Final Report

Minimising the Environmental Impact of Weed Control in Vegetables by Weed Detection and Spot Herbicide Application

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1. GROWER SUMMARY

1.1. Headline

- Results from the project have demonstrated the potential for controlling volunteer potatoes in onion and carrot crops by the spot application of glyphosate at work rates and with total system costs that are competitive with any of the alternatives.
- Novel image analysis based weed detection and spot spraying systems have been developed for volunteer potato control.
- In field trials with a full-scale experimental system, typical levels of control of 90% in carrot and onion crops were achieved with a single application and with acceptable levels of crop contamination and damage.

1.2. 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The registration for metoxuron (Dosaflo) was withdrawn with effect from the end of December 2007.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 parsnips 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 full-scale 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 (i.e. a 6.0 m wide unit travelling at 5.0 km/h).

The LINK project for which this is a report of the work conducted throughout the project set out to meet these requirements and hence the expected deliverables relate directly to the above.

1.3. 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 Potato Council. The work in the project has involved:

- Initial field studies to collect images of volunteer potatoes growing in both onion and carrot crops that could be used in the development of detection algorithms;
- The development of a weed detection algorithm that would identify the presence and positions of volunteer potato plants relative to the crop row in crops of onion and carrot;
- Field trials with both cropped and volunteer potatoes treated with variable doses and volumes of spray liquid containing a total herbicide and delivered through a pulsed nozzle system to determine a specification for a spot application system;
- A design study to identify 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;
- The development of methods for quantifying the performance of the herbicide delivery system particularly relating to the targeting of the area to be treated and the risk of contamination of plants outside of this target area;
- The design and assembling of a single bed experimental rig that could be used in field trials to validate the approaches and systems developed and provide measures of overall system performance; undertaking field trials with the experimental rig as part of the development process and to obtain initial performance data;
- The design of a full-scale field rig spanning three beds and using all of the systems developed within the project so as to test and evaluate the approaches at full scale in a final series of field trials.

2. The weed detection algorithm was developed such that the areas within an image that meet the criteria for being classified as a volunteer potato/weed could be bounded by a polygon. This series of polygons representing volunteer potato or other weed positions was 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 delivering 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 <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 that enabled the position of measured droplets within the spray fan to be mapped and hence a measure of the sharpness of cut-off to 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 that 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;
- Operating the nozzles in a wind tunnel and making measurements of the quantity of spray outside of the treated area so as to obtain information relevant to the risk of crop contamination during operation of the field system in a range of wind conditions.

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 in which 0.03 s pulses of spray were applied to both cultivated potatoes and volunteer potatoes in carrot and onion crops showed that the volunteers were more readily controlled as expected. Experiments used spray liquids containing between 4.3 and 17.7 g/L of glyphosate and, for the volunteers, pulses were delivered to the potato based on plant 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 and onion crops, close to a 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 was designed to test the complete system based on an existing tool frame but with modifications to:

7. Results with the experimental rig in the second year of the project demonstrated that the concept was capable of achieving high levels of control of volunteer potatoes in onion (circa 95% control) and carrot (circa 75% control) crops. The lower level of control in the carrot crop was due mainly to the difficulty in detecting volunteer potatoes in the crop rows that were beneath the crop canopy at the time of treatment but that would be controlled in a second pass. In the initial trials in onions, crop damage was judged to be moderate with plants typically within 23 cm of a treated volunteer potato plant being at risk of herbicide contamination. This was reduced in later trials and in work in the final year of the project by varying the percentage of the detected weed area that was treated in each case.

8. Results from the initial experiments in the first year of the project and the experimental rig trials in the second year were used to design a full-scale rig for field evaluation in the third season of the project work. This full-scale unit was front-mounted on a tractor linkage and configured to treat three crop beds with a total width up to 6.0 m. The fluidic nozzle design was chosen for development in the final stages of the project for reasons relating to simplicity of design and likely production costs. A control system for a complete machine was designed and implemented on the full-scale rig.

9. Field trials with the full-scale rig (see Figure A below) in the third season of project work in commercial crops of onion, carrot and parsnip gave levels of performance that were at least as good as the experimental rig in terms of both weed control and crop damage when travelling at forward speeds up to 5.0 km/h. Performance in all field trials in the final year of the project was judged to be commercially acceptable. The total usage of chemical was typically less than 5% of that required for the overall treatment of the cropped area with important implications for operating costs and the potential contamination of off-target organisms, ground and surface water.

FIGURE A. FULL-SCALE FIELD RIG OPERATING IN AN ONION CROP (INSET SHOWING NOZZLE OPERATION).

1.4. Financial benefits

An economic analysis was conducted using experience gained in field trials with the full-scale rig. 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 5.4 m machine operating at 5 km/h with a field efficiency of 75% giving a work rate of 2.0 ha/h; Seasonal and weather conditions limit operation to 20 8h days yielding a treatment capacity of 324 ha (this would increase if the machine was used to treat a wider range of target crops and weeds); Capital cost is estimated at £35,000 which depreciated at 20% p.a. gives an annual repayment charge of £9,240; Tractor and driver costs are assumed to be £19/h, the cost of glyphosate at £1.0/ha and maintenance £1,750 p.a.

On this basis, total costs are £37/ha if spread over the capacity area. We understand that these figures are comparable with treatment using overall sprays and should therefore provide an economic alternative when these chemicals are withdrawn. The economics of operation improve further if utilisation can be extended through the season on multiple crops and weed targets.

1.5. Action points for growers

The project has produced the technology necessary for the production of prototype systems for the detection and spot treatment of volunteer potatoes. Results from field trials have demonstrated that high levels of control can be achieved in a range of crop types (onion, carrot and parsnip) and weed densities with acceptable levels of crop contamination and damage.
Results from the work have also provided guidelines for operating such a system in practical conditions.

1.6. Exploitation and future applications

The project consortium is working to develop concepts within the project such that commercial prototype machines can be developed and made commercially available. Results from the project work have shown that the targeted application of a total herbicide can utilise a relatively wide operating window. The system developed using large droplets could operate in wind speeds substantially above those regarded as the upper limit for conventional crop spraying without the risk of large increases in crop contamination. The approach is also less sensitive to soil moisture conditions than most mechanical methods of weed control. A machine commercial developed using the principles identified in the project work would therefore be capable of achieving a relatively high utilisation, particularly if it were able to operate in a wider range of crops. The consortium is therefore also looking to develop detection, tracking and spray application techniques that would enable some of the concepts developed within this project to be applied to a wider range of crops, weeds and herbicides (including selective herbicides). Where selective herbicides are available for the control of weeds such as volunteer potatoes, the use of a spot spray system would reduce pesticide use very considerably (by up to 95%) with important implications for the potential contamination of ground water and off-target organisms. It is recognised however, that the application requirements for a selective herbicide will be different to those for a non-selective chemical.

2. INTRODUCTION

This report details progress within a Horticultural LINK project that aims to develop and demonstrate a technology that uses weed detection and the targeted application of minimum quantities of 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 of a total herbicide.

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 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 crops 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 minimise 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.

Results from the project work are detailed by objectives leading to the evaluation of a full-scale field rig in the final year of the project.

3. MATERIALS AND METHODS, RESULTS AND DISCUSSION FOR THE MAIN COMPONENT OBJECTIVES OF THE PROJECT

3.1. Development/assessment of image analysis based techniques for weed discrimination (Objective 1)

3.1.1. Acquisition of image sequences for algorithm development and evaluation

In order to facilitate the 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 and PCL 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 for 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 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 with 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.

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.

FIGURE 1. CAMERA MOUNTING USED TO OBTAIN IMAGE SEQUENCES.

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.

3.1.2. 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 practical implementation in the proposed system were:

Colour.
Feature size and shape.
Feature position with respect to crop rows.
Feature height.

Other characteristics such as leaf texture and leaf shape have not been considered as they are dependent 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 for application in this project.

3.1.2.1. 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 was needed which would 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.

3.1.2.2. 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.

3.1.2.3. 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 were located in the video images. Given knowledge (provided by the operator) of the approximate width of the crop plants within a row line, vegetation outside of the crop rows was identified potentially as weed (Hague *et al.*, 2006).

3.1.2.4. 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 and PCL 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 was not used as a discriminator in the algorithms developed in this project.

3.1.3. 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 collected 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 (DS) approach to the classification that 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.

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.

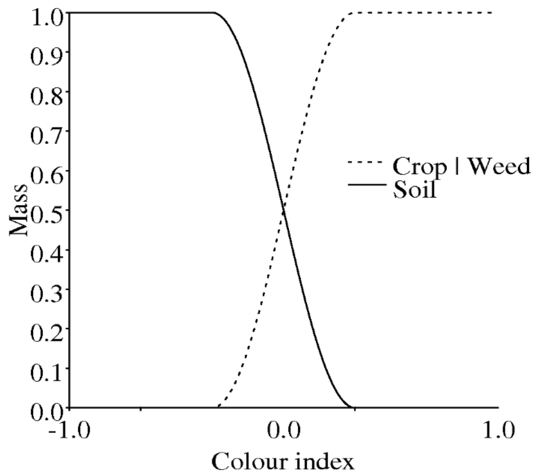

FIGURE 4. PROBABILITY ASSIGNMENT BASED ON COLOUR INDEX.

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.

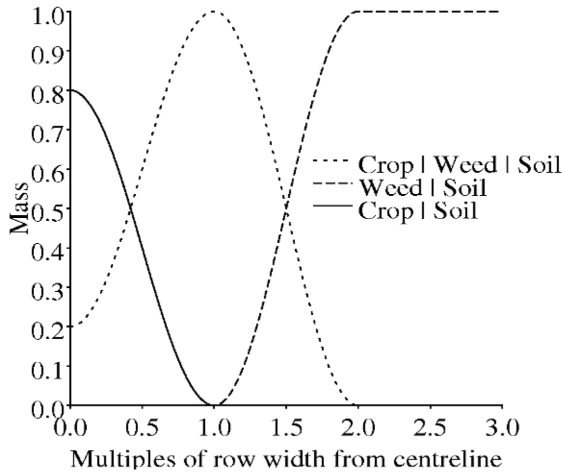

FIGURE 5. PROBABILITY ASSIGNMENT BASED ON DISTANCE FROM CROP ROW (CROP ROW FOLIAGE WIDTH = 1).

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).
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.

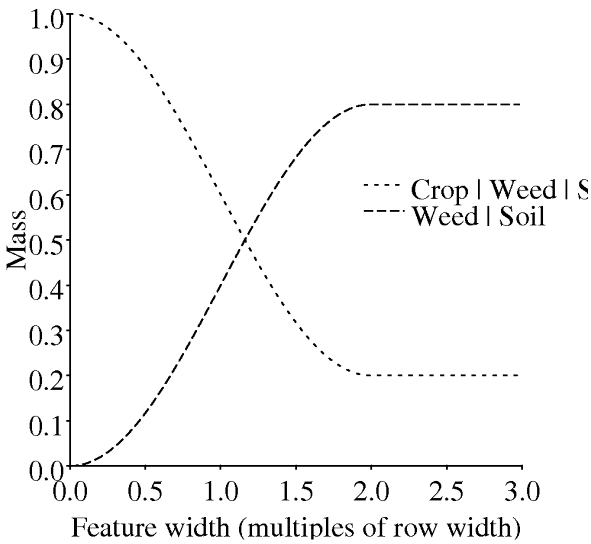

FIGURE 6. PROBABILITY ASSIGNMENT BASED ON FEATURE SIZE RELATIVE TO THE WIDTH OF FOLIAGE WITHIN CROP ROWS.

Having obtained an image onto which belief 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 the pixel is a volunteer potato plant is greater than the other categories. This is used to convert the image to a binary form depicting areas of volunteer potato plant against a background of all other categories.

The next stage is to find connected regions assigned as volunteer potato plants and to draw polygons around these 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 a volunteer potato plant. 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, 1979) 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.)

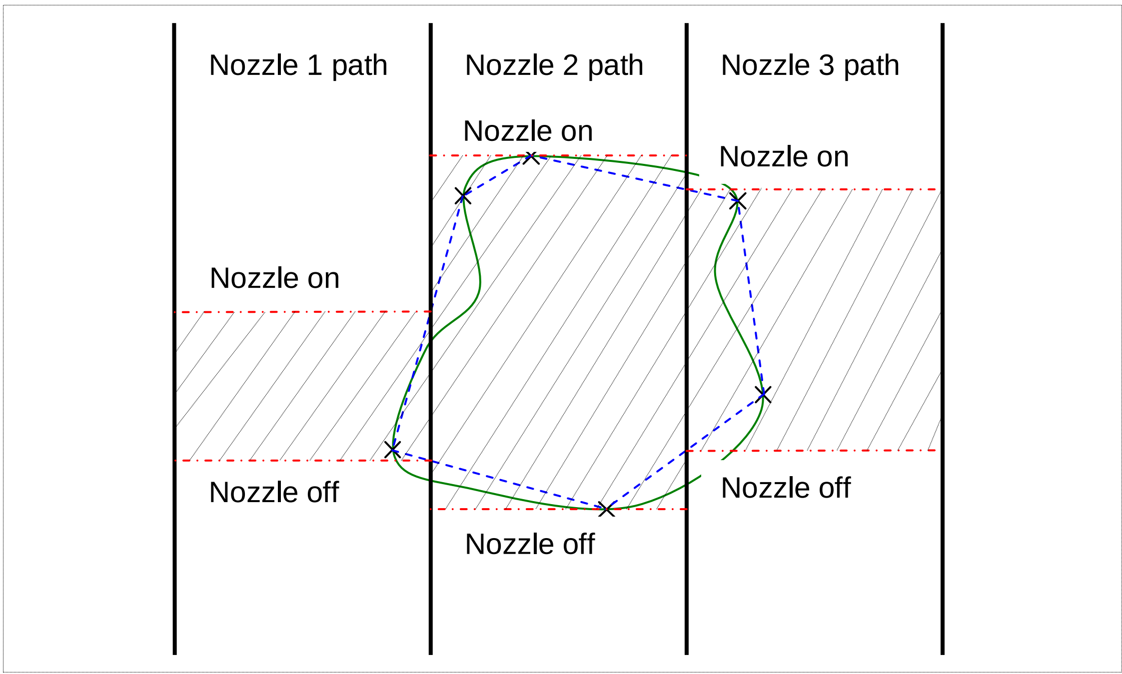

FIGURE 7. ILLUSTRATION OF HOW A POLYGON (BLUE DASHED) AROUND A VOLUNTEER POTATO PLANT (GREEN SOLID OUTLINE) TRANSLATES INTO A SPRAY MAP (DIAGONAL SHADING).

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, the percentage of the polygon covered by each nozzle is compared with a user defined figure for the minimum percentage of weed leaf area that should be targeted. If one or more nozzles can be left off completely whilst still maintaining adequate target coverage then they are left off. After that has been done the area treated by the remaining nozzles is to a first approximation eroded (by delaying switching on and advancing switching off in equal measure) until the target percentage area requirement is just satisfied. Whilst implemented in a relatively crude fashion at present this process is thought to help reduce off target contamination.

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. The complete package processing images from three cameras runs at frame rate (30 Hz) on the target hardware (Core Duo 2.16 GHz PC).

3.1.4. Performance of combined classification algorithms on stored image sequences

The following images have been chosen from a sequence to illustrate the strengths and weaknesses of the approaches implemented off line in the laboratory. Blue crosses represent raw observations of crop row location and green lines reflect the position of 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 a volunteer potato plant than either crop or soil.

3.1.4.1. In the carrot crop

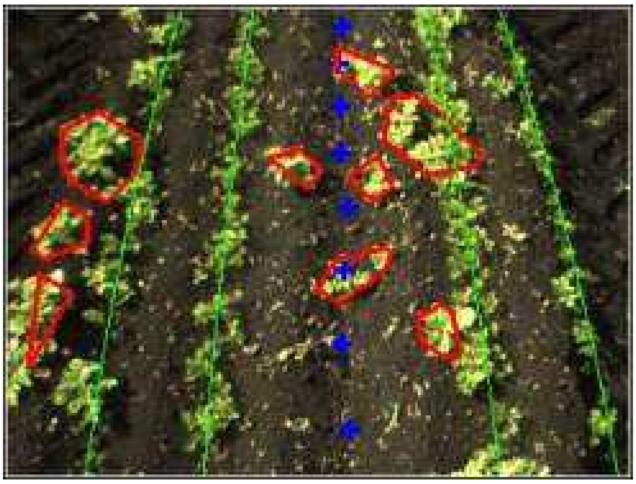

FIGURE 8. THIS EXAMPLE SHOWS HOW THE MAJORITY OF VOLUNTEER POTATO PLANTS ARE SUCCESSFULLY BOUNDED BY THE POLYGONS, BUT THAT SMALL WEEDS (NOT NECESSARILY POTATOES) AND SOME PARTS OF POTATOES WITHIN CROP ROWS ARE MISSED.

3.1.4.2. In the onion crop

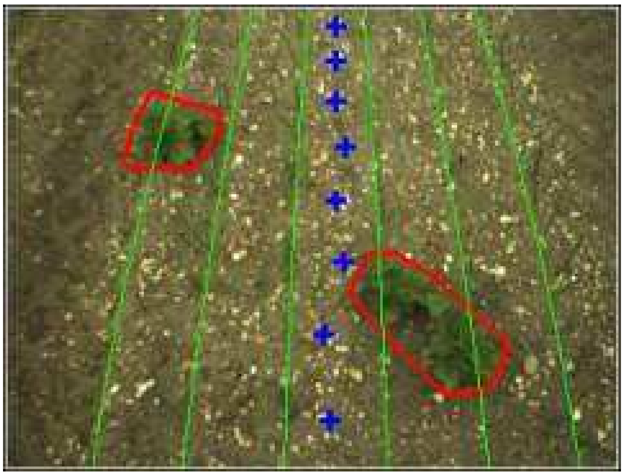

FIGURE 9. THE DETECTION OF WEED POTATOES AT THE EARLY STAGES OF ONION GROWTH IS RELATIVELY STRAIGHT FORWARD AS THERE IS A LARGE SIZE DIFFERENTIAL.

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.

3.2. Development/assessment of nozzles and application methods (Objective 2)

3.2.1. 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 a hand held 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^o spray angle: experiments with this nozzle design showed that it was not able to produce a spray when the liquid supply was pulsed for 0.03s.

b) A narrow angle (15^o) 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^o) “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 were conducted with a version of this nozzle that was provided for evaluation by Hypro EU Ltd had a flow rate and spray fan angle that were above that called for in the specification. Results from this preliminary work showed that the design 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.

3.2.2. 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 was 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 below.

3.2.3. Mechanical oscillating nozzle development

3.2.3.1. 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 in a process known as Raleigh breakup into 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 droplet sizes 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 due to the relatively low oscillation frequency and the high flow rates.

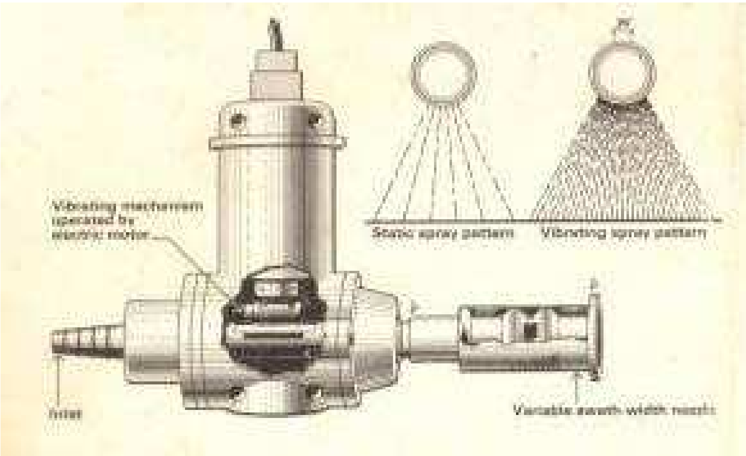

FIGURE 11. SCHEMATIC OF 1950’S “VIBRAJET”

FIGURE 12. THE “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 intention to develop 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 the fluidic and other nozzle technologies should the application demand the performance that could potentially be achieved by the oscillating nozzle.

3.2.3.2. 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 increased with the square root of pressure as expected.

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) gave a VMD of about 1.0 mm. From a coverage perspective it would be desirable to reduce VMD by reducing tube diameter and increasing pressure to maintain flow rate. However, practical issues of reliability due to contamination induced blockages dictate that 0.5 mm represents a minimum tube diameter unless special measures are taken to minimise the risk of contamination and blockage.

The design chosen for the experimental 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.

3.2.3.3. 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 at a forward speed of 1.4 m s^{-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 (Figure 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 geometry of the beam were then tuned such that the beam vibrated at close to, but below its natural frequency. An approximation to the natural frequency, ω, of the assembly is given by:

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

Where second moment of area $I = \frac{bd^3}{12}$

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 speaker systems.

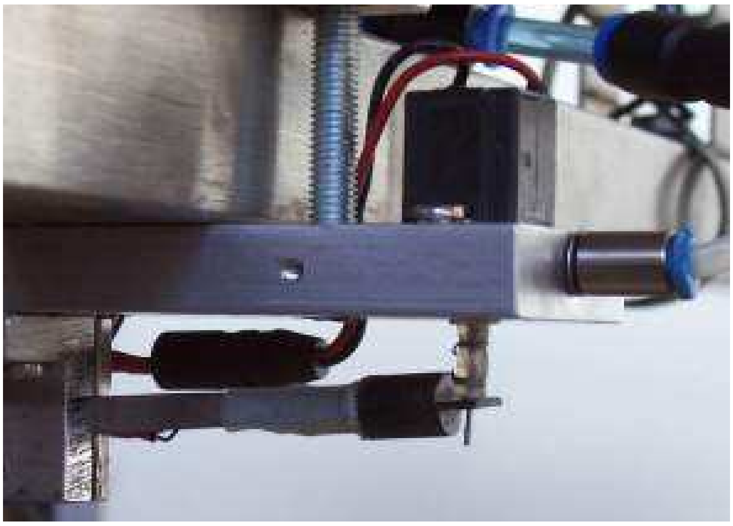

FIGURE 14. A COMPLETE MECHANICALLY DRIVEN OSCILLATING NOZZLE.

3.2.4. Evaluation of nozzle performance

3.2.4.1. 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 labelled, 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 Figures 15 a-c.

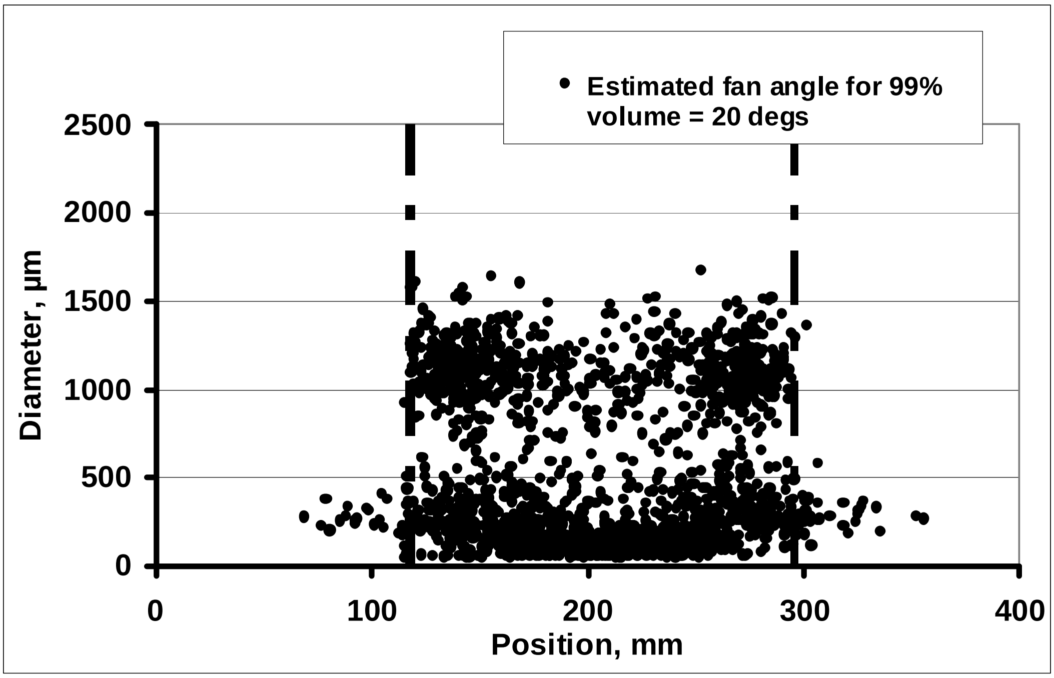

FIGURE 15A. MEASURED DROPLET SIZES WITH THE S4 FLUIDIC NOZZLE OPERATING AT A PRESSURE OF 0.75 BAR; MEASUREMENTS MADE 500 MM BELOW THE NOZZLE WHEN SPRAYING WATER ONLY.

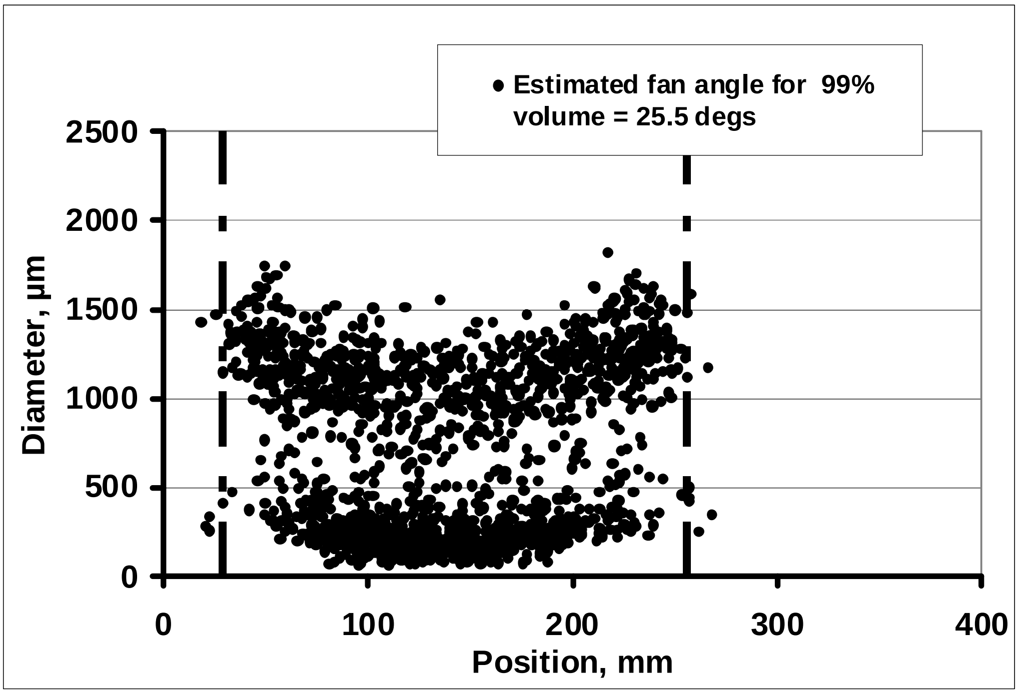

FIGURE 15B. MEASURED DROPLET SIZES WITH THE OSCILLATING NEEDLE NOZZLE FITTED WITH A 0.7 MM NEEDLE OPERATING AT A PRESSURE OF 0.50 BAR; MEASUREMENTS MADE 500 MM BELOW THE NOZZLE WHEN SPRAYING WATER ONLY.

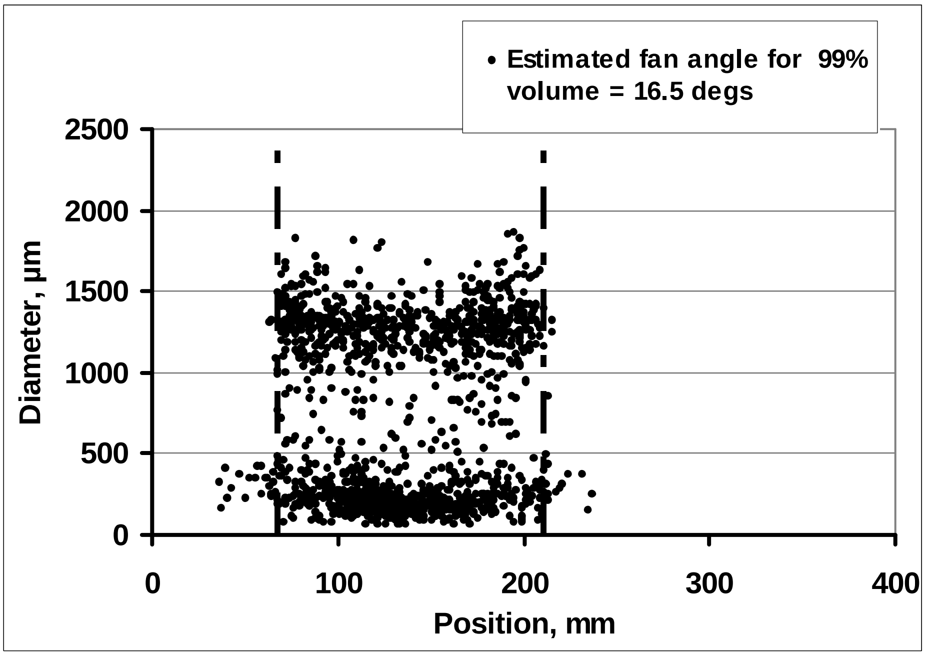

FIGURE 15C. MEASURED DROPLET SIZES WITH THE OSCILLATING NEEDLE NOZZLE FITTED WITH A 0.7 MM NEEDLE OPERATING AT A PRESSURE OF 2.00 BAR; MEASUREMENTS MADE 500 MM BELOW THE NOZZLE WHEN SPRAYING WATER ONLY.

Results of the performance assessment work with the different versions of the fluidic and oscillating needle nozzles are summarised in Figures 16a–e.

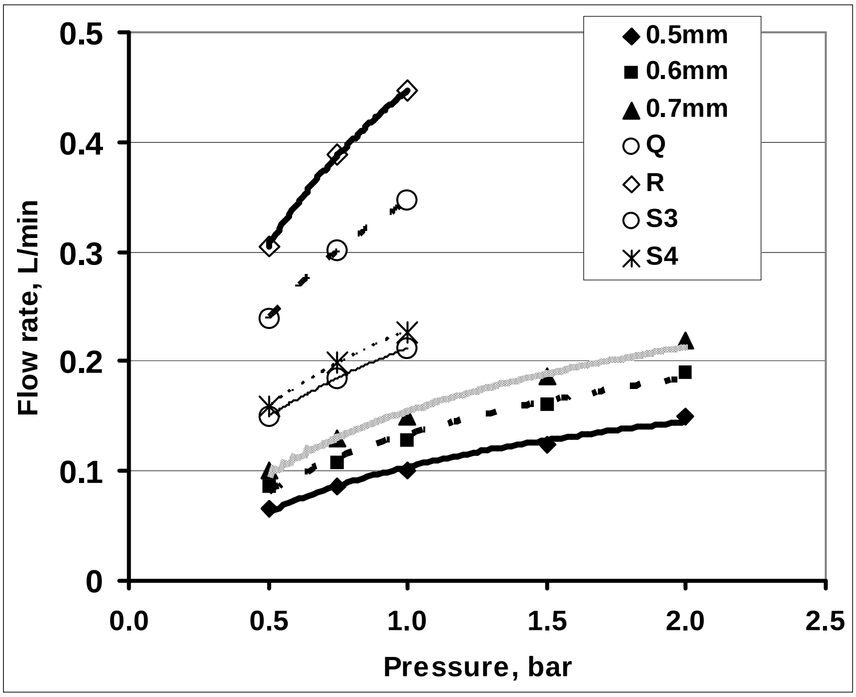

FIGURE 16A. LIQUID FLOW RATES FOR THE NOZZLE OPTIONS EVALUATED; OSCILLATING NEEDLE FITTED WITH 0.5, 0.6, 0.7 MM NEEDLES; FLUIDIC DESIGNS Q, R, S3, S4.

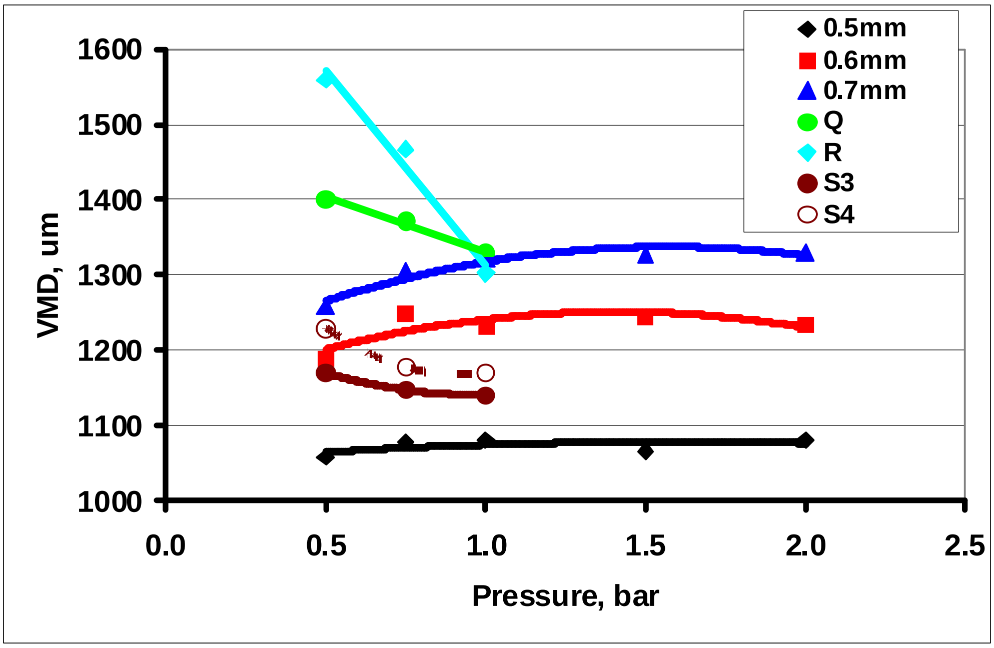

FIGURE 16B MEAN DROPLET SIZES AS VOLUME MEDIAN DIAMETER (VMD) FOR THE NOZZLE OPTIONS EVALUATED; OSCILLATING NEEDLE FITTED WITH 0.5, 0.6, 0.7 MM NEEDLES; FLUIDIC DESIGNS Q, R, S3, S4.

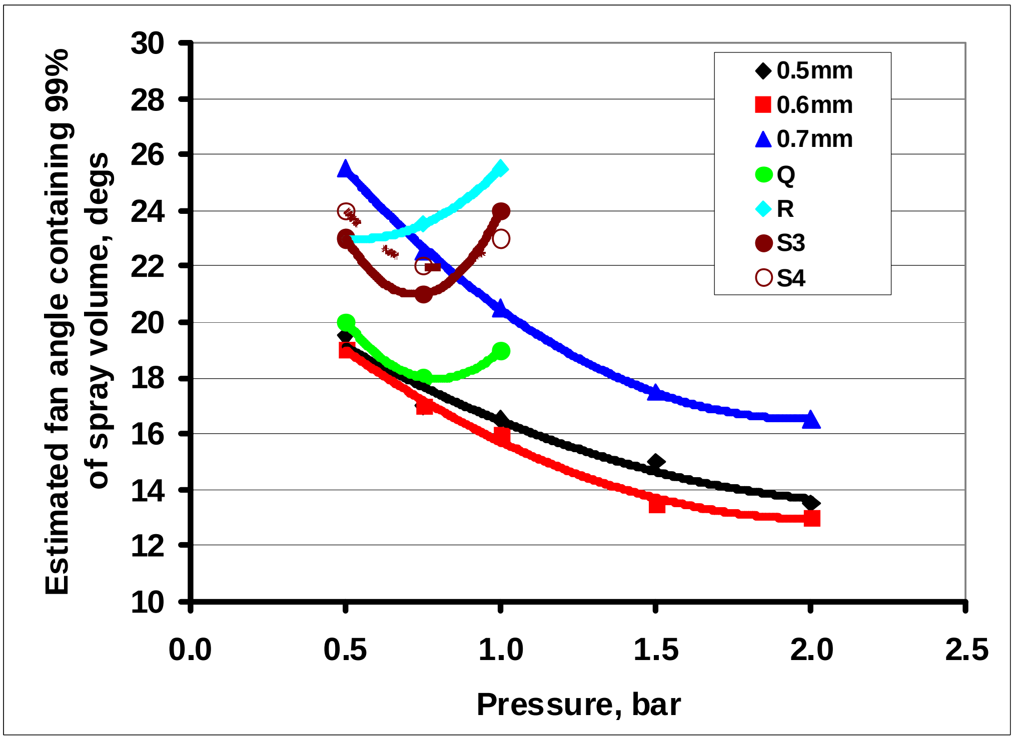

FIGURE 16C. ESTIMATED SPRAY FAN ANGLES FOR THE NOZZLE OPTIONS EVALUATED; OSCILLATING NEEDLE FITTED WITH 0.5, 0.6, 0.7 MM NEEDLES; FLUIDIC DESIGNS Q, R, S3, S4.

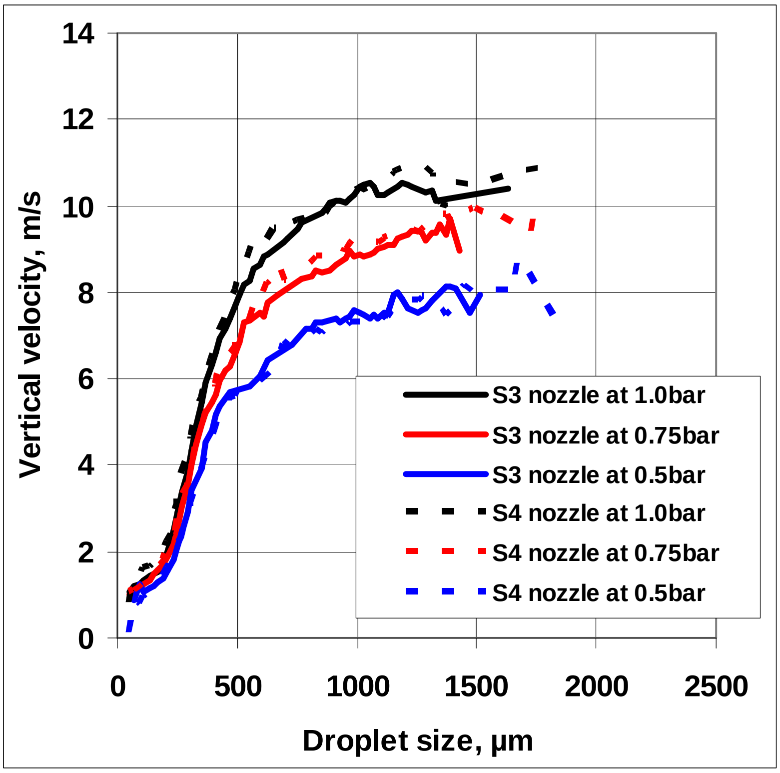

FIGURE 16D. DROPLET VELOCITIES FOR THE FLUIDIC NOZZLE DESIGNS Q, R, S3, AND S4.

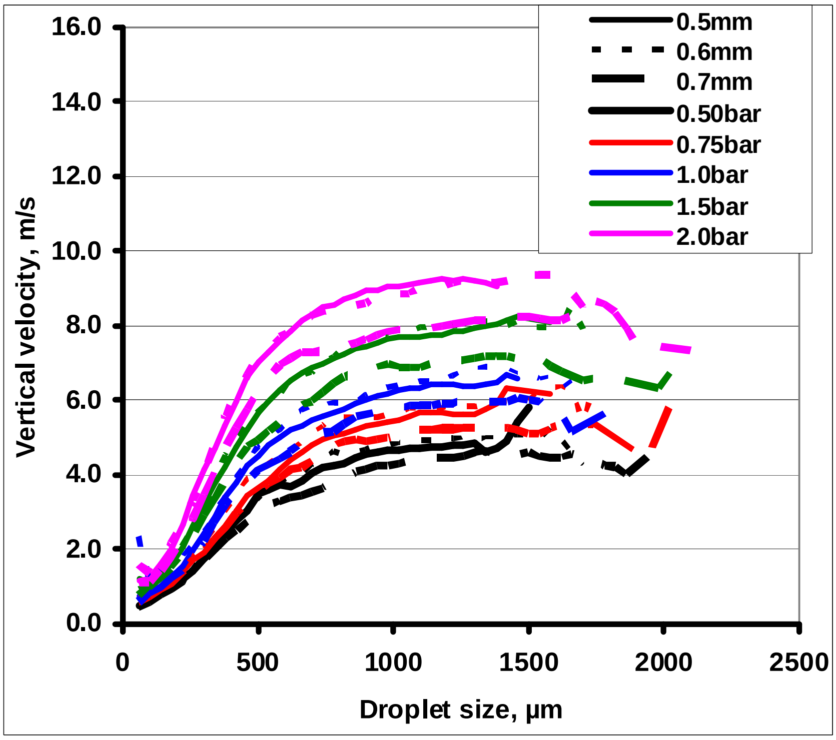

FIGURE 16E. DROPLET VELOCITIES FOR THE OSCILLATING NEEDLE NOZZLE FITTED WITH 0.5, 0.6, AND 0.7 MM NEEDLES.

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 17a) 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 later designs (S3 and S4), mean droplet sizes as defined by the volume median diameter (VMD) were still large and in the order of 1150 µm reducing slightly with increasing pressure as expected;

Spray fan angles when operating at a pressure of 0.75 bar were in the order of 20^{o} 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 17b) and 17c) 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.

3.2.4.2. 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.

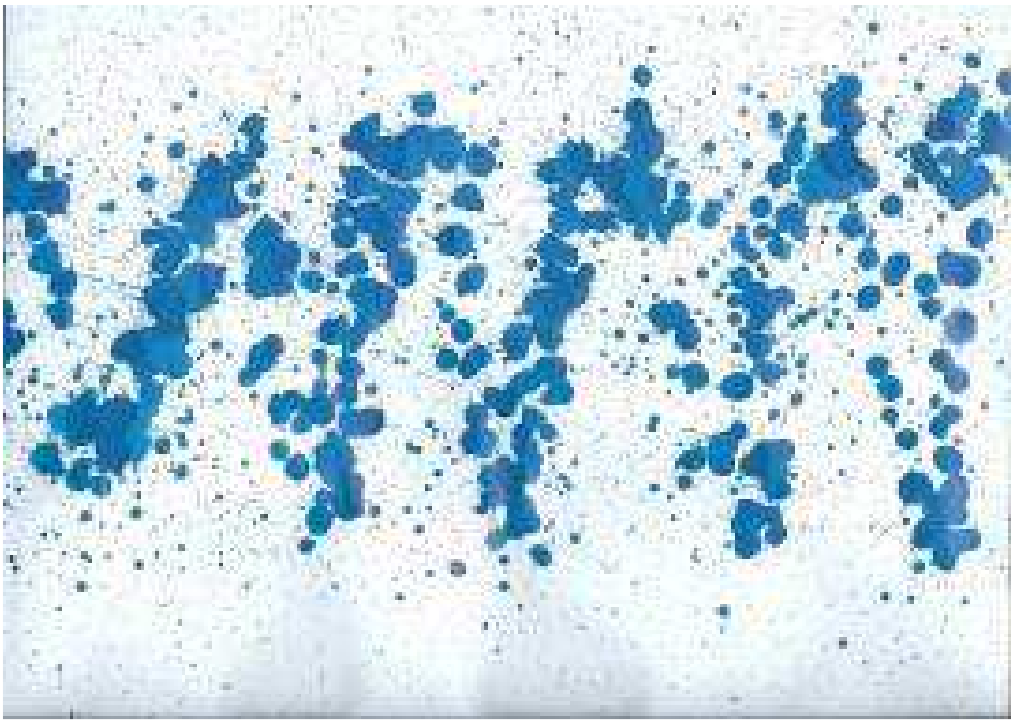

FIGURE17. PATTERN OBTAINED WITH THE R DESIGN OF FLUIDIC NOZZLE OPERATING AT A HEIGHT OF 0.5 M AND TRAVELLING AT A SPEED OF 2.1 M/S.

Given an application rate of 120 L/ha and a droplet VMD of approximately 1.0 mm we can expect the average ground area occupied by a single droplet to be in the order of 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.

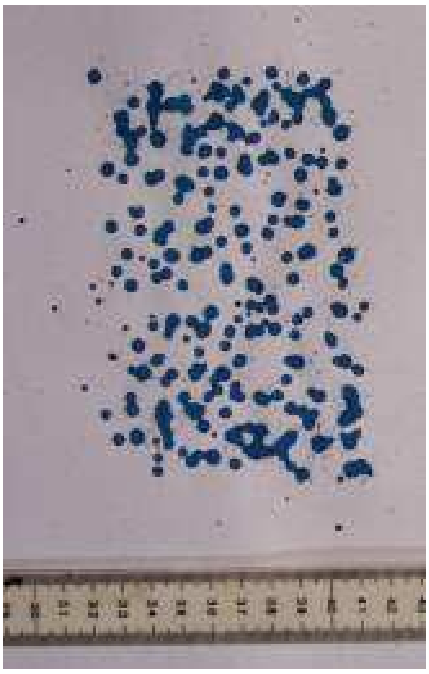

FIGURE 18. PATTERN ACHIEVED FROM A 60 MS PULSE OF A 0.5 MM DIAMETER OSCILLATING NEEDLE NOZZLE SUPPLIED WITH WATER (+DYE) AT 2.0 BAR RUNNING RIGHT TO LEFT AT A HEIGHT OF 0.5 M AND A SPEED OF 1.34 M/S.

3.2.4.3. Wind tunnel measurements of spray behaviour

Measurements were made of the spray deposition on a nominal 10.0 cm wide strip in the wind tunnel on the Silsoe site using a coloured tracer dye and collectors mounted immediately adjacent to the target area to determine the quantity of spray that was deposited outside the target area on a horizontal paper surface and airborne spray as collected on cylindrical passive collectors. Measurements were made in still air and in wind speeds of 2.0 and 3.0 m/s. These wind speeds represent values that are approximately double those at which crop spraying is acceptable since wind speeds were measured at the equivalent of the top of the crop and wind speed varies logarithmically with height above the ground. The results plotted in Figure 19 show that approximately 90% of the nozzle output from both nozzle designs was deposited within the target strip and that the effect of wind on the deposition pattern was negligible. There was no consistent relationship between upwind and downwind deposits for either nozzle system and differences between the two nozzle systems were also small. Most (>90%) of the off-target spray was measured on the horizontal surfaces close to the edge of the treated area with very low volumes of airborne spray as expected from the droplet size distribution data. It was concluded that the operation and performance of the nozzles was very unlikely to be influenced by wind although splash of chemical from treated volunteer potato plants could lead to some contamination of adjacent crop plants.

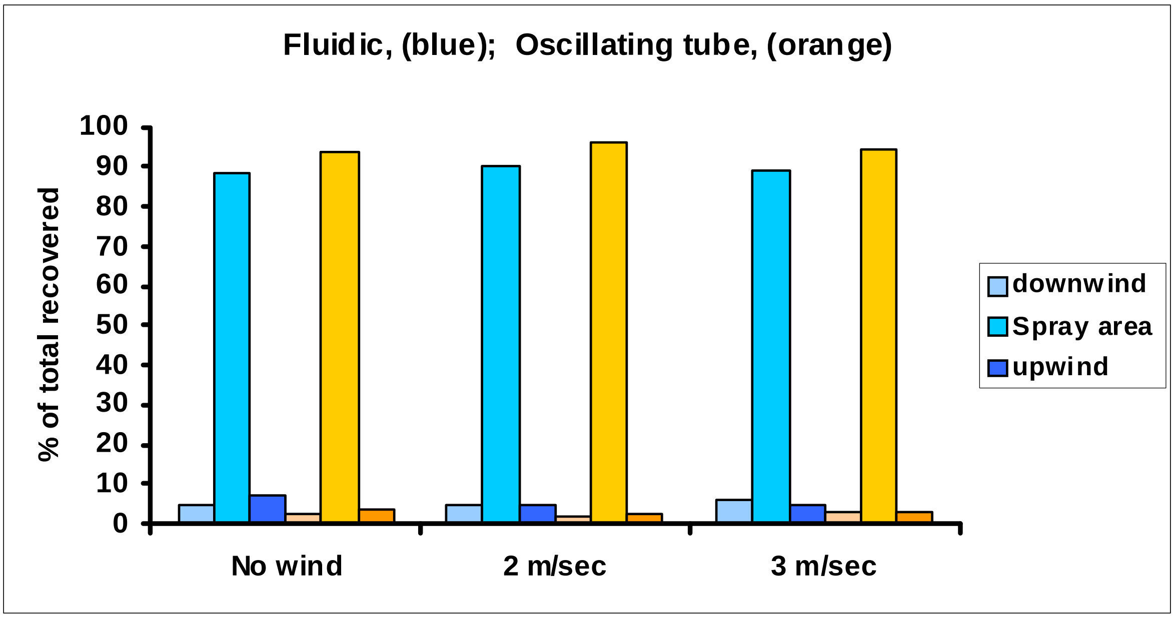

FIGURE 19. SPRAY DEPOSITS WITH AND IMMEDIATELY OUTSIDE A 10.0 CM WIDE TARGET STRIP SPRAYED IN A WIND TUNNEL WITH DIFFERENT WIND SPEEDS.

3.2.4.4. 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 non-selective herbicides to detected volunteer potatoes, and that both designs would be taken forward for further evaluation in both field and laboratory trials during 2008. 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 designs.

3.3. Agronomic assessment of candidate treatments (Objective 3)

3.3.1. 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 25^{o} flat fan “evenspray” nozzle of an “01” size operating at 2.0 bar pressure, 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 mm^2 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 20) 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 the concentrations used for wiper applications.

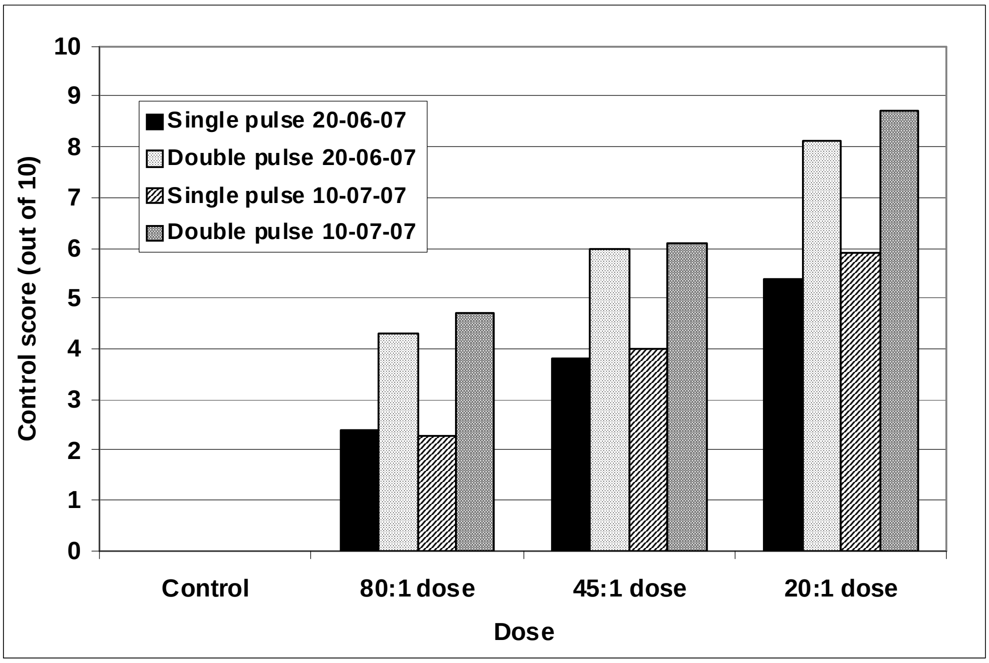

FIGURE 20. RESULTS OF EXPERIMENTS CONDUCTED IN AN ESTABLISHED POTATO CROP TREATED WITH PULSES OF GLYPHOSATE SPRAY AT DIFFERENT CONCENTRATIONS.

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 ("01" and "015") of 25^{o} "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 all plots. The potential damage to the crop was also determined by visual inspection and was generally low – see Figure 21. 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. The results also confirmed observations reported in the literature and seen in the earlier study (Miller & Tillett, 2006) that indicated that each stem of a potato plant needed to be hit by the spray if good control was going to be consistently achieved (Lutman and Richardson, 1978; Lutman, 1979 (a)&(b); Coupland and Lutman, 1982).

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

 

FIGURE 21. VOLUNTEER POTATOES IN A CARROT CROP 9 DAT WITH A HAND-HELD PULSED NOZZLE.

3.4. Development of rapid switching control technologies (Objective 4)

The ability to hit relatively small volunteer potato plants from a relatively fast moving implement requires switching on and off to be both rapid and deterministic. For example, a nozzle passing over a volunteer potato plant 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 appropriate valves. 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 actuating coils having a low electrical current consumption.

One way of reducing the electrical load further is to employ latching solenoid valves sometimes known as bi-stable valves. In these devices permanent magnets and springs 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 relatively symmetrical between switching on and off. A number of valves were considered with one type selected that best matched the detailed requirements for this application, though alternatives would probably be available from other manufacturers. The selected device, a bi-stable pulse controlled valve from A K Muller (Figure 22) has been primarily designed as a pilot valve but is also suitable for controlling small flows directly. The plastic of which the valve is manufactured and the seals it uses are likely to be suitable for operation with glyphosate solutions in water, but may not be suitable for all agrochemicals. The manufacturer may be willing use other materials by negotiation. The valve as used 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 22. A 1.8 W LATCHING BI-STABLE VALVE SELECTED TO CONTROL SPOT SPRAY NOZZLES.

3.5. 2008 Plot scale experimental system (Objectives 5, 6 and 7)

3.5.1. Design and construction of experimental tool frame

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

The spray nozzles were fitted on a side shifting frame so that lateral position of nozzles relative to crop rows could be maintained. This side shifting sub-frame was 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 23. THE TOOL FRAME TRACTOR USED AS A PLATFORM FOR THE 2008 TRIAL.

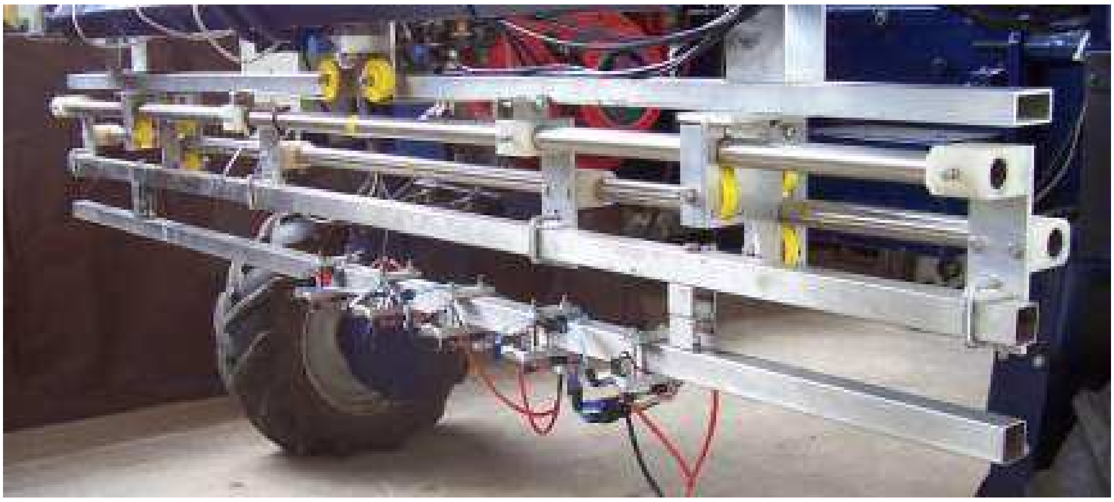

FIGURE 24. SIDE SHIFTING SPRAY BAR WITH FIVE NOZZLES FITTED.

3.5.2. Design and construction of computing systems

In order to conduct field trials it was necessary to design and construct circuits to control the bi-stable solenoid valves, the vibration motors, and the side shifting electric motor. It was also necessary to be able to read the side shift position potentiometer. It was 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 a main computer (a Core Duo 2.16 GHz PC).

The resulting device pictured in Figure 25, was designed with 16 channels of bi-stable solenoid valve and vibration motor outputs. Communication between the microprocessor (a Silicon Labs C8051F341) and the main computer was via a RS232 serial interface synchronized with image acquisition at 30 Hz. The board was supplied with 12 v from the tractor battery and generated the +/- 6 v for the bi-stable valves, and the voltages required to operate vibration and side shift motors using pulse width modulation (PWM) techniques.

FIGURE 25. THE MICROCONTROLLER SPRAYER BOARD - CUSTOM DESIGNED AND BUILT FOR THIS PROJECT.

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

The Core Duo PC was installed in a cabinet mounted over one of the drive wheels. Also in this cabinet were the power supply and other custom electronics relating to vehicle control. A VGA display was mounted so as to be visible to the driver. A Robydome camera was connected to the PC via an IEEE1394 interface and mounted viewing forward and down from the spray bar. The PC also connected to the custom designed microcontroller described in Section 2.4 via an RS 232 serial interface.

3.5.3. Demonstration and evaluation of the experimental system

3.5.3.1. In onion crops

The first series of field trials conducted on 19 May 2008 involved two treatment areas - one in which detailed observations and records were made of both the kill of volunteer potatoes and damage to the onions and a larger area where the total population of volunteer potatoes before and after treatment were recorded. The crop comprised 8 rows on a 1.8 m wide bed and therefore required 17 nozzles to cover a bed in a single pass – one nozzle above each row and one nozzle above each inter-row gap. Nine nozzles were fitted to the boom on the experimental vehicle to cover one half of the bed, four fluidic nozzles and five vibrating jet nozzles in two banks with each nozzle treating a strip approximately 9.0 cm wide when actuated. Each bed was therefore treated in two passes travelling in opposite directions at a nominal speed of 3.6 km/h. Nozzles were supplied with a spray liquid at a pressure of 1.5 bar at the nozzle and two concentrations of glyphosate were used (containing 17.1 and 60 g/L glyphosate) with no other additives. The weed detection algorithm was set to spray 100% of the detected target area and this meant that, given the nozzle configuration, some over-spraying of the crop was inevitable.

Results in the area monitored in greater detail were obtained by marking individual volunteer potatoes and some clumps of annual meadow grass with coloured sticks and then making observations at 9, 12 and 35 days after treatment. On each monitoring occasion, the levels of weed control and crop damage were noted and recorded photographically. At 12 DAT, detailed measurements were made of the nearest surviving onion plant to a treated weed and the distance from the weed to the furthest onion plant showing signs of damage. In the larger plots, overall counts of volunteer potatoes surviving 9 DAT were counted together with those that were judged to have merged since the application of the treatment.

Good control of volunteer potatoes was achieved in all the treatment conditions (Figure 26) and there was also good control of the annual meadow grass (Figure 27). There was evidence of damage to onion plants particularly where these had been growing close to treated weeds. In the crop areas monitored in detail, the mean distance from the centre of a treated weed to a damaged onion plant was 19.4 cm (S.D. = 7.8 cm) for the nearest to the weed and 27.4 cm (SD = 10.3 cm) for the furthest away. The results from the larger scale observations made over beds 340 m long are summarized in Table 1.

There was some evidence of a higher level of kill when using the higher dose of chemical although the bed treated with the higher dose rate also had a higher initial population of volunteer potatoes. It should be noted that the area treated with chemical was less than 2% of the field area and that chemical use was therefore much less than 5% of the maximum field rate for an overall treatment. The continued emergence of volunteers following treatment suggests that there may be a need for multiple treatments in a season so as to achieve high levels of control.

FIGURE 26. CENTRAL TWO BEDS OF ONIONS WHERE EXPERIMENTAL TREATMENTS WERE APPLIED – BEDS TO THE RIGHT OF CENTRE WERE UNTREATED.

FIGURE 27. MARKED GRASS WEEDS AT THE TIME OF TREATMENT (LEFT) AND 12 DAT (RIGHT).

	Bed 1	Bed 2
Pre-treatment volunteer potato population	0.56 plants/m	0.95 plants/m
Glyphosate concentration applied	17.1 g/L	60.0 g/L
Overall control achieved	91.4 %	97.8 %
New emergence post treatment compared with original population	16.2 %	15.2 %

TABLE 1 SUMMARY OF RESULTS FROM INITIAL TRIALS IN ONION CROPS CONDUCTED IN THE 2008 SEASON, ASSESSED 9 DAT

A second series of experiments was conducted in the same crop on 9 June 2008 when both crop and weed plants were larger. The same machine configuration as used as for the initial trials applying glyphosate at 60 g/L but the spray algorithm was changed so that only 75% of the detected weed area was sprayed. This was achieved by modifying the on/off timings so that the changes to the dimensions of the sprayed area were in only the direction of travel. This change was made to reduce the over-spray and damage to the crop. Detailed measurements of performance of this second series of experiments were not made but observations showed that the level of crop damage was reduced while the level of control of volunteer potatoes had been maintained at a high level – see Figure 28.

FIGURE 28. EXAMPLES OF VOLUNTEER POTATOES AT 10 DAT FOLLOWING APPLICATIONS ON 9TH JUNE 2008 SHOWING THE EXTENT OF CROP DAMAGE AND WEED KILL.

3.6. 2009 Field scale experimental system (Objectives 5, 6 and 7)

3.6.1. Design and construction of a guided tool frame spanning three beds

In order to assess the spot spray technology under commercial conditions a new tractor mounted tool frame spanning three 1.8 m beds was specially designed and constructed by project partners Garford Farm Machinery. It was based on their front mounted self steering inter-row cultivator design (Figure 29) in which the implement is free to slide laterally with respect to the tractor. For the application in this project work it is important that spray nozzles are held in a stable manner at a relatively constant height so that the spray pattern on the ground remains in alignment with crop rows. It is also useful if the camera can remain a fixed height above the bed. This can be difficult to achieve under field conditions particularly in wet years when wheeling depth can be highly variable. To solve this problem, an automatic frame levelling system was implemented. The frame was supported by four wheels with the depth of each being controlled by hydraulic cylinders. The inner wheels were hydraulically steered and equipped with central flanges to improve grip. The outer two were allowed to castor so as not to oppose lateral movement. Load was shared between pairs of inner and outer depth control wheels by connecting their depth control cylinders hydraulically. Frame height relative to the bed surface was monitored by two lightweight narrow wheels positioned over each of the outer beds. As the wheels moved up and down relative to the bed they triggered proximity sensors that, via a microcontroller, caused a hydraulic valve to be actuated metering oil into or out of the pair of depth control cylinders on the appropriate side. These sensing wheels were also fitted with encoders to provide an accurate measure of forward motion.

FIGURE 29. THREE SECTION EXPERIMENTAL SPOT SPRAYER BASED ON A GARFORD CULTIVATOR TOOL FRAME.

Three cameras were fitted, one centrally over each bed at a height of 2.0 m looking forward an down at an angle of approximately 35° to the vertical. This provided a field of view covering the full bed width and a distance of approximately 2.5 m in the direction of travel.

The machine was equipped with three spray bars each consisting of a 2 m long extruded aluminium section with mounting faces on all four sides. This allowed mounting brackets, electronic boxes and hoses to be conveniently mounted on the bar whilst allowing unrestricted lateral adjustment of nozzles mounted along the forward face. A revised design of fluidic nozzle by project partners Hypro EU Ltd's was chosen in preference to the oscillating needle due to its relative simplicity and the ability to manufacture them in sufficient quantities for fitting to the experimental unit. This nozzle was specifically designed to interface with the latching solenoid valves used in the 2008 trials and is illustrated in Figure 30. The nozzle fan angle was 13° which when mounted 400 mm above the bed gave a 90 mm wide spray pattern on the ground. Flow rate per nozzle was 0.17 l/min at 1.0 bar.

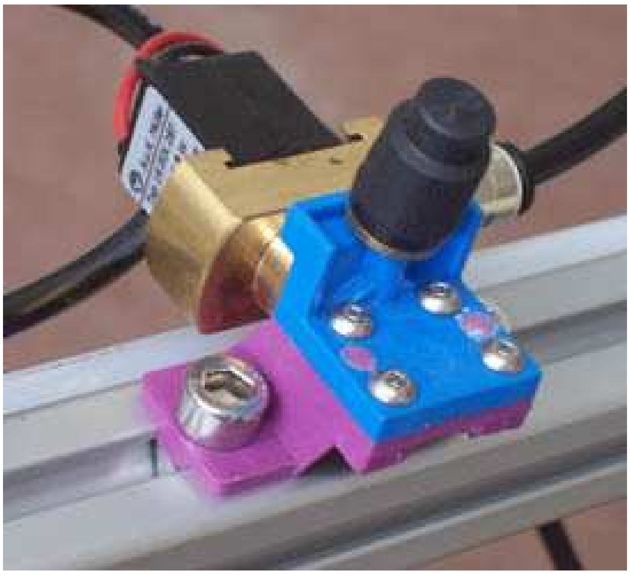

FIGURE 30. EXPERIMENTAL FLUIDIC NOZZLE DESIGNED AND MANUFACTURED BY HYPRO EU LTD TO INTERFACE WITH THE LATCHING SOLENOID IDENTIFIED IN SECTION 2.4.

3.6.2. Design and construction of a computing system handling three sections

A custom design computing system was devised as shown in Figure 31. Each spray bar was controlled by its own microcontroller capable of switching up to 20 nozzles. Each nozzle microcontroller communicated with a master microcontroller via a CAN bus. This meant that there were only three connectors to individual spray bars, two electrical (CAN and power) and one for herbicide. This made the spray bar system modular and flexible.

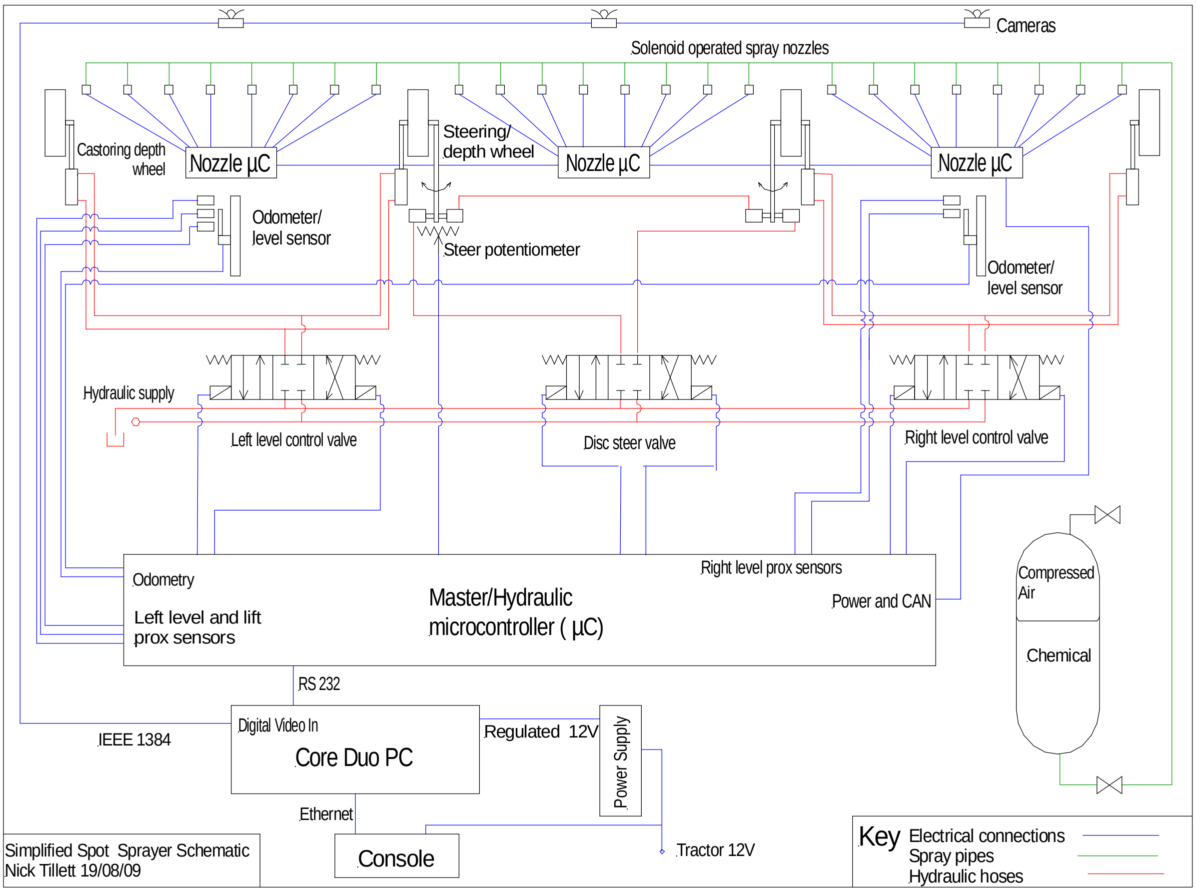

FIGURE 31. SIMPLIFIED SCHEMATIC OF 2009 EXPERIMENTAL CONTROL SYSTEM.

In addition to passing nozzle control instructions to the boom microcontrollers, the master microcontroller performed general tool frame control functions including steering and levelling. The master microcontroller was mounted on the implement in a control cabinet that also housed a Core Duo PC with associated power supply as illustrated in Figure 32. The Core Duo PC provided the main computing power required analyse images from all three cameras (at 30 Hz), track weeds and send instructions to the master microcontroller (via RS232). The computer algorithms were based on those described in Section 2.1, but significant additional code was required to run three sections and control the implement.

In order to reduce the computing load on the main PC and to provide a convenient user, interface a second PC, packaged as a console with a screen, was networked (via Ethernet) with the Core Duo PC and mounted in the tractor cab. This console acted as a terminal providing the operator with a means of monitoring performance and adjusting settings. In normal working mode the display includes live images from all three cameras as thumbnails and allows the user to select one for a larger view in which the outlines of weed targets were visible.

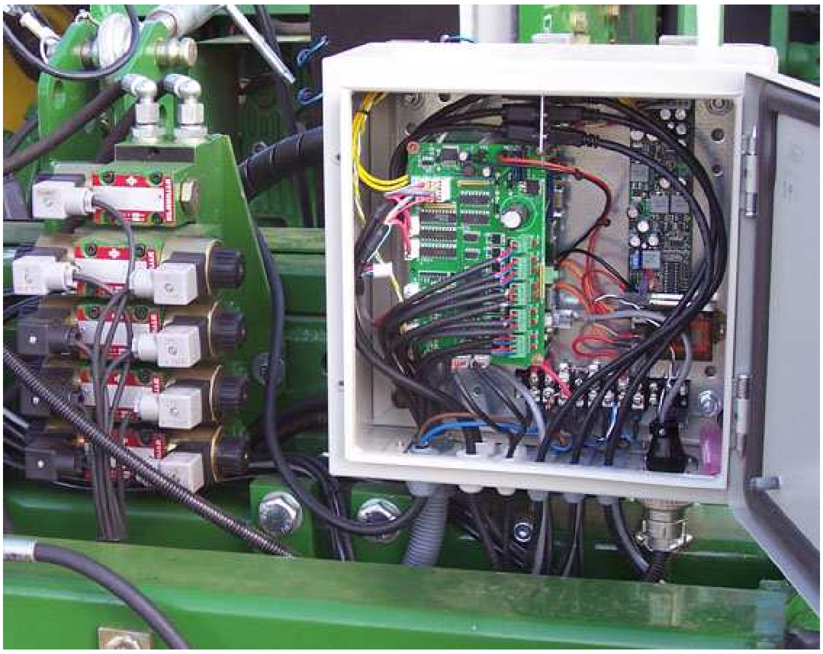

FIGURE 32. MAIN CONTROL CABINET CONTAINING THE MASTER MICROCONTROLLER (TO THE LEFT) WITH THE CORE DUO PC STACKED BEHIND (NOT VISIBLE) AND THE POWER SUPPLY BOARD TO THE RIGHT.

3.6.3. Field scale experimental evaluation

The high work rate (5.5 m working width at 4 to 5 kph) of the new experimental rig enabled commercial crops to be treated on a field scale and the long term practicality of the technology assessed in a field environment. The full-scale rig was operated in three crops onions (F.B. Parrish, Chicksands) in late May, Parsnips (Chennels, Newark) in early June and carrots (Chennels, Newark) in mid June. A 20:1 glyphosate mix was used for all of the trials reported here and the machine programmed to spray 50% of leaf area for each individual weed. Efficacy was measured as an overall weed potato count before and approximately 2 weeks after treatment. No detailed measurements were made of crop damage, but photographic records were kept particularly of crop plants close to treated volunteer potatoes. These crop plants were marked and were sampled at between one month and six weeks post treatment to assess the risk of such crop plants being accepted into the output crop and the glyphosate residue levels that might be associated with such crop plants.

3.6.3.1. In the onion crop

3 beds of crop 200 m long were treated with the full-scale rig travelling at a nominal speed of 3.0 km/h on 21st June 2009 and a 15 m length of each bed was marked for detail study. Plant counts at the time of treatment and at 5 and 11 DAT were made and the results are summarised in Table 2.

	Bed 1	Bed 2	Bed 3
Initial plant count	49	34	45
At 5 DAT			
Assessed as missed	4	1	3
Plants assessed as emerged since treatment	1	4	0
At 11 DAT			
Assessed as missed	4	0	3
Assessed as partial kill	1	2	4
Plants assessed as emerged since treatment	2	3	8

TABLE 2 - PLANT COUNTS IN 15 M PLOTS IN THE ONION CROP TREATED AT A SPEED OF 3.0 KM/H

Beds were also treated when travelling at speeds of 2.0, 3.0 and 4.0 km/h and the results are summarised in Table 3. There were differences in the plant populations in the treated beds but no evidence of a consistent trend with increasing forward speed of the unit over the range 2.0 to 4.0 km/h. All of the plants that remained post treatment in all beds were small at the time of treatment and this is consistent with both the detection and treatment algorithm settings used in the trials.

	Forward speed, km/h		
	2.0	**3.0**	**4.0**
Initial plant count, plants/100 m of bed	85.3	153.5	83.8
Plant populations at 5 DAT including newly emerged plants.	17.7	17.7	13.3
Control, %	79.2	88.5	84.1

TABLE 3 - THE EFFECT OF FORWARD SPEED ON THE FIELD PERFORMANCE OF THE UNIT IN ONIONS

Crop plants that were assessed as possibly showing damage due to glyphosate damage 11 DAT and that had been marked in the field at this time were re-assessed on 13 July 2010 to determine the probability of such plants being part of the harvested crop. Of 62 marked plants in beds treated when travelling at 3.0 km/h, 16 (25.8%) were completely dead, 41 (66.1%) had survived but had not produced an onion bulb that was of a size that would be included in the harvested crop and 5 (8.1%) were of a size that could have been harvested with the crop plants – see Figure 33.

FIGURE 33 SAMPLES OF CROP PLANTS CLOSE TO TREATED VOLUNTEER POTATOES AND THAT WERE LIKELY TO BE HARVESTED WITH THE CROP (LEFT) OR REJECTED (RIGHT).

Samples of these bulbs were bagged, weighed and frozen prior to being taken for chemical analysis to determine the magnitude of any glyphosate residues that could be in the bulbs.

Some preliminary observations were also made in which a mixture of fluroxypyr (as Starane) and ioxynil (as Totril) were applied at the rate of 500 ml of each product per hectare – this rate being the equivalent to that used as an overall spray. The advantages of using this tank mix while it has maintained recommended uses in the onion crop is that there are no specific residue concerns relating to the chemical use and method of application. Results from the preliminary observations were that the machine could deliver this type of formulation and relatively high levels of control of volunteer potatoes were achieved although no detailed assessments were made. However, it was noted that after some 1 1/2 hours of operation with this tank mix, some of the nozzle/valve combinations stopped working correctly – a situation that had not been encountered when spraying the true solutions of glyphosate. Further work is required to examine the reasons for this failure and to define the conditions for satisfactory operation with this type of spray liquid.

3.6.3.2. In carrots

A crop of carrots (cv. Nairobi) was treated on 16 June 2010 with the machine travelling at a nominal speed of 4.0 km/h. The crop was at the 3-4 true leaf stage (GS 13-14; a few crop plants with the 3rd true leaves unfolded but with most at the 4th true leaf unfolded stage, BBCH Growth Stage Scale for Carrots). Initial plant counts of volunteer potato populations across a 55 m length of 3 beds gave an average value of 117.7 plants/100 m of bed. Assessments of the treated crop on 26th June showed of plants that would have been large enough to be treated, the population had been reduced to a mean value of 2.4 plants/100 m of bed although there were some plants that were assessed as having emerged post the treatment. Volunteer potato control was observed to be very good and there was little evidence of collateral damage to the carrot crop. A small number of carrot plants had been killed by the glyphosate application and a very few exhibited signs of glyphosate damage – chlorosis, narrowed distorted leaves, severe stunting and small roots.

Carrot plants close to volunteer potatoes and that were showing signs of being contaminated at the time of treatment were again identified on 26th June and were sampled on the 10th July (24 DAT) as the crop approached harvestable size at the bunching stage. In this crop, the crop that was contaminated and survived was severely stunted and produced only small roots 0.5 to 0.8 cm in diameter and 4.0 to 7.0 cm long that were unlikely to be harvested with the crop – see Figure 34. Normal un-contaminated roots in this crop were 2.0–2.5 cm diameter, 170–190 cm long with leaves 43–48 cm tall. Samples of contaminated roots were again taken for residue analysis.

FIGURE 34 AN EXAMPLE OF A CONTAMINATED AND UNCONTAMINATED CARROT PLANT AT 24 DAT.

3.6.3.3. In parsnips

Volunteer potatoes growing in a crop of parsnips (cv. Javelin) were treated on the 5th June 2009 using the full scale rig operating at a nominal speed of 4.0 km/h. The volunteer potato plants were small and the crop was at the 2-4 true-leaf stage (GS 12–14; a few 2nd or 4th true leaves unfolded but most were at the 3rd true leaf unfolded stage, BBCH Growth Stage Key) and the roots had not began to expand. Assessments of the level of volunteer potato control were made on18th June (13 DAT) by counting plants in a randomly selected 50 m length of bed and the results summarised in Table 4. Given that some completely dead plants may not have been visible at the time of this assessment control was estimated to be greater than 85%.

Volunteer potato plant counts	Plants not showing signs of glyphosate damage (including those that would have emerged post treatment)	Plants showing glyphosate damage but not completely dead	Plants that were completely dead
Bed 1	15	16	25
Bed 2	13	25	39
Bed 3	41	64	137
Totals	**69**	**105**	**201**

TABLE 4. VOLUNTEER POTATOES COUNTS ASSESSED AT 13 DAT IN A PARSNIP CROP.

The crop was again assessed on 26th June when it was noted that the level of collateral damage to the parsnip crop was small (less than in the carrot crop) with only a few plants exhibiting the typical signs of glyphosate damage – chlorosis, narrowed distorted leaves and severe stunting. Those plants close to treated potatoes and showing symptoms of glyphosate damage were marked and were hand-harvested on 13th July (25 DAT) when the crop was at the "baby" stage. All of the marked plants had survived but the foliage was severely stunted. The greatest effect was on the roots which were in the range of only 0.5 to 1.0 cm in diameter and 13–20 cm long compared with the normal crop that had roots mainly around 4.0 cm in diameter with some down to 2.5 cm diameter and were 134–137 cm long – see Figure 35. The affected plants produced roots that were assessed as being unmarketable and that would have fallen through the webs of harvesting machinery. The foliage of the affected plants was also much shorter than that of the main crop. Samples of contaminated crop were again taken for residue analysis.

FIGURE 35. EXAMPLES OF CONTAMINATED AND UNCONTAMINATED PARSNIP PLANTS AT 25 DAT.

It was concluded that the field performance of the full-scale rig was consistent with expectations and was judged as very satisfactory by the growers that hosted the performance evaluation assessments. Treated field areas assessed visually showed high levels of control from a single pass of the machine with low levels of crop damage and any surviving volunteer potatoes being small plants at the time of treatment. In crops where volunteer potatoes were likely to continue to emerge over extended time periods, two passes of the machine may be necessary in a given growing season. It was also noted that the glyphosate use in the field trials was always less than 5% of that corresponding to the whole field application of the chemical (recognising that such an application would not be appropriate) with important implications for ground water contamination, run-off and contamination of non-target areas.

An important feature of the designed system is that the performance will be very much less sensitive than that of a standard spraying system to the effects of wind. The wind tunnel studies reported in Section 2.2.4 above showed that at wind speeds of more than double those recommended for conventional crop spraying, the effect on the targeting of the spray were negligible. This has important implications for the width of the operating window for the system developed within the project.

4. CONCLUSIONS

The overall objective of the project to develop and evaluate a system for controlling volunteer potatoes in carrot and onion crops based on detecting the weeds and treating them with a non-selective herbicide was fully achieved. This had components relating to the following aspects.

The use of cameras mounted over each crop bed to collect images that were then analysed to identify the positions of crop rows and of volunteer potatoes with respect to the crop rows: this discrimination used the combination of a number of factors including plant position in relation to the crop row and the size of the plant.

The development and evaluation of two potential nozzle designs capable of treating areas down to 75 mm by 75 mm (or smaller) with a sharp cut-off in the volume distribution pattern both the direction of travel and at right angles to the direction of travel: one design used an oscillating tube while the other used fluidic principles within the nozzle body to oscillate a fine stream of liquid leaving the nozzle. Both designs were shown to meet the specification while generating very large droplets (circa 1.0 mm in diameter) that were very resistant to the effects of wind drift.

The interfacing of the nozzle designs with a latching solenoid unit to give a rapid system response and relatively low electrical power consumption.
The integration of all the machine components and the development of a control system for undertaking the control of the tool frame, analysis of images to determine row and volunteer potato positions, to implement the control strategy and actuate the nozzles and to provide an interface for the operator.

The definition of target requirements to control volunteer potatoes with pulses of spray of a total herbicide.

The evaluation of the complete system under a range of conditions in crops of onion, carrot and parsnip. Results from this work showed that the system could achieve levels of control well in excess of 90% for large volunteer potatoes and with low levels of crop damage. Performance in terms of control, crop damage and work rate was judged to be commercially acceptable by the host farmers and other technical representatives associated with the work.

Work by the commercial partners in the project has continued after the formal completion of the work to develop units that could be made commercially available.

5. TECHNOLOGY TRANSFER

HDC Technical Seminar and field walk, Kirton, 3rd July 2007 (Presentation).

HDC carrot field day, Bawtry, South Yorkshire, 4th October 2007 (Poster).

AAB Meeting, Wellesbourne, 13th November 2007 (Presentation).

Horticulture LINK event, London, 28th November 2007 (Poster).

Carrot and Onion Conference, Peterborough, 21st-22nd December 2007 (Poster and presentation).

HDC precision technology event, Spalding, 26th March 2008, (Presentation).

HDC/BCGA Technical Seminar, Stockbridge Technology Centre, 19th March 2009 (Presentation).

Demonstration and presentation to invited interested parties, Chicksands, Beds. 29th May 2009.

Carrot and Onion Conference, Peterborough, 18th November 2009 (Presentation).

ADAS/Syngenta Vegetable Conference, Peterborough, 27th January 2010 (Presentation).

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