Cauliflower maturity detection using microwaves

A range of maturity sensing techniques were initially assessed in the Caulicut project. Eventually it was decided to fully investigate the potential of microwave and X-ray technologies. Two different types of microwave sensing arrays were examined. The first used multiple sender-receiver pairs mounted on top of each other. The transmitter of one pair was positioned on one side of the cauliflower, whilst its corresponding receiver was mounted on the other side. The images received from the stacked sensor pairs generated a line of pixels relating to the curd seen. The result of this image from the pixel count determined whether the curd was ready for cutting.

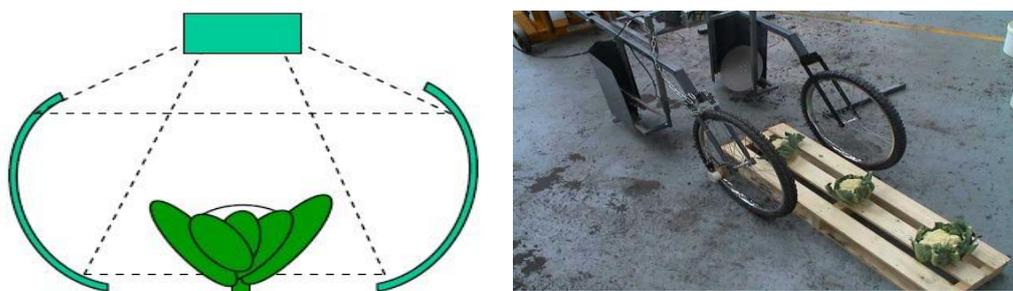


Figure 27. Microwave reflector schematic and bench testing it in the laboratory, HDC project FV 224.

The second device used a microwave reflector arrangement, see above. This sensor only needed one sender-receiver which was mounted above two reflector discs arranged either side of the cauliflower.

Using test runs under laboratory conditions, the microwave sensors clearly identified different sized cauliflowers. However, in subsequent field tests, on six different occasions, the sensors were unable to reproduce the same clear results in field conditions. After more tests it was found that the microwave devices were only able to penetrate 5 leaves and then the signal was almost completely blocked. The team then went on to seek higher power horns from a specialist supplier in the US. Microwave-Radio-Frequency devices effectively work by sensing the water content of the target. Unfortunately, in the case of the higher powered sensors there was good correlation with appropriately sized containers of water, but poor correlation between cauliflowers. In the project conclusions it was reported that the microwave reflector sensor could distinguish 40% of curds to an accuracy of +/- 10 mm. This was well below the target specification of 90% due to vary variable and noisy readings. The research team felt that microwave sensing still had potential but time constraints prevented further research, so the results were inconclusive.

In March 2010, Dr. Richard Dudley of the National Physical Laboratory (NPL) released a press statement regarding a new initiative with respect to robotic harvesting and remote sensing of cauliflower maturity. Part of the BBC News version, Ward (2010), reads; *Dr Dudley and colleagues at NPL along with agricultural firm Vegetable Harvesting Systems (VHS) are working on robots that are as fast as humans at working out if a cauliflower is ready to be picked. One prototype has a multi-axis arm and the other is equipped with a blade that simply cuts and gathers. Field trials of both are being carried out on a farm in Cambridgeshire. For a robot equipped with the right sensors, far infra-red, terahertz and microwave, then working out if a cauliflower is ready to pick is easy. "Once they reach a certain size you know they are ripe," said Dr Dudley. Current prototypes will likely be attached to a harvester but future versions could patrol the fields themselves. "They'll use GPS and imaging systems to see the crops and understand how they are growing," said Dr Dudley. "They can start monitoring, managing and predicting so you can maximise the yield per acre." The robot cauliflower picker could be, he said, the harbinger of a new era in farming that makes far greater use of technology.*

In correspondence with Dr Dudley, in June 2010, he outlined the position then as: *The current state of development for the device is we have created a first demonstrator to show how our technology works and that it can identify crops in certain scenarios, Cauliflowers and lettuce show the greatest promise with our basic system at present. Further development will lead to imagers with greater resolution and crop identification capabilities.* Dr. Dudley also pointed out that with research funds running out he could not say when and whether a commercial version of their imaging device would become available. Correspondence with another researcher in the microwave sensing field continues to suggest that further investment in this technology may yet provide the breakthrough required.

Cauliflower maturity detection using x-rays

The Caulicut researchers chose to study x-rays as their second technique to assess the maturity of a cauliflower. Initial investigations were carried out using an airport type baggage scanner. Tests on 20 cauliflowers showed that x-rays produced images that, when analysed, exhibited a close linear relationship with the measured physical dimensions. Given these promising results they went on to produce a field rig, see below.

The rig was heavy due primarily to the mass of the x-ray source but also as a result of the lead shielding incorporated as a safety measure. Nevertheless, it demonstrated that curd maturity could be measured to an accuracy of 95 – 98%, (see image below).



Figure 28. X-ray rig being field tested, HDC project FV 224.

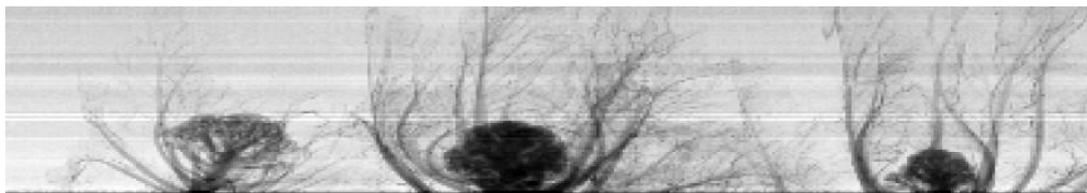


Figure 29. Field rig X-ray images

X-Ray Image Analysis Results

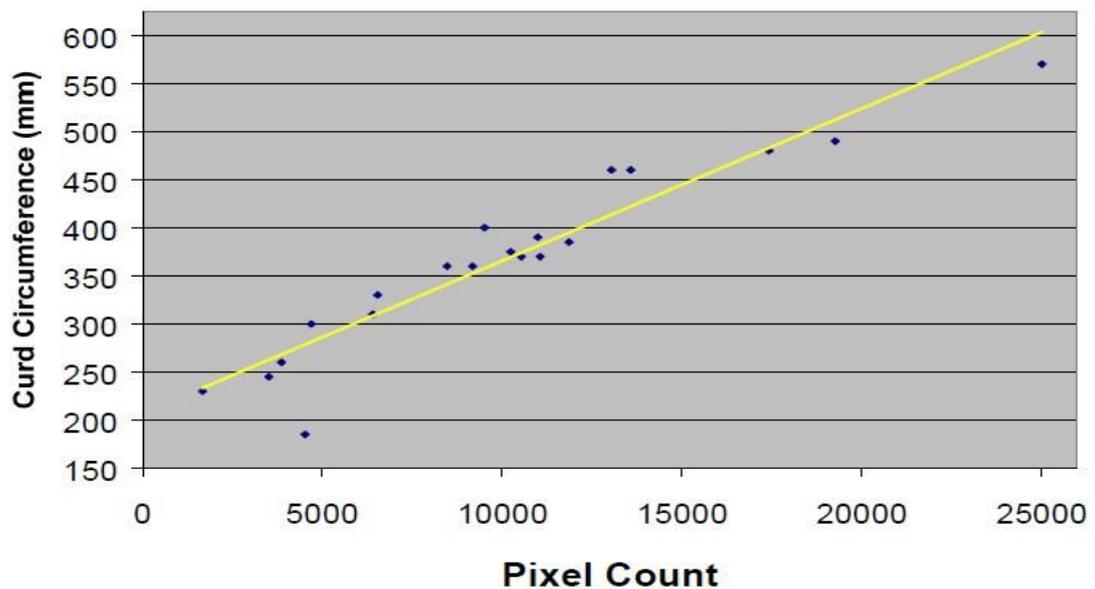


Figure 30. Graph showing good correlation between curd size and x-ray pixel analysis

The results from project FV224's x-ray field rig demonstrated that this method of detection was technically reliable. However, equipping each row of their proposed 10 row harvester with separate x-ray detectors would have been very expensive, very heavy and impractical.

Cleverly, the team conceived the idea of using information gained from a central, x-ray-guided trimming unit and passing it back to the individual picking heads. In essence, each harvested plant from the cutting heads would be centrally x-rayed and size checked against the set point of cauliflower size. This would then be used to adjust the threshold value on each of the cutting head sensors to enable the machine to continually adapt to changes in field and plant maturity whilst it was harvesting. The decision to cut or not would therefore be made on the basis of a set point size value from the central controller and input from the individual maturity sensor on each row.

It is apparent that when the microwave sensing technique proved to be unreliable and the x-ray technique impractical, the Caulicut team were left with a dilemma. What to do about producing an integrated demonstrator? Their solution was to design and incorporate a mechanical, tactile sensor to detect curd size. This sensor and the associated cauliflower cutting and transport mechanisms are discussed in the next section.

Mechanical size sensing, selective cutting and elevating of cauliflowers.

The robotic harvesting developments alluded to by Dr Dudley in the previous section remain confidential and are unknown to the author. Therefore, the Caulicut project (FV 224) is still the most recent attempt, in the public domain, to produce a mechanical picking module. Their selective-cutting demonstrator is shown below.



Figure 31. Caulicut selective cutting and handling demonstrator, HDC project FV 224.

The frame of the demonstrator is made from extruded aluminium section. The frame supports a disc cutter and a pair of articulated belt conveyors. The belt conveyors are hinged along their longitudinal axes. If a cauliflower is not ready for harvest the cutter remains parked to one side of the row. Also, the belts are pivoted to be edge-on to the forward direction of motion, so the cauliflower passes through the gap between them. If a cauliflower is to be harvested the cutting disc is moved from the side to the centre of the frame to cut the

stem. At the same time the belts pivot inwards so their edges meet on the row centre line forming a v conveyor to elevate the plant.

In 2007, a patent application based on ideas conceived in the Caulicut project was published, GB2432096 (2007). This patent contains details of how a commercial version of the selective cutting and handling system might work. In the patent diagrams, shown below, two vertical-axis-sensing-rollers (12) mounted on trailing, pivoted arms (28) are spring loaded together. As the harvester proceeds, the cauliflower, or other type of vegetable, pushes the rollers apart allowing the produce size to be estimated. After the roller comes a cutting unit. The blade (22) and anvil (23) of the cutting unit can be opened and closed via arms (6) and (7) and mechanism (24) to sever the cauliflower stem. Attached to the bottom of the cutters are a pair of opposed slatted belts (11). These belts grasp the product and elevate it upwards as soon as it is cut. They open and close with the cutter allowing immature cauliflowers to pass through. The decision to cut is made by a local processor based on information from the size sensor and a central controller communicating with all the cutting heads.

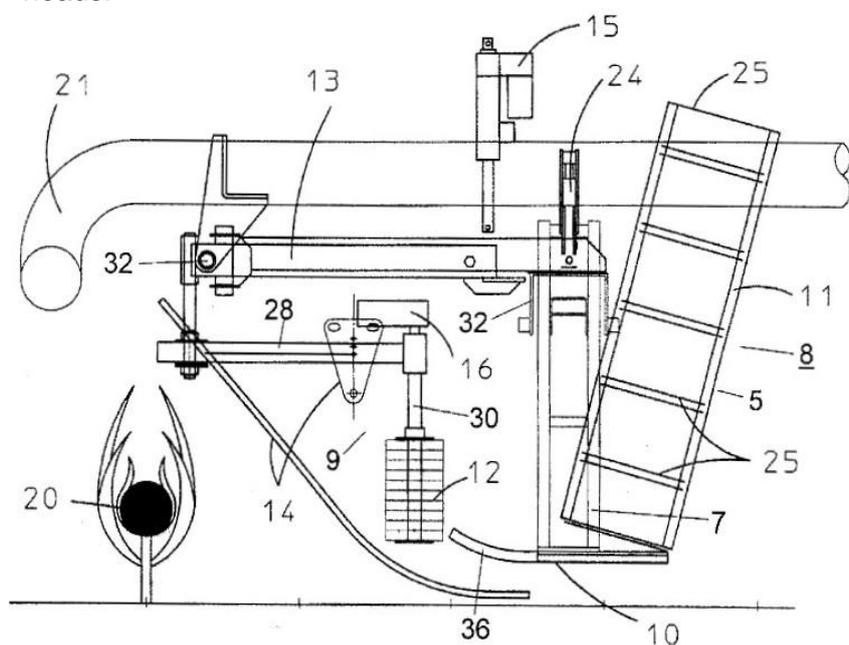


Figure 32. Side view of mechanical sensor, cutter and gripping elevator.

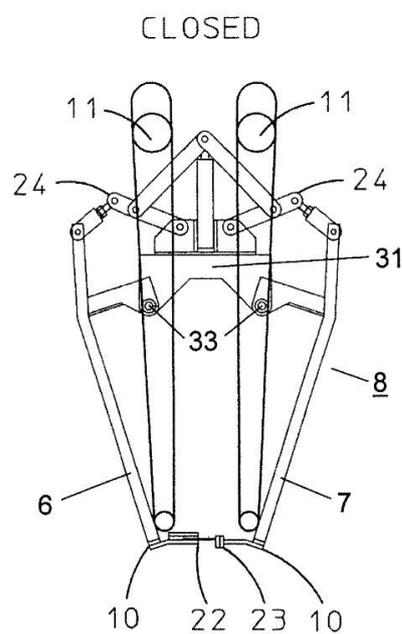


Figure 33. Front view of cutter-elevator.

The mechanisms described in the patent application differ considerably from those fitted to the original demonstrator. Clearly, a lot of further thought was given regarding the details of what would be needed to make a practical cutter-elevator system work commercially. Despite this attention to detail the development of a commercial harvester still remains to be seen. The most likely technical reason for this is that a reliable, and affordable, maturity sensor has yet to be developed.

Automatic trimming of cauliflowers

Part of the Caulicut project's brief was to investigate automatic trimming techniques. After a number of design iterations they developed a simple cup holder and top trim cutter. The cauliflowers fitted in the cups in a manner that allowed them to be passed, by conveyor, through an x-ray unit. The resulting images were used to control the height of cut of leaves above the curd. How the cauliflowers would be automatically placed in the cups was not reported. In the robotic harvesting section below the concept of using robotic pick and place handling techniques is examined. Such techniques could potentially be used to present the product to automatic trimmers.

Robotic harvesting

Robots were originally developed for the nuclear and automotive industries. As these industries matured, the robot manufacturers sought new outlets. The food industry was one of their targets but take up by this sector was very slow. Like the agricultural sector, margins and individual product values are relatively low. The robots were not suited to the variability in the product, and they were expensive. That was over ten years ago and since then the cost of robots has fallen whilst the cost of labour has risen. At the same time the number of types and capabilities of robots has increased. The food industry installed more robots in the UK than any other sector last year (including the automotives).

In Spain a lettuce packing plant installed 68 Fanuc robots in an almost fully automated factory, see images below. Lettuce arrives from the field in trays stacked on a euro pallet. Robots first de-stack the trays then tip the contents onto a conveyor.



Figure 34. Robotic trimming and packing of lettuce at El Dulze's plant in Spain

A vision system next measures the shape and form of the lettuce, then determines where to cut the root. Robots then pick up and present the heads to a stem cutter. Other robots then help to perform a second check on the size of the lettuce. Heads that pass this final test are packed by robots into plastic containers. Items that fail the test are rejected and discarded. The robots have reduced the level of rejected items by 15%. The system is capable of packaging 550,000 lettuce heads per day.

Industrial robots are generally heavy and rigid but very precise (small fractions of a mm). The requirements of robots for handling food and harvesting produce are different. Absolute precision is not the primary goal as accuracy in the order of a millimetre would be more than adequate. What is required is speed and delicate but dextrous, handling. Using robotic techniques in the design of future vegetable harvesters could deliver effective solutions. The CAD image below outlines just one simple robotics approach.

Product size and position would be assessed with the camera. The specialised sensor would provide extra information on product maturity. It could be tactile, yielding size and firmness data, or non-contact e.g. using microwave sensing. The gripper-cutter would be deployed using a robotic manipulator, not shown because it could take a number of forms.

In the main image below the gripper has just cut and lifted the product (cauliflower). It is about to deposit it on the belt elevator. A simple belt has been shown to save modelling time. In reality the product could be easily orientated and accurately placed into any suitable cup or carrying device. The 3 smaller images depict a typical pick and place sequence. Whilst the CAD models below may be simple they represent a fresh approach to the type of handling system design we currently see and expect on agricultural equipment.

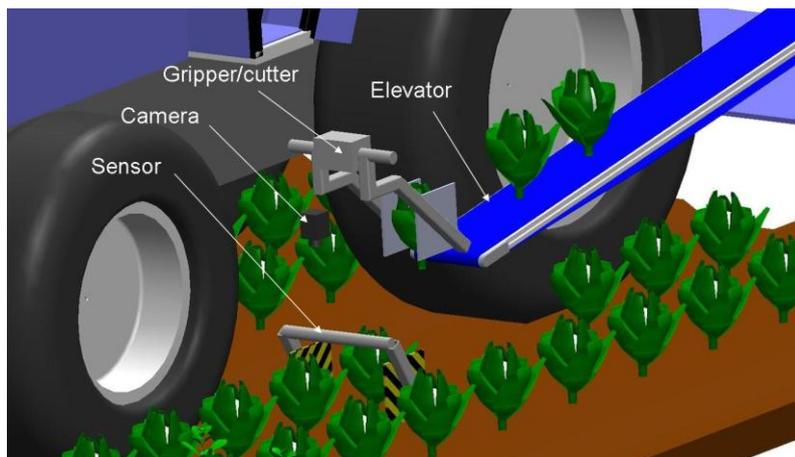


Figure 35 (above) picking elements of a robotic harvester.

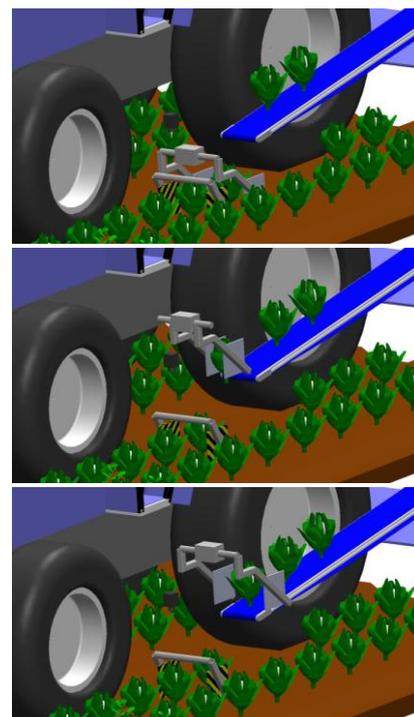


Figure 36 (right) cutting, gripping, lifting and depositing.

It is now common for robot manipulators to pick product from a moving belt. In our case the product is stationary and the harvester is moving. Tracking the plant position with the gripper would be straightforward. Depending on its design, it is possible that the gripper itself could be used to extract information about the plant e.g. firmness. A decision could then be made to continue with the pick i.e. to cut, or to release the plant for harvesting another day. Such machines would be “sensor rich” with individual modules for each harvesting task. The modules would be able to communicate with each other, and a central controller, sharing information to ensure each product was picked, processed and appropriately packed.

Factors limiting the development of automated harvesting

A significant part of the discussion section contains information relating to the Caulicut harvesting project. No apologies are made for this because, if selective harvesting of cauliflowers could be solved, the resulting technologies could be applied to cabbage, lettuce and broccoli.

The key factor limiting the development of a selective cauliflower harvester is the lack of a reliable, affordable, produce maturity sensor. Technically, it has been shown that x-rays can measure curd size to an accuracy of 95 – 98%, (see discussion section). Unfortunately, x-ray devices are heavy, expensive and quite large so fitting one per row on a multi-row machine is considered impractical. If the cost, size and weight of x-ray devices could be reduced then the technique could offer a way forward.

It has been claimed, as recently as last year, that using microwaves in conjunction with infrared sensing offers a potentially more affordable technique, (see discussion section). Microwaves may indeed prove to be a cost effective maturity sensing technique. However, performance would need to be considerably improved from the 40% success rate achieved in the Caulicut project. Even the author of the recent claims regarding microwaves concedes that “it can identify crops in certain scenarios” and “further development will lead to imagers with greater resolution and crop identification capabilities”.

The microwave devices mentioned above essentially work by sensing the water content of the target. On its own this may not be enough to sense maturity. Humans select cabbage and lettuce on the basis of appearance, size and firmness. Using multiple sensing devices then combining the information (sensor fusion) maximises the chance of making the correct decision (in our case whether to pick or not). A typical set of sensors might include a camera to measure position, size and colour; a microwave device to detect internal parameters and a tactile sensor to estimate firmness.

Details are given in the discussion section about a research project aimed at detecting broccoli maturity using machine vision techniques. If taken forward this promising research could provide the necessary plant information data and subsequent sensor function to enable the development of a selective broccoli harvester.

The percentage of high quality produce that could be harvested by the one-pass harvesters would be increased if the uniformity of the crops could be improved i.e. better plant breeding and improved agronomic management. In Australia, due to variations in broccoli maturity, it was found that the number of harvestable quality heads available to a one-pass harvester was only 50%. They initiated a project to improve this and were able to improve the potential harvest percentage by up to 90%, by ensuring a uniform plant stand, (see discussion section). The Australian approach of reducing head size by planting more densely would not be suitable in the UK. Compared with Australia the UK market requires larger heads and lower populations so uniformity is still a limiting factor.

On the one-pass harvesters and picking rigs it is still necessary to employ many people to inspect, trim, prepare and pack the produce by hand in order to achieve fresh market quality standards. Emulating the human's ability to do all these tasks is impossible using traditional agricultural engineering techniques. Mechatronic design blends mechanical engineering, electronics and computing in a way that allows the development of intelligent devices. Labour would be saved if mechatronic design principles were applied to the development of integrated inspection, preparation and packing systems on the picking rigs and one-pass harvesters.

Automation of product handling tasks is generally most effective if the position and orientation of the object continues to be known throughout the handling process. The first step in this process is to control the orientation and position of the product as it enters the automatic system e.g. the type of systems proposed in the previous paragraph. Methods of controlling the singulation and orientation of product exiting the belts of the one-pass harvester would need to be developed. This task would be much easier, or not be required, with the picking rigs providing the product was accurately orientated and placed in appropriately designed cup conveyors.

When produce moves from one part of a harvester to the next, e.g. at the transition between conveyors, knowledge of that products position and orientation is usually lost. Controlling a products presentation to automated equipment is crucial if system efficiency is to be maximised. Adopting robotic design methodologies to the selective harvesting and subsequent handling of produce would permit all aspects of the products presentation to be controlled as it transfers from one process to another i.e. cutting, gripping, elevating, trimming, packing etc.

A significant factor that could inhibit further development of automated harvesters, at least in the UK, is the level of investment needed in research, design and build. Reducing availability of research funds and the limited number of UK manufacturers willing to invest remain serious obstacles.

Conclusions and recommendations

This review was undertaken on the basis that it would concentrate on the technical aspects of harvesting cabbage, lettuce, broccoli and cauliflowers. The following conclusions and recommendations have been drawn from the discussion and factors limiting the development of automated harvesters sections of the review.

There are no automatic, selective vegetable harvesters currently in production. At present selective harvesting of vegetables relies wholly on manual labour making the decision whether to pick or not.

One-pass cabbage harvesters that pull the plant from the soil, then cut the stem separately, appear to give the best chance of producing cabbages suitable for the fresh market (compared to the ground level cutters).

The percentage of high quality produce that could be harvested by one-pass harvesters would be increased if the uniformity of the crops could be improved i.e. better plant breeding and improved agronomic management. A project to do this for broccoli in Australia improved the potential harvest percentage by up to 90% but only by increasing plant populations.

Multi-row, whole-head lettuce harvesters are now widely available. As with other one-pass harvesters manual workers are used to inspect, prepare and pack the produce for it to be suitable for the fresh market. Using mechatronic design principles would enable these tasks to be automated. The development of an x-ray guided cauliflower top trimmer, in the Caulicut project, is a typical example of the type of system that could form part of an on-board, integrated produce preparation and packing system.

One-pass broccoli harvesters are becoming a reality. A promising new machine has been produced by Dobmac agricultural machinery in Australia. Details of this and other one-pass broccoli harvester developments are given in the discussion section.

A Virginia Tech researcher has successfully detected the state of maturity of broccoli head images using advanced image analysis. This could potentially open the way to the development of a selective broccoli harvester.

Italian researchers have successfully used image analysis to detect the position and size of radicchio. They then used this information to guide an experimental cutter-gripper to pick the plant. Their research is potentially relevant to the development of a selective cabbage or lettuce harvesters.

X-ray technology can successfully distinguish the size of 90 % of obscured cauliflower curds to within +/- 10 mm. However, the large size, weight and cost of x-ray devices currently make it impractical to use one per row on a selective harvester. If low-cost, compact x-ray systems were to come on to the market then this would open up the possibilities for selective harvesting.

The key factor currently limiting the development of selective harvesters is the lack of a reliable, affordable, produce maturity sensor. If selective harvesters for cabbage, lettuce and cauliflowers are to become a reality then further research is needed to develop a suitable device. The reliability of successfully predicting the readiness for picking of a plant would be improved if inputs from multiple sensors could be combined. A project to investigate all these factors is recommended.

Robotic systems are now widely used in the food industry for handling variable objects. The types and capabilities of robots has increased whilst their cost has reduced over the last 2 decades. The technology is now ripe for exploitation in the agricultural sector e.g. in the

design of high-speed, selective picking mechanisms. It is recommended that a feasibility study into the potential use of robotics for harvesting be commissioned.

Technology transfer

One of the review's conclusions is that adopting robotic techniques developed in other industries would lead to improved harvester designs. Once the feasibility of using these techniques has been addressed the resulting methods could be used in other agricultural applications.

The key factor currently limiting the development of selective harvesters is the lack of a reliable, affordable, produce maturity sensor. A project to investigate produce sensing and combining inputs from multiple sensors e.g. tactile, visual, microwave, will be need to be completed in order to enable the technology to be disseminated.

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