Project Title	Minimising the environmental impact of weed control in vegetables by weed detection and spot herbicide application.
Project number:	FV 307
Project leader:	Professor Paul Miller
Report:	First Annual report of a LINK project
Previous report	None
Key staff:	Professor Paul Miller (Silsoe Spray Applications Unit –SSAU) Mr Andrew Lane (SSAU) Dr Nick Tillett (Tillett and Hague Technology Ltd) Dr Tony Hague (Tillett and Hague Technology Ltd)
Location of project:	Wrest Park, Silsoe, Beds
Project coordinator:	Dr David Cole
Date project commenced:	1st April 2007
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Key words:	Volunteer potatoes, image analysis, control, spraying, herbicide, targeted application, weed control.

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.

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Grower Summary

Headlines

- Results from a feasibility study conducted prior to the current project indicated that the control of volunteer potatoes in onion and carrot crops based on detection using image analysis and the targeted application of a total herbicide was a potentially viable option worthy of further development.
- Results from the first year of this LINK project have confirmed the potential to identify volunteer potatoes in carrot and onion crops using the analysis of images captured with a camera mounted on a machine and to derive treatment plans based on the detected volunteers.
- Two methods of applying pulsed doses of a total herbicide to detected volunteer potatoes have been identified as a basis of further development within the project. Both are able to operate with short duration pulses (down to 0.03 s) and give very large droplet sizes (circa 1.0 mm in diameter) for spray drift control.
- Techniques have been developed for quantifying the performance of the pulsed spray delivery systems particularly with regard to a sharp-edged distribution pattern, droplet size and velocity distributions. Results with the two systems being developed showed that in the order of 99% of spray volume could be delivered to the target area from a slow moving nozzle in still air.
- Results from experiments in which pulsed sprays of a total herbicide were applied to cultivated potatoes using a range of herbicide concentrations indicated that good control could be achieved at the higher concentrations representative of field sprayer applications rather than wipers. The results also confirmed previous information that showed that it was necessary to target each stem of the volunteer potato plant in order to achieve good control.

Background and expected deliverables

- The registration for metoxuron (Dosaflo) was withdrawn with effect from the end of December 2007. This herbicide had been used to give weed control in carrots and other vegetable crops when applied as an overall spray. Work to identify products that might be used as an alternative has found some products that will give control for some species, but the control of volunteer potatoes in vegetable crops continues to be a problem.

- Selective application of a total herbicide where there is a height differential between the weed and crop is an established method of weed control using relatively low cost chemicals. Whilst recent developments have improved the performance of wiper applicators by sensing chemical on and controlling delivery to the wiping element, the approach relies on good height control and an adequate height differential in order to achieve high levels of control. In many circumstances relating to volunteer potatoes in vegetable crops, it will be difficult to reliably achieve high levels of control with such systems.
- Results from a feasibility study conducted prior to the project work reported here concluded that a control system based on the detection of individual weeds using image analysis systems and the targeted application of a total herbicide would be commercially viable. Such an approach would also have the potential to reduce the overall herbicide use required to achieve adequate weed control.
- The feasibility study also identified that the major requirements to be met to enable an approach of weed detection and the targeted application of a total herbicide to be implemented commercially related to:
    - (i) establishing methods of reliably detecting volunteer potatoes and similar weeds in the vegetable crop from which information to control a targeted application system could be generated;
    - (ii) identifying and developing methods of applying the herbicide doses to detected volunteer potatoes and similar weeds in a manner that would ensure effective control of the weed while minimising the risk of contamination and damage to the adjacent crop;
    - (iii) assembling a prototype system that could operate at a field scale and demonstrate the ability to achieve acceptable levels of weed control and crop contamination/damage while operating at work rates that would be commercially attractive.

  The LINK project for which this is a report of the work in the first year set out to meet these requirements.
- The expected major deliverable from the project is therefore the basis for the design of a commercially viable unit for detecting volunteer potatoes in onion and carrot crops and treating them with a targeted dose of a total herbicide or a herbicide having a level of selectivity that could not be justified on the basis of an overall application.

Summary of the project and main conclusions

1. This LINK project has built on the results from the initial feasibility study that was jointly funded by the Horticultural Development Council and British Potato Council. The work in this first year of the project involved:

   - the collection of further images of volunteer potatoes growing in both onion and carrot crops that were then used in the further development of the detection algorithms;
   - the identification of possible methods of delivering a total herbicide spray to detected volunteer potatoes and similar weeds in such a way as to achieve high levels of control and minimise the risk of crop contamination and damage;
   - some design studies and initial performance evaluation work with two systems that were identified as being best able to meet the specification for the spot herbicide delivery system;
   - further field trials with both cropped and volunteer potatoes treated with a variable dose of total herbicide delivered through a pulsed nozzle system similar to that which may be used in the final design of the equipment for applying such treatments;
   - the design and construction of a prototype system for implementing both the detection and application;
   - some work with existing systems to establish the potential for treating the between row and within row areas separately using a range of approaches and the use of a shrouded spraying system operating between the rows.

2. The weed detection algorithm has been developed such that the areas within an image that meet the criteria for being classified as a volunteer potato/weed can be bounded by a polygon. This series of polygons representing volunteer potato or other weed positions is then used to produce a spray map for controlling individual nozzles incorporating information relating to the ground position of the detected weed and the potential spray path of each nozzle.

3. Two application systems were identified as potentially meeting the requirements for delivery the targeted total herbicide doses to detected volunteer potatoes or other weeds, namely:

- a fluidic nozzle; and
- an oscillating needle system.

Both systems were required to deliver a sharp edged spray pattern with a spray fan angle of approximately 20^{o} and a flow rate in the range 100 to 250 ml/min. Prototypes of both systems were constructed and the performance evaluated in a series of laboratory experiments.

4. Methods for quantifying the performance of the herbicide delivery system were developed based on:

- using a pulsed-laser spray analyser system to measure droplet size and velocity distributions in the spray: mounting the nozzles on a computer-controlled x-y transporter system programmed to traverse the sampling laser along the wide angle of the spray fan enabled the position of measured droplets within the spray fan to be mapped and hence a measure of the sharpness of cut-off could be obtained;
- mounting the nozzles and controlling solenoids on a linear transporter and arranging them to deliver a pulse of a coloured tracer dye spray while travelling over a white paper surface at a pre-set speed enabled the switch on/spray establishment and switch off/spray collapse characteristics to be observed particularly in relation to the footprint of the sprayed pulse.

Results from measurements with both prototype nozzle designs showed that they were both capable of giving a sharp cut-off at the edge of the spray pattern with the oscillating needle system being slightly better in this regard. Typically 99% of spray volume output was within the specified footprint and no spray was detected outside of a 50 mm boundary around the footprint. Droplet size distributions from both nozzle types tended to be bi-modal with a significant percentage of droplets above 1.0 mm in diameter particularly for the oscillating needle design.

Droplet velocities for the oscillating needle design at 500 mm below the nozzle were a function of droplet size, needle diameter and pressure as expected with vertical velocities of between 4.0 and 9.0 m/s for a 1.0 mm droplet. Droplet velocities from the fluidic nozzle were a function of the same variables and were higher than from the oscillating needle with values of between 7.0 and 11.0 m/s for a 1.0 mm diameter droplet.

Both nozzle designs were able to deliver a pulse of spray with a sharp cut-off in the direction of travel. For the fluidic nozzle at speeds in the order of 8.0 km/h, the oscillation of the liquid stream could be clearly seen within the treated area although it is not thought that gaps in the coverage pattern would have important implications for the control of treated weeds and volunteer potatoes.

5. Results from field studies conducted in the 2007 growing season in which 0.03 s pulses of spray were applied to both cultivated potatoes and volunteers in a carrot crop showed that the volunteers were more readily controlled as expected. Experiments used glyphosate concentrations of between 80:1 and 20:1 and for the volunteers pulses were delivered to the potato based on size so simulating the action of the system. For the cultivated crop, kill was proportional to the applied dose with a mean score of 8.5 (out of 10 for complete kill) achieved at the highest concentration used. For volunteers in the carrot crop, 100% control was achieved at the highest concentration with very low levels of crop damage due partly to the shading effect of the volunteer potato plant.

6. A field rig has been designed based on an existing tool frame but with modifications to:

- update the on-board computer system so as to be able to reliably control all vehicle functions and implement the detection and control algorithms;
- incorporate a spray bar for mounting the nozzles that includes a side-shift so as to correctly align nozzle positions with the crop row based on control signals from the vision guidance system;
- mount nozzle assemblies that were designed and assembled using small solenoid valves operating on a latched principle so as to achieve a rapid response with minimum power requirements.

Financial benefits

An initial economic analysis was conducted as part of the separate feasibility study and is repeated here for completeness. It was based on the following:

The cost of treatment based on this technology has been estimated to be £44/ha based on the following assumptions: A 6 m machine operating at 5 kph with a field efficiency of 80% giving a work rate of 2.4 ha/h; Seasonal and weather conditions limit operation to 20 8h days yielding a treatment capacity of 380 ha; Capital cost is estimated at £35,000 which with a write of period of 5 years at 10% interest gives an annual repayment charge of £9,240; Tractor and driver costs are assumed to be £20/h, the cost of glyphosate £200 pa and maintenance £4,000 pa.

Total costs are therefore £16,640 pa or £44/ha spread over capacity area. Operating at half capacity reduces the total annual cost to £13,940 (assuming maintenance down to £3000 pa), but increase area costs to £73/ha. We understand that these figures are comparable with treatment using Dosaflo and should therefore provide an economic alternative now that this chemical is withdrawn. Economics of operation improve further if utilisation can be extended through the season on multiple crops, e.g. carrots and onions.

Action points for growers

The project is on track to produce the technology necessary for the production of a commercial prototype system for the detection and spot treatment of volunteer potatoes. Further field scale evaluation will take place in the 2009 growing season with manufacturing partners aiming to have machines available commercially for subsequent seasons.

Exploitation and future applications

The project consortium is working to develop concepts within the project such that prototype machines can be trialed during the 2009 season with commercial machines being available after this date.

Science Section

Introduction

This report details progress within the first year of a LINK project that aims to develop and demonstrate the technology that uses weed detection and the targeted application of minimum quantities of a total herbicide to control volunteer potatoes in a range of vegetable crops particularly onions and carrots. It follows an initial feasibility study (Miller et al., 2006) that involved the collection of images from a vehicle mounted camera travelling down crop rows, some analysis of these images to determine the potential for detecting volunteer potatoes, some work to examine the potential for delivering short pulses of spray from different nozzle systems and initial field trials to examine the requirements for controlling potato volunteers with pulses of spray. It was concluded that it was feasible to develop a system based on the detection of volunteer potatoes and the spot treatment with a total herbicide as a means of achieving adequate control.

The background to the current work with regard to the main aspects of the project was given in the report of the feasibility study (Miller et al., 2006) and included the following main points.

a) The need to control volunteer potatoes in vegetable relates to both yield and quality considerations that are difficult to quantify in financial terms because of the variability in growing situations. Control of volunteer potatoes is also important in relation to the carry-over of disease in the potato crop.
b) Significant progress has been made in the last decade in relation to the use of image analysis for machine guidance and control particularly leading to the commercial introduction of the Garford “Robocrop”.
c) Weed detection has been the subject of much research effort aimed at developing systems that will minimize pesticide use. The most successful approaches have been those operating in widely spaced row crops including vegetables.
d) There is little published information about the performance of wiper applicators in terms of herbicide transfer or crop contamination. The height differential between weed and crop is crucial to the performance of such systems and accurate control of operating height is therefore necessary.
e) Pulsed nozzle designs have been developed for selective chemical thinning operations and although not exploited commercially on a wide scale, some of the under-pinning research is relevant to the current project.

The work in the period covered by this report therefore aimed at:

i. Further developing the methods for collecting and analysing images so as to detect volunteer potatoes and similar weeds and to derive a treatment map for controlling individual spray nozzles so as to treat the detected weeds;
ii. Identifying methods and quantifying the performance of those methods for applying a controlled pulse of herbicide to a targeted area;
iii. Conducting field trials to refine the definition of the target in terms of spatial area, dose rates and spray delivery to be used to achieve high levels of control of volunteer potatoes;
iv. The design, development and refurbishment of a field rig that can be used for experimental work in the 2008 growing season.

Progress, results and discussion (by objective)

Development/assessment of image analysis based techniques for weed discrimination

Acquisition of image sequences for algorithm development and evaluation

In order to facilitate off line development and testing of image analysis algorithms image sequences were obtained from commercial crops with varying degrees of weed potato infestation. Some of these images were obtained under the earlier HDC project (FV 281) and some additional sequences were obtained under this project. Both sets were obtained using the same equipment and both have been used in the subsequent development work.

Details of the image capture procedure are given in the final report to HDC project FV 281 (Miller et al., 2006) but are included in abbreviated form here for completeness. The experimental apparatus consisted of a digital camera mounted on the front of a tractor (Figure 1) connected via an IEEE 1394 serial connection to a laptop computer kept in the cab. The camera was mounted centrally at a height of 1.4 m looking ahead and down such that the bottom of the field of view was substantially vertically below the camera and the full width of the bed was visible over approximately 2.5 m. The resolution of the images was 320 by 240 pixels leading to a resolution of approximately 6 mm in ground coordinates. This resolution limits the ability of the system to detect small weeds, but is not thought to be a problem of volunteer potatoes which rapidly grow beyond this size after emerging. Higher resolutions e.g. 640 by 480 pixels could be achieved using the same camera if necessary, though with an increase in computational burden.

Figure 1 Camera mounting used to obtain image sequences.

The camera settings (e.g. white balance, gain, integration time and frame rate) were controlled from the computer using custom software developed for the purpose. Experience has shown that it is important to control the camera specifically for the application as standard settings designed to obtain aesthetically pleasing results often loose information due to saturation, or invalidate the assumptions made in subsequent colour transformations. The software also enabled sequences of images to be stored onto the computers hard disc for subsequent analysis.

Image sequences were obtained of two crops of onions and two crops of carrots. The onion sequences were obtained on a light soil at Caldecote, Bedfordshire on 30 May 2006 and on a spatially variable soil type at Chicksands, Bedfordshire on 21 May 2007. The carrot sequences were obtained on a peat soil at Home Fen on 25 May 2006, with a particularly bad infestation and on a light soil at Perlthorpe, Newark on 31 May 2007.

Figure 2 A carrot crop at Perlthorpe with a weed potato infestation from where image sequences were obtained.

Figure 3 An onion crop at Caldecote, near Shefford, Beds, with a weed potato infestation from where image sequences were obtained.

Selection of discriminating features

A variety of features could be considered in order to detect the occurrence of volunteer potatoes in vegetable row crops in general and onion and carrot crops in particular. The ones that were felt to offer most promise for a practical implementation were:

1. Colour.
2. Feature size and shape.
3. Feature position with respect to crop rows.
4. Feature height.

Other characteristics such as leaf texture and leaf shape have not been considered as they are dependant on higher quality, higher resolution images (pixel size <1 mm in ground coordinates) than those employed in this study (6 mm). Maintaining adequate image quality under field conditions due to effects such as saturation, noise and motion blur introduces significant technical challenges. In our judgment the cameras and the very powerful computing necessary to perform such detailed analysis would not be economically practical. We will however, continue to keep this under review as technology advances.

Colour

It has been shown (Marchant *et al.*, 2004) that analysis of colour can be used to discriminate between vegetation and a soil background with a good degree of reliability under a wide range of natural lighting conditions.

There have been some reports (e.g. Vrindts and Baerdemaeker, 1997; Lieberman, 2006) of successful discrimination between species of plant on the basis of colour, but with a small set of species, and not under natural lighting conditions. A method is needed which will distinguish potato volunteers from a range of crops. Moreover, the method should work even when the potatoes have been already received a previous herbicide application - which can have a significant effect on leaf colour.

Accordingly, green colour can be reliably used to distinguish all types of plant matter from the background, but not between crop and potato volunteers.

Feature size

In general potatoes will be larger than the crop plants, so size is a useful source of evidence for classification. However, implicit in the use of size is the need to find the boundary of the plant. This is straightforward only where the volunteers are non-overlapping with the crop rows.

We have considered a simpler measure based upon the width of a feature (i.e. size in a direction perpendicular to the crop rows). If a feature is abnormally wide relative to the width of foliage covered by a single crop row, it is judged most likely to be potato.

Feature position with respect to crop rows

A robust Kalman filter based method of crop row location and tracking has been developed in previous work for the purpose of guiding inter-row cultivation machinery (Hague and Tillett, 2001). By application of this approach, a known pattern of crop rows can be located in video images. Given knowledge (provided by the operator) of the approximate width of the crop plants within a row line, it is possible to identify vegetation outside of the crop rows as weed (Hague *et al.*, 2006).

Feature height

Once volunteer potatoes have become well established they often grow to be significantly taller than the crop. Potentially this height difference could be used as a distinguishing feature. Height might be detected using an array of laser scanners, ultrasonic range finders, stereo vision or optical flow. Optical flow is a stereo vision technique that analyses disparity between successive images from a single camera displaced due to movement over time, rather than two images taken simultaneously from two spatially displaced cameras. Optical flow is preferred to the other options because of its potential to use the same hardware required for measurement of the other discriminating features. However, there are a number of problems; in order to obtain the best differentiation of height a low camera position is preferred - but this viewpoint is undesirable for most other methods of vision based crop/weed discrimination, which are best suited to a plan view from a relatively high viewpoint to limit occlusion. The previous HDC project concluded that it was not worth compromising other vision based metrics to measure feature height (which often correlates with other easier to measure parameters such as size) and so this parameter has not been used as a discriminator though this decision will be kept under review.

Combining measurements of characteristic features to obtain a classification

It is important to note that individual features don't fully resolve the classification - for example green material can be crop or volunteer; locations far from a crop row may be weed or soil. In order to get the most accurate and reliable discrimination between crop, weed and soil it is desirable to combine the information gleaned using some, or all, of the characteristic features described above. This should provide the best possible result.

There are a number of possible mathematical frameworks under which this merging of information might be performed. We have chosen a Dempster-Shafer approach. A Dempster-Shafer (DS) approach to classification has an advantage over Bayesian methods here as the later must assign a prior probability to each outcome as a starting point which can bias the result in a situation where information is sparse.

For the reasons given above, colour, size/shape and position relative to crop rows have been selected in to provide the evidence for classification into crop, weed or soil.

The DS approach to classification of a scene distributes a unit mass of belief across an exhaustive set of all possible classification outcomes {Plant, Weed, Soil} and all its possible subsets. Initially the mass of 1 is assigned to the set {Plant, Weed, Soil} denoting that a location may be any member of that set, but without indication any relative likelihood of a particular classification outcome.

To combine the evidence offered by a pixel's colour, a form of vegetative index is first computed based on a ratio of red, green and blue pixel intensities. The index is then transformed into a *basic probability assignment* as shown in Figure 4. Low indices assign the full unit mass to the belief that the pixel represents the soil background. Higher indices assign the unit mass to the set of classifications {Crop, Weed} - since the colour appears to indicate some form of vegetation, but does not reliably indicate which.

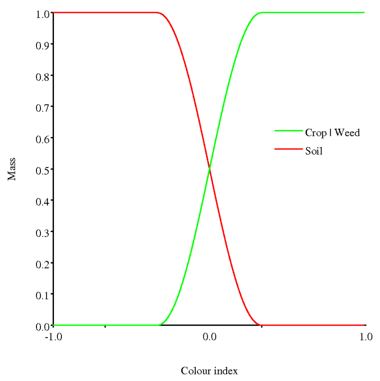

Figure 4 Probability assignment based on colour index.

The location of a pixel also provides evidence; for each pixel in the image, the distance is determined from that pixel to the mid line of the nearest row. This is divided by a (user supplied) estimate of crop row foliage width. The graph of Figure 5 illustrates how this is used to generate a basic probability assignment; pixels near to the crop row are most likely crop or soil, so most mass is assigned to the set {Crop, Soil}; some mass is assigned to {Crop, Weed, Soil} too since it is possible for weeds to occur in the row. Pixels far from the crop row have the unit mass assigned to {Weed, Soil} since crop should not occur in this position. At around the nominal row width, any of {Crop, Weed, Soil} could occur, so the mass of belief is assigned accordingly.

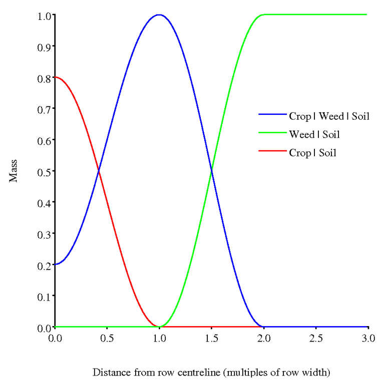

Figure 5 Probability assignment based on distance from crop row (crop row foliage width = 1).

Feature size and shape is used similarly; features very much wider than the crop row foliage width are considered to be unlikely to be crop (Figure 6). In this implementation size is based on a width of consecutive horizontal pixels (approximately perpendicular to crop rows) that exceed a threshold of greenness. That threshold is based on an average of the colour indexes used to define what is certainly soil and what is certainly plant material (Figure 6).

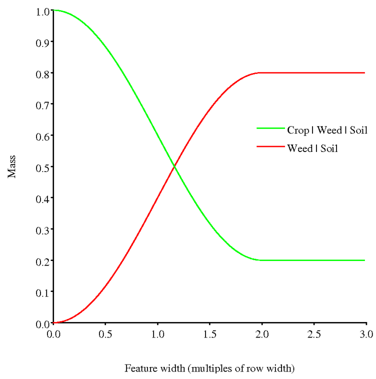

Figure 6 Probability assignment based on feature size relative to the width of foliage within crop rows.

The three items of evidence are then combined using Dempster's rule to provide an overlay of belief for each classification on a pixel by pixel basis.

Having obtained an image onto which believe for each classification is mapped it is then necessary to make decisions on which areas are to be sprayed. The first stage in this process is to identify pixels for which the belief that pixel is a potato is greater than the other categories. This is used to convert the image to a binary form depicting areas of potato against a background of all other categories.

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The next stage is to find connected regions assigned as potato and to draw polygons around those clusters. This is done in two steps the first is a fast single pass process that identifies local maxima in both horizontal and vertical axis. These maxima are then joined to form a polygon that bounds most, but not all the area defined as potato. What is actually required by subsequent processes is a convex polygon with bounding points listed in order around the shape. To achieve this, an algorithm (Green and Silverman) is applied to each polygon. The fact that the bounding points are listed in order allows the bounding box to be efficiently displayed as an overlay on the live video image. All processes described above are conducted in image coordinates unaltered from when the image was acquired. For subsequent spray processes it is necessary to work relative to features on the ground and so that bounding polygons are mapped into ground coordinates.

Once a bounding polygon is transformed into ground coordinates it is necessary to calculate which nozzles should be turned on and when in order to cover that particular potato. This is done by running a sweep line algorithm for every polygon with every nozzle path to determine intersections that indicate when a nozzle should be on. This process is simplified as the nozzles are mounted on a side shifting frame so that lateral nozzle position relative to crop rows remains fixed (within the accuracy of the side shift system estimated to be 10 mm S.D.)

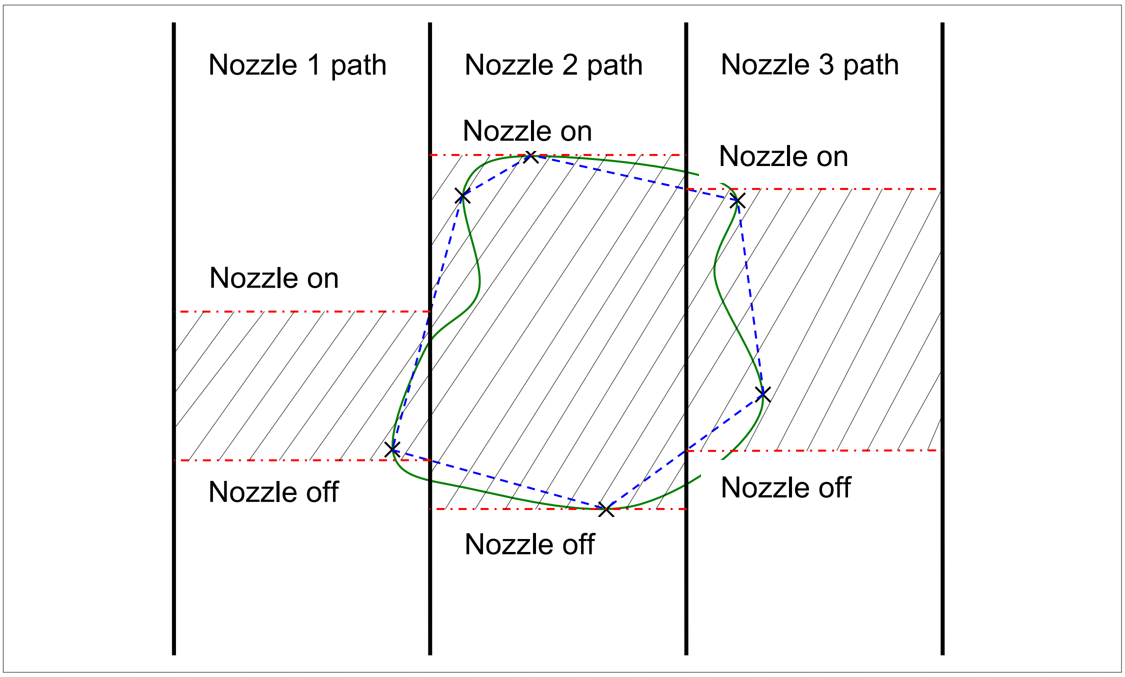

Figure 7 Illustration of how a polygon (blue dashed) around a potato (green solid outline) translates into a spray map (diagonal shading).

The process for creating bounding polygons and spray nozzle on/off schedules is repeated for every image at a rate of 30 Hz. In order to benefit from multiple estimations of spray schedules, information from successive images is combined to form an overall rolling treatment map that learns about new targets as they come into the top of the image, refines them as the progress down the image and finally forgets them as they pass behind the nozzles. The union of schedules is based on taking an average of on/off transitions where they are close (and probably due to minor errors in speed estimation) or by a logical OR where there are significant differences indicating a new part of the feature may have been detected allowing sprayed areas to grow if required. At present there is no mechanism by which sprayed areas can shrink if features disappear before they reach the bottom of the image.

As a final process for nozzles placed over crop rows for which on/off timing is particularly critical the sprayed are is shrunk by half the spray nozzle pattern width so as to reduce overspray. Whilst not currently implemented it may also be possible at this stage in the process to further refine the spray on/off schedule to reflect knowledge about the efficacy of treatment and the need or otherwise to achieve 100% coverage on all targets.

The algorithms described above for image capture, colour processing, feature selection and treatment map generation have all been written with the need for high speed processing in mind. Preliminary tests show that the complete package can run at frame rate (30 Hz) on the target hardware (Core Duo 2.16 GHz PC).

Performance of combined classification algorithms on stored image sequences

The following images have been chosen from the sequences of images to illustrate the strengths and weaknesses of the approaches implemented off line in the laboratory. The blue crosses represent raw observations of crop row location and the green lines reflect the position of the crop rows as tracked by the Kalman filter. Those parts of the images bounded by red polygons have been identified as clusters of pixels being more likely to be potato than either crop or soil.

Carrots

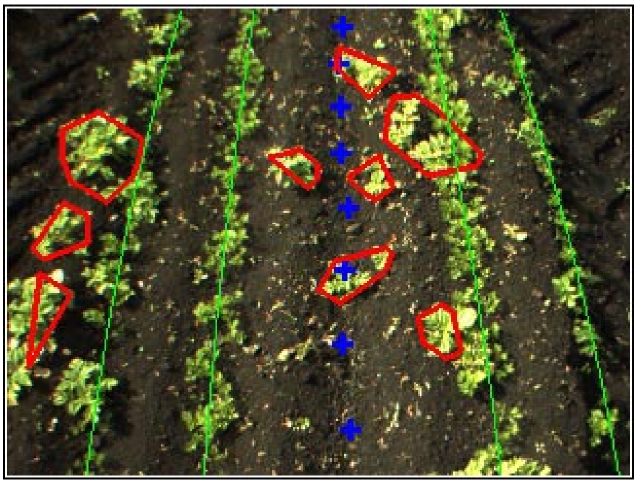

Figure 8 This example shows how the majority of potatoes are successfully bounded by the polygons, but that small weeds (not necessarily potatoes) and some parts of potatoes within crop rows are missed.

Onions

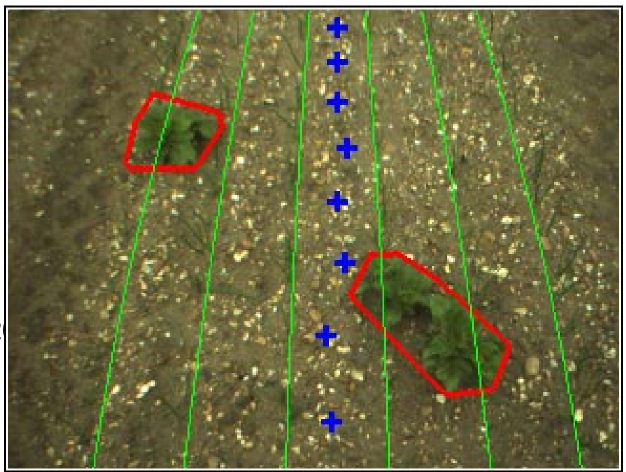

Figure 9 The detection of weed potatoes at the early stages of onion growth is relatively straight forward as there is a large size differential.

As position relative to crop rows is an important contributing factor in weed discrimination, performance will be at its best when drilling is accurate and care is taken when conducting post emergence operations such as spraying to avoid running over rows. The precautions taken by growers who practice inter-row cultivation should be adequate in this respect. Similarly some planting geometries are better than others with respect to both ease of detection and treatment e.g. onions grown on twin rather than single rows generally provide more clearly defined rows. In these respects the commercial crops used in this trail represented more challenging situations than is sometimes the case.

It will be useful in future field work to investigate a wider range of crop situations especially earlier growth stages. These earlier growth stages may make discrimination easier as size may be a better discriminator especially in carrots.

Development/assessment of nozzles and application methods

Identification of nozzle systems capable of meeting the specification

Work as part of the separate feasibility study had shown that is was possible to pulse the output from a conventional flat fan nozzle for pulse durations down to 0.03 seconds and a control system and nozzle assembly had been constructed for use in field experiments using this nozzle arrangement. The feasibility study had also shown that cone nozzles were not appropriate for the application because complete spray formation did not occur sufficiently quickly. The use of a pulsed conventional flat fan nozzle has potential disadvantages relating to the uniformity of the spray volume distribution across the treated area and the risk of spray drift. It was also considered advantageous to have a spray angle of less than 25^{o} so that relatively high nozzle heights above the target could be used and the sensitivity to nozzle height reduced. The study therefore considered the following options.

a) An air-induction nozzle having a nominal flow rate of 0.6 L/min that was based on an existing commercial nozzle design but in which the final output tip was modified by replacing the output tip to produce a 25° spray angle: experiments with this nozzle design showed that it was not able to produce a spray when the liquid supply was pulsed for 0.03 s.

b) A narrow angle (15°) conventional flat fan nozzle having a nominal flow rate of 0.6 L/min: again experiments with this nozzle option showed that when supplied with a short pulse of pressurised spay liquid, no spray was formed.

c) A narrow angle (25°) "evenspray" nozzle having a flow rate of 0.4 L/min at a pressure of 3.0 bar: experiments with this nozzle showed that it was able to meet many aspects of the specification but was likely to pose a high risk of drift and contamination of crop adjacent to detected weeds.

d) A fluidic nozzle design in which a stream of liquid passes through a chamber in the nozzle that sets up an oscillation and hence generates a spray by the action of the oscillating stream – see Figure 10.

Figure 10 Spray formation from a fluidic nozzle with an oscillating jet.

Experiments with a version of this nozzle that was available for evaluation but that had a flow rate and spray fan angle that were above that called for in the specification showed that it was able to operate with a short pulsed supply, provide a relatively large mean droplet size and an approximately uniform volume distribution across the pattern (edge heavy due the oscillating action of the spray stream). It was therefore decided to further develop this nozzle type in conjunction with Hypro EU Ltd, commercial partners in the project.

Fluidic nozzle development

Two initial designs of nozzle were designed and manufactured as prototypes by Hypro EU Ltd. These were designated Q and R, had flow rates at a pressure of 1.0 bar of 0.35 and 0.45 L/min and spray fan angles of 19 and 25^{o} respectively. A second series of this nozzle design were also made, designated S3 and S4 having flow rates in the order of 0.2 L/min at a pressure of 1.0 bar and a spray fan angle of 20 to 24^{o}. The performance of all versions of this nozzle was evaluated against the required performance criteria – see Section 2.2.4.

Mechanical oscillating nozzle development

Specification and principle of operation

One method of tightly controlling droplet size is to issue liquid through a tube with a relatively long length to diameter ratio such that a continuous stream is produced. That stream then breaks up due to surface tension effects into reasonably regular sized droplets. To turn that into a spray pattern, it is possible to mechanically oscillate the tube producing a line pattern that becomes a two dimensional spray as it is moved perpendicular to the plane of oscillation. In this respect it is very similar to a fluidic nozzle, though it has the advantage in principle of having a narrower size range of droplets with more clearly defined edges to the spray pattern. It can also be adjusted to operate over a very wide range of spray fan angles including very narrow angles enabling nozzles to be placed higher for a given spray width. The principle disadvantage over a fluidic nozzle lies in the cost and complexity of providing a mechanism to oscillate the tube. Both types of oscillating nozzles suffer from the same disadvantage of providing an edge heavy pattern due to the periodic nature of the oscillation motion. In principle a mechanically driven oscillation devise could be driven in such a way as to reduce this effect but this possibility has not been explored.
The principle of obtaining a spray pattern by mechanically oscillating jets is not new. In the 1950's ICI marketed the "Vibrajet" which used an electric motor to drive a cam that caused a tube with multiple jets to oscillate. The device illustrated in Figures 11 and 12 was designed for use with paraquat applied in very large volumes by modern standards. These devices are no longer in production and would in any case be unsuitable to the relatively low oscillation frequency and the high flow rates.

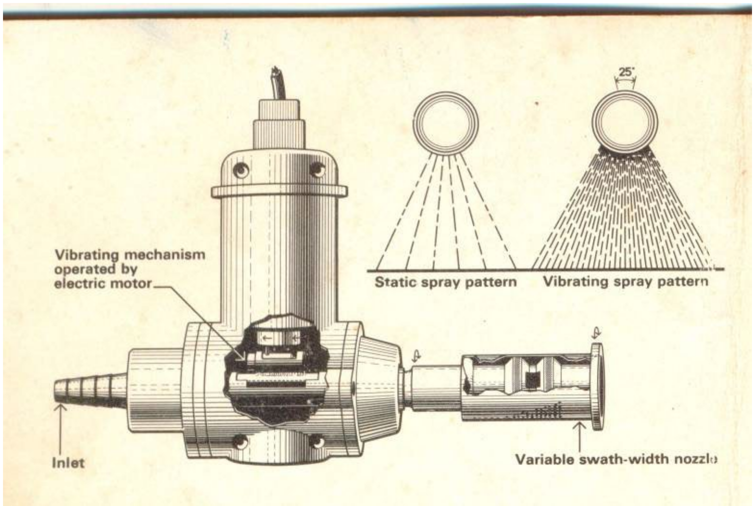

Figure 11 Schematic of 1950's "Vibrajet".

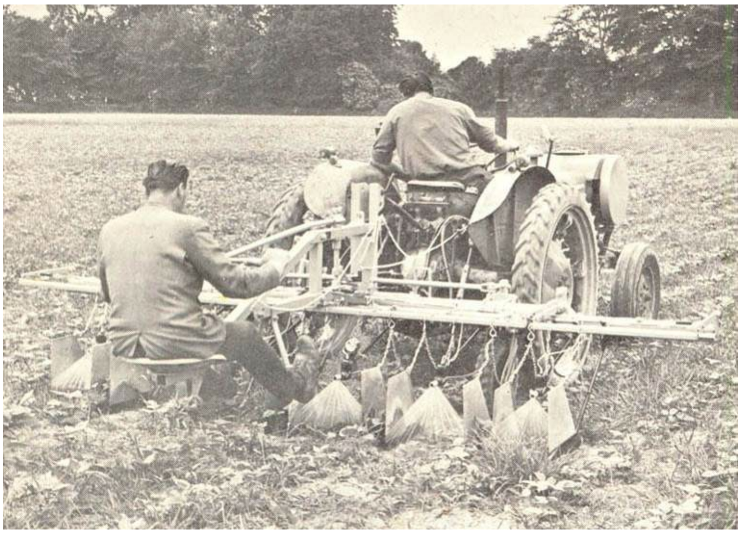

Figure 12 "Vibrajet" in use.

The decision was made to develop a mechanically oscillating nozzle as it was thought to offer the closest to the ideal spray pattern that could be practically achieved and would therefore provide a good bench mark against which other nozzles could be tested. It was not the intension to developing the mechanical oscillating nozzle into a commercially viable device, though in developing the experimental device some of the barriers to commercial use have been at least partially addressed. The device could therefore be regarded as a fall back with respect to fluidic and other nozzle technologies should the application demand that performance.

Nozzle design

The issues of flow rate, droplet size and droplet velocity for a mechanically oscillating nozzle are broadly similar to those for fluidic nozzles. The diameter of droplets and flow rates increase with orifice (tube) diameter – see Section 2.2.4. Experimental results indicated that droplet diameter over the range with which we are interested increased to approximately twice tube diameter as the cylinder of liquid exiting the tube breaks up and forms into a stream of spheres as illustrated in Figure 13. Experimental results also indicated that a 120 Hz mechanical oscillation has only a minor role in deducing droplet size. Flow rate and droplet velocity increase with the square root of pressure.

Figure 13 View of droplets forming out of a jet issuing from a mechanically oscillating tube.

If the target application rate is 120 L/ha, the spray band width 150 mm and the forward speed 1.4 ms^{-1} (5 kph) then the required flow rate from each nozzle is 0.16 L/min (9.6 L/h). This flow rate was achieved in a system incorporating the bistable solenoid valve (see section 2.4.1) and an oscillating tube of 0.5 mm diameter supplied at 2.0 bar. Droplet size analysis at this configuration (see Section 2.2.4) yielded a VMD of about 1.0 mm. Whilst from a coverage perspective it would be desirable to reduce VMD by reducing tube diameter and increasing pressure to maintain flow rate, practical issues of reliability due to contamination induced blockages dictate that 0.5 mm represents a minimum tube diameter.

The design chosen for the nozzle used a length of hypodermic needle connected to manifold accommodating the solenoid valve via a short length of silicon tube. This had the merit of providing both a hinge and a path for the liquid that minimized dead volume.

Vibrating beam oscillating mechanism

A mechanism was required to oscillate the needle in a single plane at the required frequency and amplitude. The minimum frequency of oscillation was chosen as 100 Hz at that frequency and a forward speed of 1.4 ms-1 (5 kph) the distance covered over one cycle would be 14 mm. It was felt that any distance greater than that may result in an insufficiently uniform coverage.

To achieve oscillation in a single plane it was decided to use a vibrating beam whose axis of vibration was perpendicular to both the axis of the needle and the direction of motion (Fig. 14). A number of methods of causing that beam to vibrate were considered, but it was thought simplest to mount a small DC vibration motor on the end of the beam. The mass of the motor and beam and the beams geometry were then tuned to that the beam vibrated at close to but below its natural frequency. An approximation to the natural frequency ω of that assembly is given by:

$$\omega = \sqrt{3EI \big/ L^3 m}$$

Where second moment of area $I = bd^3 \big/ 12$

and

L = beam length (to centre of gravity of motor and end cap)
E = Youngs modulus of beam material
m = mass of motor and end cap (neglecting beam)
b = beam width
d = beam thickness

Use of vibration motors of this type is convenient as the motors are readily available and low in cost due to their mass manufacture for the mobile phone and other markets. However, there are alternative means of generating mechanical excitation that may be more appropriate should commercial versions be required. These could be based on non contact methods involving moving coils in a static magnetic field similar in principle to load speakers.

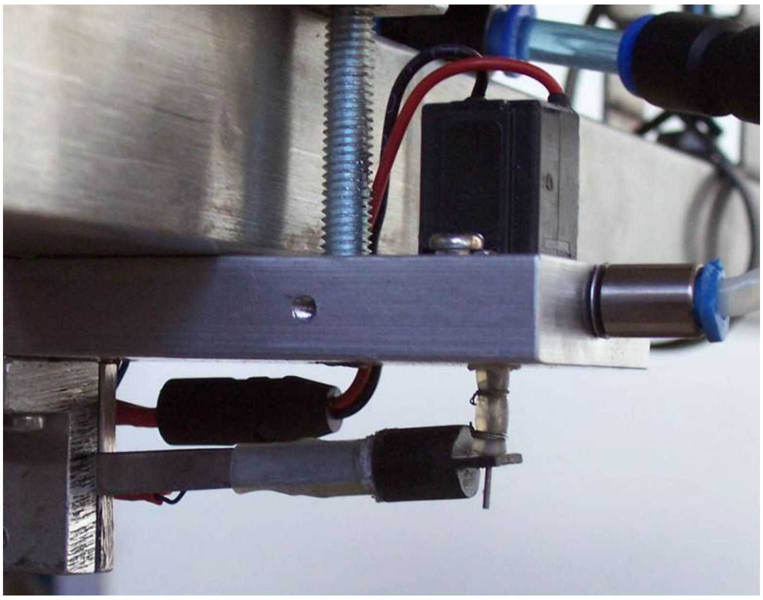

Figure 14 A complete mechanically driven oscillating nozzle.

Evaluation of nozzle performance

Droplet size, velocity and spray volume distributions

Nozzles were mounted on a computer controlled x-y transporter that was programmed to move the nozzle such that the wide axis of the spray passed through the sampling volume of a pulsed laser spray analyser (Oxford Lasers "Visisizer). The spray analyser collects single or double images from within the spray and uses these images to determine the droplet size and velocity distributions within the spray. Since each droplet is time labeled, the spray structure showing individual droplets can be mapped across the whole of the spray pattern. A method of analysis has been developed that enables the boundary positions representing 99% of the spray volume to be plotted on the measured droplet profiles.

Measurements were made with both the fluidic and oscillating needle nozzle at a height of 500 mm and with a scan speed of 20 mm/s. Typical results are as shown in Figure 15 (a–c).

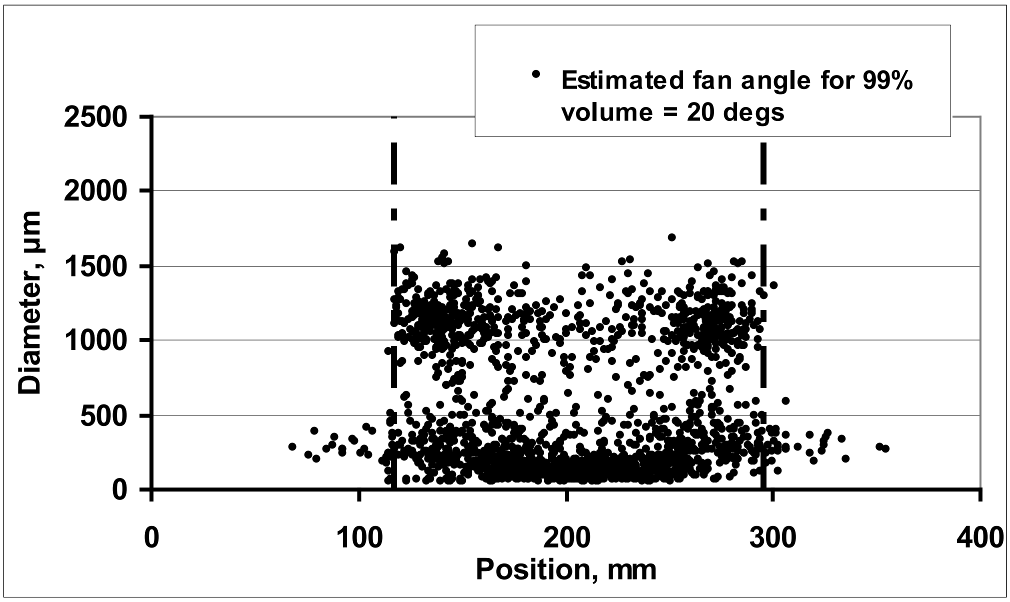

Figure 15 (a) Measured droplet sizes with the S4 fluidic nozzle operating at a pressure of 0.75 bar; measurements made 500 mm below the nozzle when spraying water only.

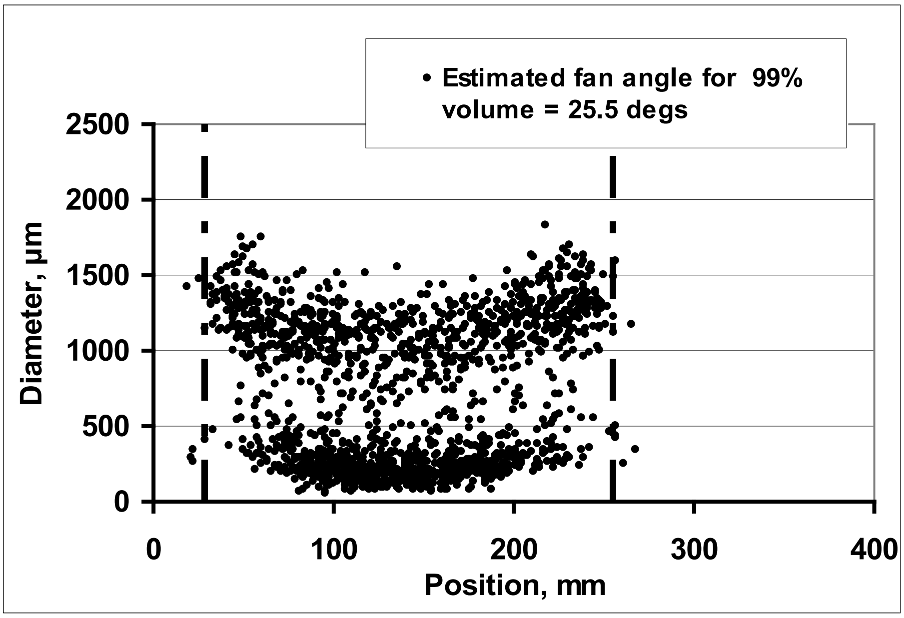

Figure 15 (b) Measured droplet sizes with the oscillating needle nozzle fitted with a 0.7 mm needle operating at a pressure of 0.50 bar; measurements made 500 mm below the nozzle when spraying water only.

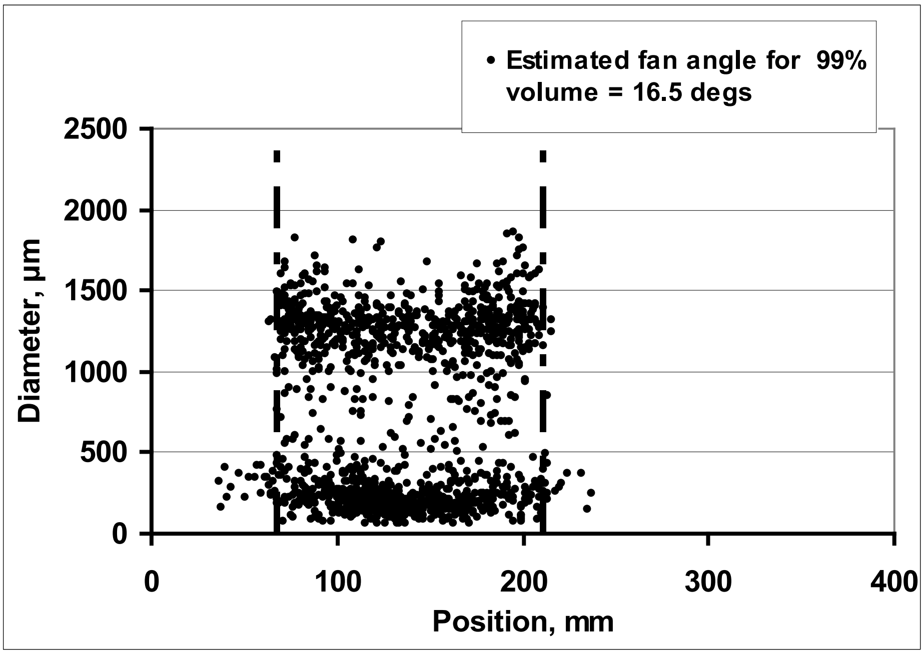

Figure 15 (c) Measured droplet sizes with the oscillating needle nozzle fitted with a 0.7 mm needle operating at a pressure of 2.00 bar; measurements made 500 mm below the nozzle when spraying water only.

Results of the performance assessment work with the different versions of the fluidic and oscillating needle nozzles are summarised in Figures 18 (a–e).

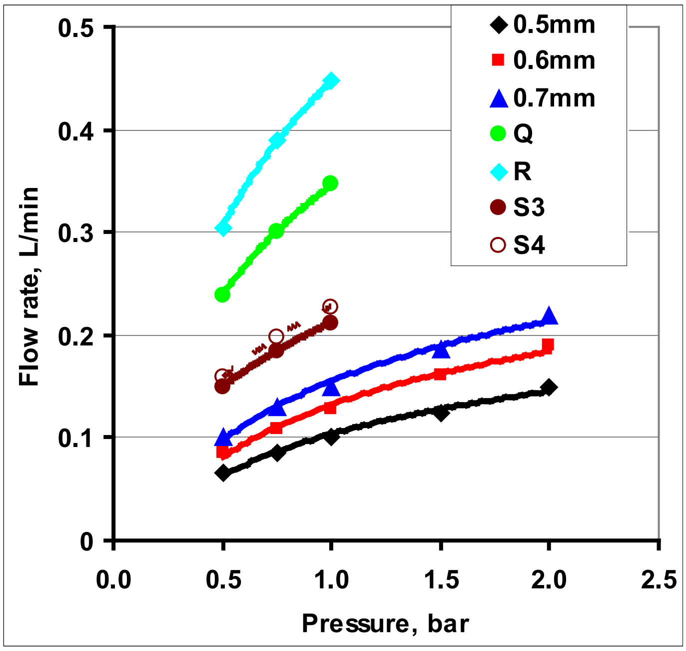

Figure 16 (a) Liquid flow rates for the nozzle options evaluated; oscillating needle fitted with 0.5, 0.6, 0.7 mm needles; fluidic designs Q, R, S3, S4.

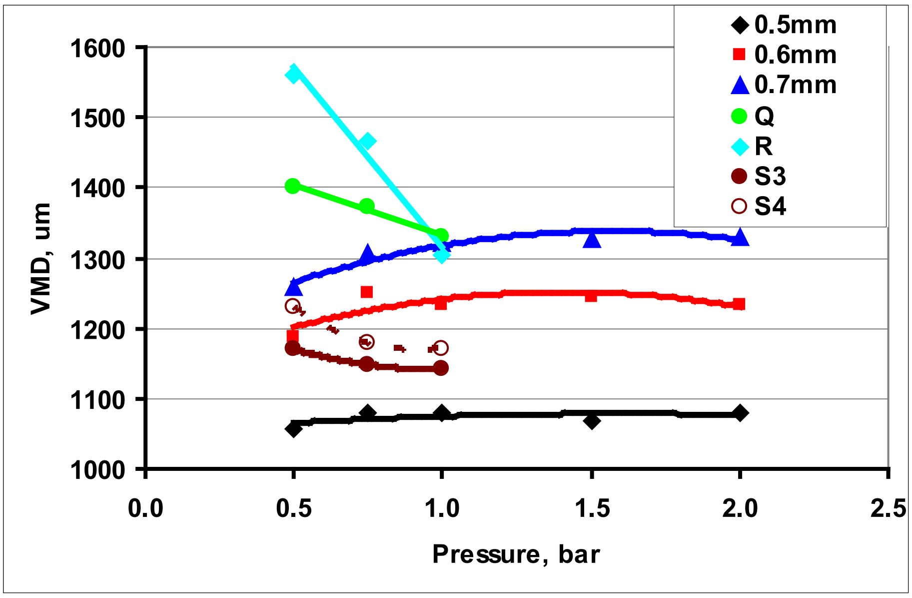

Figure 16 (b) **Mean droplet sizes as volume median diameter (VMD) for the nozzle options evaluated; oscillating needle fitted with 0.5, 0.6, 0.7 mm needles; fluidic designs Q, R, S3, S4.**

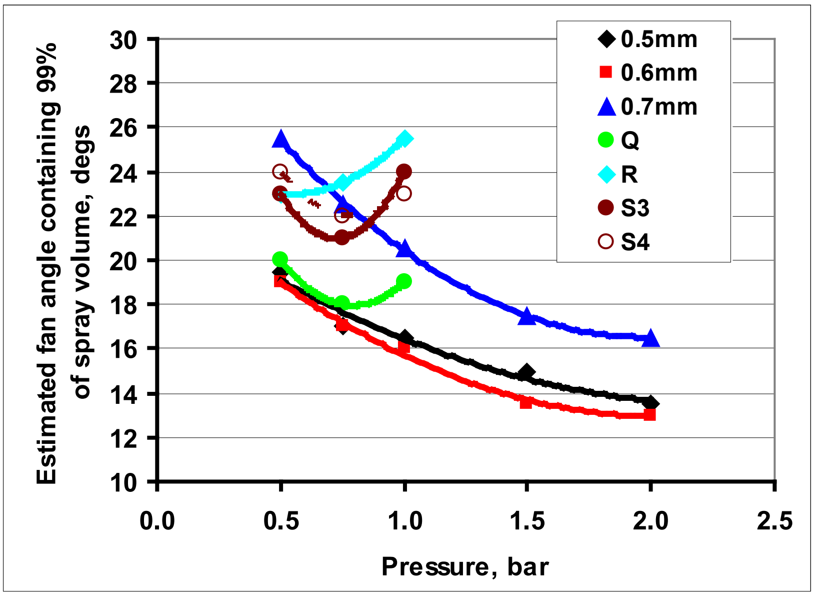

Figure 16 (c) **Estimated spray fan angles for the nozzle options evaluated; oscillating needle fitted with 0.5, 0.6, 0.7 mm needles; fluidic designs Q, R, S3, S4.**

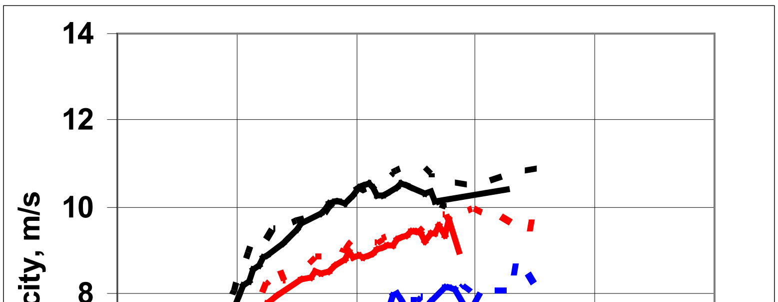

Figure 16 (d) Droplet velocities for the fluidic nozzle designs Q, R, S3, and S4.

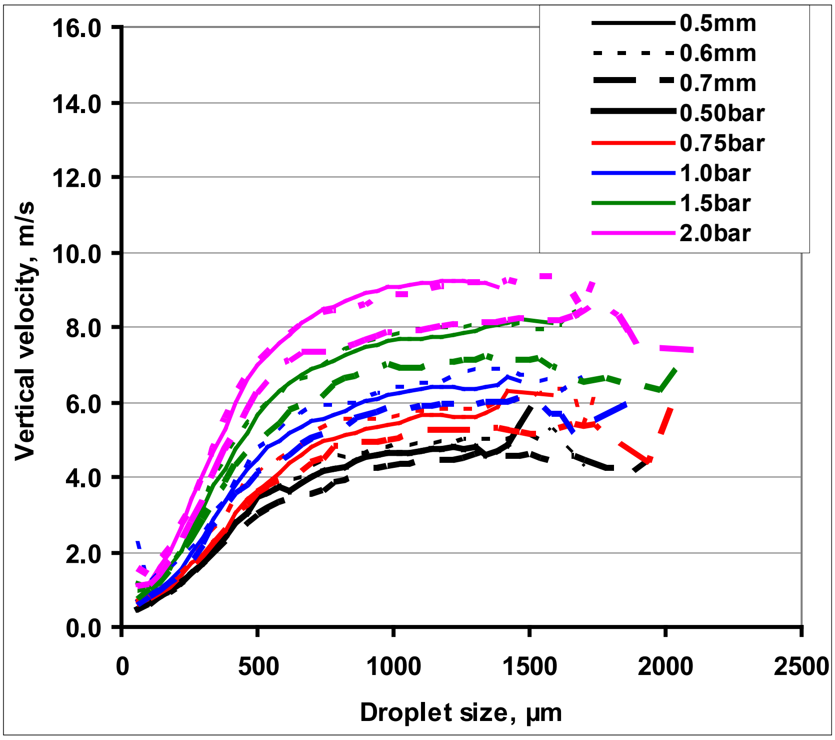

Figure 16 (e) Droplet velocities for the oscillating needle nozzle fitted with 0.5, 0.6, and 0.7 mm needles.

Results from the measurements of the droplet size, velocity and spray volume distributions for the two nozzle systems showed the following.

For the fluidic nozzle design:

- there was a reasonably good cut-off at the edges of the spray pattern (Figure 17(a)) but with a small number of relatively small droplets (circa 250 μm in diameter outside of the main edge of the pattern but within 50 mm of this edge;
- flow rates increased with pressure in an approximately square root relationship as expected;
- droplet sizes and flow rates for the initial designs (Q and R) were above those required for this application for the latter designs (S3 and S4), mean droplet sizes as defined by the volume median diameter (VMD) were in the order of 1150 μm and reduced slightly with increasing pressure;
- spray fan angles when operating at a pressure of 0.75 bar were in the order of 20° for the S3 and S4 versions of the nozzle and increased slightly at pressures either side of this value;
- droplet velocities were a function of pressure and at a pressure of 1.0 bar, most droplets were travelling at a velocity of just above 10 m/s;
- the droplet size distribution was very bi-modal with large parts of the droplet size distribution centred on about 200 μm diameter and at about 1200 μm diameter.

For the oscillating needle nozzle design:

- there was a good cut-off at the edge of the spray pattern (Figures 17(b) and 17(c)) although there were still some small droplets beyond the edge of the main pattern;
- droplet sizes were again bi-modal and were mainly a function of needle size rather than operating pressure, increasing size from 0.5 to 0.6 mm diameter increased mean droplet sizes (as VMD) by approximately 15%;
- spray fan angles decreased with increasing pressure mainly due to the change in effective stiffness of the nozzle support and supply pipes as pressure and flow rate increased;
- flow rate increased with increasing pressure as expected but the rate of increase was less than that for a nozzle (or orifice) due to frictional flow characteristics in the needle section;
- droplet velocities were less than with the fluidic nozzle at about 6.0 m/s for an operating pressure of 1.0 bar.

Spray pattern delivered from a moving pulsed nozzle

Visualisations of the spray patterns delivered by a moving pulsed nozzle were made by mounting the nozzles on a variable speed transporter mechanism and arranging for the nozzles to deliver a spray pulse of a coloured tracer dye to a horizontal sheet of white paper. Results from this work showed that both the fluidic and oscillating needle nozzle were able to achieve sharp cut-offs in the pattern in the direction of travel at both switch on and switch off. For the fluidic nozzle, the path of the oscillating stream coming from the nozzle could be clearly seen in the pattern on the sprayed area – see Figure 17.

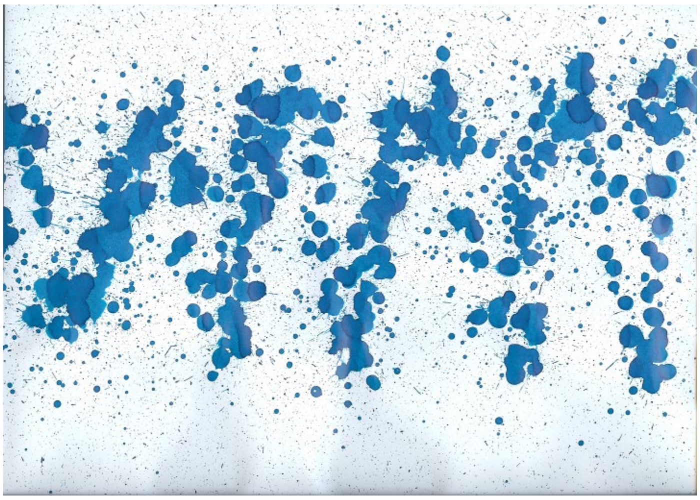

Figure 17 Pattern obtained with the R design of fluidic nozzle operating at a height of 0.5 m and travelling at a speed of 2.1 m/s.

Given an application rate of 120 L/ha and a droplet VMD of approximately 1 mm we can expect the average ground area occupied by a single drop to be 0.4 cm^2 , which is probably acceptable for spraying relatively large targets such as volunteer potatoes with glyphosate but may not be suitable for smaller targets with other herbicides. These findings are visually consistent with the results of spraying dye onto white paper as illustrated in Figure 17 and 18.

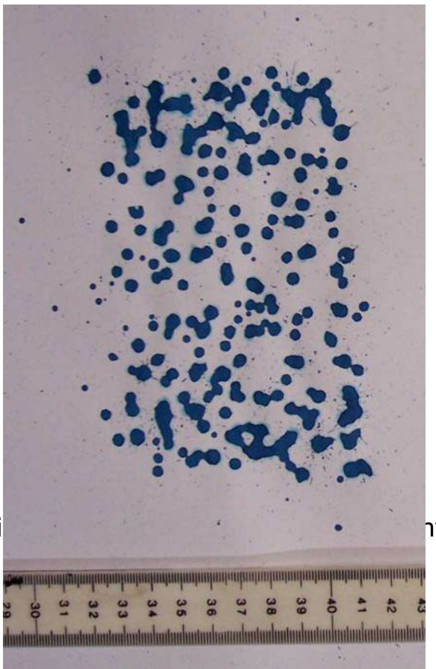

Figure 18 Pattern achieved from a 60 ms pulse of a 0.5 mm diameter oscillating needle nozzle supplied with water (+dye) at 2 bar running right to left at a height of 0.5 m and a speed of 1.34 ms^{-1}.

Interim conclusions relating to the performance of the nozzle options for use in this application

It was concluded that both the fluidic and oscillating needle nozzles had characteristics that were useful for the application of herbicides to detected volunteer potatoes, and that both designs would be taken forward for further evaluation in both field and laboratory trials. The oscillating needle nozzle had some advantages in terms of performance and the ability to adjust characteristics by changing needles and oscillating characteristics. However this design is more complex, expensive and potentially prone to blockage than the fluidic nozzle design.

Agronomic assessment of candidate treatments

Experiments in an established potato crop

Pulses of spray of 0.03 s duration were delivered to established potatoes on 05/06/07 using a 25o flat fan "evenspray" nozzle positioned 300 mm above the plant and using herbicide concentrations of 80:1; 45:1 and 20:1. Measurements of the physical size of the potato at the time of treatment showed that they had a mean of 3.5 tillers, a plan area of 570 mm2 and a mean height of 16.5 mm. Plants were treated in a randomised block design with either single or double pulses being applied to target plants. Assessments of outcomes were made on 20/06/07 (15 DAT) and 10/07/07 (35 DAT) using a scoring system in which a score of zero was no effect and a score of 10 was a complete kill. The results (Figure 19) show the expected form of dose response with both herbicide concentration and number of spray pulses. The results confirmed those from the initial feasibility study that indicated that high levels of control were achieved when all plant tillers received some herbicide. This result suggests that control of volunteer potatoes can be achieved using the highest field spray concentrations of glyphosate rather than those used for wiper applications.

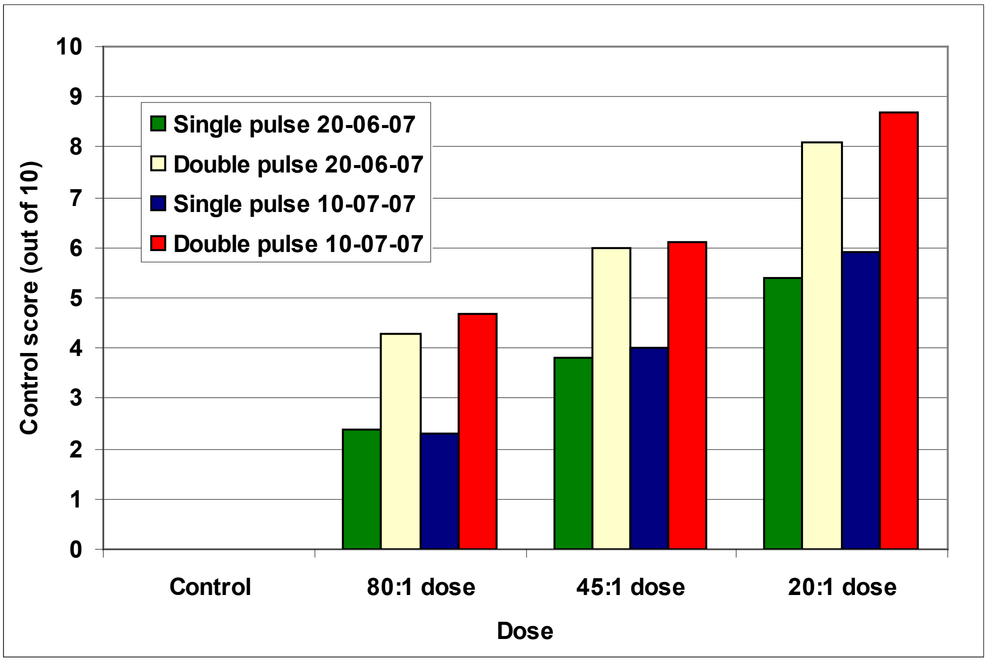

Figure 19 Results of experiments conducted in an established potato crop treated with pulses of glyphosate spray at different concentrations.

Experiments treating volunteer potatoes in a carrot crop

Pulsed spray applications of 0.03 s duration and 20:1 concentration of glyphosate were made to volunteer potatoes on 06/06/07 in a commercial carrot crop at Perlthorpe, Newark, Notts. Volunteers were assessed by size on a scale of 1-5 and two spray pulses were delivered to plants scored as 4 or 5 with a single pulse applied to those scoring 1, 2 and 3. Two sizes of 25o "evenspray" nozzles were used at a pressure of 1.5 bar. Results were assessed on 15/06/07 (9 DAT) with very high levels of kill recorded on cell plots. The potential damage to the crop was also determined by visual inspection and was generally low – see Figure 20. It was difficult to assess the effects that shading of the crop by the presence of the volunteer potato had caused but there was some evidence of herbicide damage to crop plants immediately adjacent to the position of the volunteers. There was also evidence that the volunteers had shaded the crop from herbicide contamination.

It was concluded that control of volunteer potatoes was more easily achieved in a growing crop than with cultivated plants and that low levels could be achieved with herbicide delivered from nozzles accurately positioned with respect to targeted plants.

Figure 20 Volunteer potatoes in a carrot crop 9 DAT with a hand-held pulsed nozzle.

Development of rapid switching control technologies

Solenoid valve selection

The ability to hit relatively small potatoes from a relatively fast moving implement requires switching on and off to be both rapid and deterministic. For example a nozzle passing over a potato measuring 50 mm in the direction of travel at 5 kph (1.4 m/s) should be on for only 36 ms (or less if allowance is made for spray pattern width). It follows then that the response time for the valve must be comfortably inside this period. Solenoids used to switch conventional spray nozzles typically have response times of the order of 100 ms and so it has been necessary to look at other sources of equipment. Fortunately the low flow rates (typically 0.1 to 0.3 l/min) and smaller orifice sizes required for spot spraying mean that there are opportunities for faster smaller solenoids. The relatively narrow spray widths required for this work will require large numbers of solenoids which also favours small solenoids with low current coils.

One way of reducing the electrical load further is to employ latching solenoid valves sometimes known as bistable valves. In these devices permanent magnets are arranged so that the valve can be held either open or closed without the application of an electromagnetic field. To change state a short pulse is applied to the valves coil forcing the actuator to a new state. By changing the polarity of this short pulse the valve can be switched on or off.

Further advantages of this principle include fast action that is symmetrical between switching on and off. A number of valves were considered with one type selected as it best matched our detailed requirements, though alternatives would probably be available from other manufacturers. The selected device a bistable pulse controlled valve from A K Muller (Figure 21) has been primarily designed as a pilot valve but is also suitable for controlling small flows directly. It has the following specification:

Orifice size, DN 0.8 mm (CV 0.31 l/min)
Operating voltage, +/- 6V
Switching pulse, 15 ms square
Coil power, 1.8 W
Seals, EPDM (others are available and may be required for production machines)
Operating pressures, 0 – 10 bar

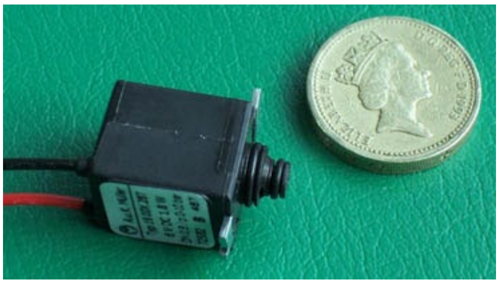

Figure 21 A 1.8 W latching bistable valve selected to control spot spray nozzles.

Electronic switching circuit and control software

In order to conduct field trials it is necessary to design and construct circuits to control the bistable solenoid valves, the vibration motors, and a side shifting electric motor (or solenoid valves). It is also necessary to be able to read side shift position using a potentiometer and to have the facility to read a distance measuring encoder (though the vehicle to be used for 2008 trials has its own encoder system). It is convenient for all these functions to be built into a single printed circuit board along with a microprocessor to provide low level control of these functions and an interface with the main computer.

The resulting device pictured in Figure 22, has been designed with 16 channels of bistable solenoid valve and vibration motor outputs. If more channels are required then more than one of these microcontroller boards could be used. Communication between the microprocessor (a Silicon Labs C8051F341) and the main computer (a Core Duo 2.16 GHz PC) is via a RS232 serial interface synchronized with image acquisition at 30 Hz. The board is supplied with 12 v from the tractor battery and generates the +/- 6 v for the bistable valves, and the voltages required to operate vibration and side shift motors using pulse width modulation (PWM) techniques.

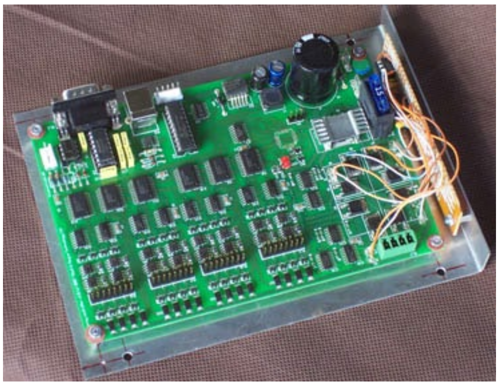

Figure 22 The microcontroller sprayer board custom designed and built for this project.

Microprocessor software has been written to manage the serial interface, read analogue and encoder inputs and to generate the timing signals for the various PWM electronic circuits. The software handles the changing of state of the bistable valves according to the latest demand from the main computer. It also controls side shift position via an on/off control in accordance with the latest instruction from the main computer.

Design and construction of experimental tool frame

For experimental convenience a small toolframe tractor has been chosen to provide the motive power for the experimental system during 2008 trials. This hydrostatically driven machine (Figure 23) has the advantage of light weight, good low speed control and has previously been equipped with some computing equipment, though this has been upgraded to fulfill the needs of this project.

Figure 23 The toolframe tractor to be used as a platform for the 2008 trial.

As previously discussed the spray nozzles are fitted on a side shifting frame so that lateral position of nozzles relative to crop rows can be maintained. That side shifting sub frame is mounted forward of the front drive wheels under the camera as illustrated in Figure 24. Side shift movement was via a DC motor driving a toothed belt with position feedback provided by a multi-turn potentiometer.

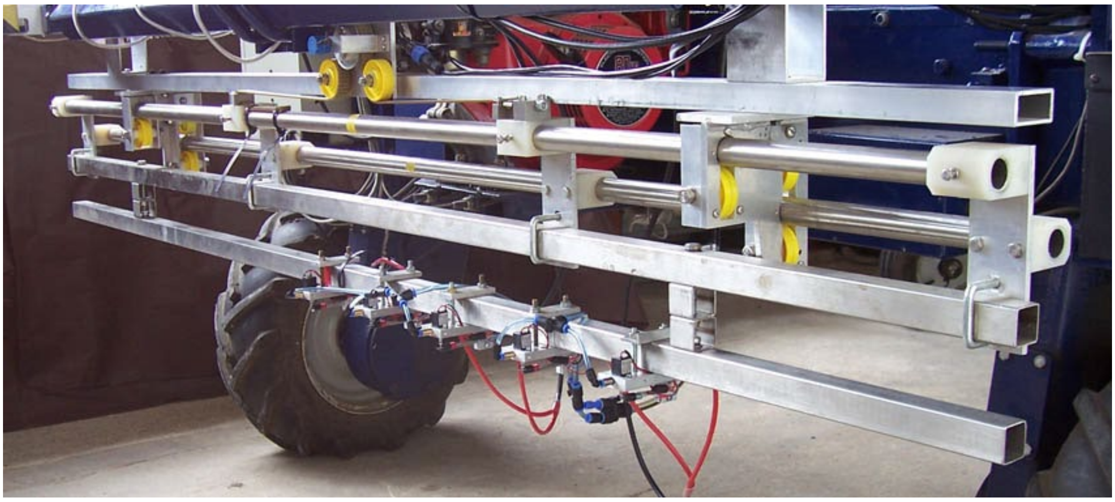

Figure 24 Side shifting spray bar with five nozzles fitted.

It is likely that an experimental implement designed to fit on a more conventional tractor will be used in field trials for 2009.

Design and construction of computing systems

Image sequence capture in commercial carrot and onion crops in 2007 was conducted using specially written software running on standard PC based lap to computers. The cameras provided by Robydome were identical to those used in commercial Robocrop guidance systems and connected to the lap top computers via an IEE1394 serial interface.

The computing system developed for field trails in 2008 is based on a Core Duo 2.16 GHz PC installed in a cabinet mounted over one of the drive wheels. Also in this cabinet are the power supply and other custom electronics relating to vehicle control. This PC connects to a

VGA display mounted to be clearly visible to the driver and an IEEE1394 camera viewing forward from the spray bar. This PC also connects to the custom designed microcontroller described in Section 2.4 via an RS 232 serial interface.

Initial assessment of the computing system suggests that it will be sufficiently powerful to run the plant location, discrimination and tracking software at a camera frame rate of 30 Hz.

Demonstration and evaluation of the experimental system

There has been no opportunity in the first year of the project to evaluate the experimental system in field or plot conditions. However, preliminary evaluation of the engineering principles based on tracking and spot spraying green blocks against a brown mat background has yielded promising results.

Overall conclusions

1. Image analysis based discrimination between weed potatoes and target crops has been developed and shown to work on stored image sequences.
2. Two novel nozzles that demonstrate potential to meet precision targeting specifications have been developed to the point that they are ready for field testing.
3. Preliminary manually applied glyphosate sprays simulating machine placement have demonstrated good weed potato control.
4. A high speed solenoid valve has been selected and a custom microcontroller board developed to facilitate rapid (15 ms) switching of individual nozzles.
5. A side shifting frame capable of accommodating up to 16 nozzles has been constructed and fitted to a small toolframe tractor in preparation for field trials in 2008.
6. A computing system capable of running the plant location, discrimination and tracking software at 30 Hz.
7. Preliminary engineering evaluation of the experimental systems has been satisfactory.

Technology transfer

- HDC Technical Seminar and field walk, Kirton,3rd July 2007 (Presentation)
- HDC carrot field day, Bawtry, South Yorkshire, 4 October 2007 (Poster).
- AAB Meeting, Wellesbourne, 13 November 2007 (Presentation).
- Horticulture LINK event, London, 28 November 2007 (Poster).

- Carrot and Onion Conference, Peterborough, 21-22 December 2007 (Poster and presentation).
- HDC precision technology event, Spalding, 26 March 2008, (Presentation).

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Appendices

None.