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Mechanical weed control for integrated and organic salad and Brassica production

Final report
June 2007

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Project leader:	Dr Andrea Grundy Warwick HRI University of Warwick
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The following are members of the consortium for LINK project Mechanical weed control for integrated and organic salad and Brassica production

- Warwick HRI
- Horticultural Development Council
- Robydome Limited
- Garford Farm Machinery
- Edwards Brothers
- Robert Montgomery Limited
- Allium & Brassica Centre
- AGCO limited
- Tillett and Hague Technology Ltd (as subcontractors to Warwick HRI)

The results and conclusions in this report are based on an investigation conducted over a one year period. The conditions under which the experiments were carried out and the results obtained have been reported in detail and with accuracy. However because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results especially if they are used as a basis for commercial product recommendations.

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HEADLINE

Reliable and effective in-row mechanical weed control, with low levels of crop damage, was successfully demonstrated using a novel cultivation tool. The project highlights savings on weed control costs with a short pay-back time.

BACKGROUND AND EXPECTED DELIVERABLES

This project aims to produce a cost effective adaptable mechanical control of in-row weeds for a range of integrated and organic salads and Brassica crops.

- The project aim will be achieved through the development of an experimental prototype demonstrating the technology.
- The project will also provide knowledge necessary for post project development of prototype commercial machines

Diminishing herbicide options, fear of ground water contamination and customer pressure to minimise herbicide use are all pushing the industry away from reliance on herbicides. However, product contamination concerns, much of which relate to weeds, necessitate high levels of weed control and have resulted in increasing use of unsustainable hand weeding.

- A major constraint to continued growth of processed bagged salads is contaminants. Major contaminants are weeds and weed seeds, however other pest and disease contaminants are enhanced by poor weed control.
- The majority of salad crops are hand weeded once and some twice at a cost of £400-£1000/ha depending on weed levels. This task is not liked and leads to back problems.
- Brassica production is also affected by weed contamination, but to a lesser extent. Better weed control will reduce these problems. It is estimated that only 5% of Brassica crops currently require hand weeding, though that is expected to rise after the loss of herbicides such as Cyanazine in 2007. Most organic Brassica crops are hand weeded and costs are typically lower at £100 - £250/ha due to wider plant spacing and a greater tolerance to weeds.
- Typical Brassica residual herbicide costs are expensive - between £45 and £60/ha.
- More cost-effective weed control will have the added commercial benefit of reducing potential reliance on imports of certain produce from outside the UK in the future.

Weeds growing within crop rows continue to be the major problem because of

1. gaps in the herbicide control of certain weed species and
2. the close proximity of the weeds to the crop making conventional mechanical weeding difficult without risking crop damage.

THT's imaging and crop row tracking technology has been successfully applied to cultivation equipment for improved inter-row mechanical weed control. There is an opportunity to develop an adaptable, cost-effective technology for mechanically controlling weeds, specifically in-row weeds, for a wide range of Brassica and salad crops that would enable machinery to control in-row weeds mechanically. Such a development would increase UK industry competitiveness in a way that is sustainable in a low herbicide environment

The main deliverable of the project will be an experimental prototype demonstrating the technology developed and capable of being taken forward for development by the manufacturing parties.

SUMMARY OF THE PROJECT AND MAIN CONCLUSIONS

Objective 1:
To develop the mechanical control of in-row weeds, we need to be able to take regular observations of plant positions in the field and then quickly pass this information to a fast tracking algorithm that can then follow plant location from a moving vehicle. Importantly, this tracking algorithm will need to be able to cope with variability in the spatial planting of the crop.

During the first 6 months of the project, extensive measurements were made in both commercial Brassica and salad crops to quantify the degree of planting variability. We identified from discussions with growers and the literature, that the most important time for us to target the mechanical weeding operation was approximately 3 to 4 weeks after transplanting. The relatively short period of time salads remain in the field and the competitive nature of Brassicas, make later weeding less critical.

Objective 2:
The project also addressed the challenge of following a typical range of salad and Brassica crop colours, in particular red salad plants. During the first six months, samples of crops of different colours have been supplied by our commercial Partners. We found that all crops can be tracked with Near Infrared (NIR), unfortunately NIR, red and blue cameras are not yet commercially available. However, an alternative (Red Green Blue - RBG) camera was identified.

Objective 3:
An algorithm based on a two dimensional wavelet approach to crop location (a type of mathematical template) coupled with Kalman filter tracking of individual plants was developed during the first year.

Objective 4:
A novel shallow cultivation mechanism with a cut out disc was field tested with encouraging results.

A phase lock loop control system was devised to synchronise approaching plants, as tracked by the vision system, with the cultivator. A single row rig using both electrical and hydraulic drives was successfully tested using artificial plants (green blocks).

Objective 5:
An experimental toolframe based on a commercial steerable front mounted inter-row cultivator was constructed by Garford Farm Machinery. The single row cultivation mechanism, developed earlier in the project, was redesigned and two modules were mounted on the experimental toolframe.

The computing system and microcontroller used in initial trials were replaced with a new system with the capacity to operate up to five cultivation disc modules as well as provide inter-row guidance for the steerable toolframe. The main computer, a 1.6GHz Pentium M, was mounted on the implement and connects to a cab mounted console to provide a user interface and display live video images.

The complete system was commissioned and underwent engineering evaluation. Tests indicated that a dish-shaped intra-row cultivation disc gave a finer tilth than a flat disc that had a tendency to create larger clods under some soil conditions. A dish-shaped disc was therefore used for the agronomic field trials. Results indicated that the control system was maintaining disc angle to within 10° of the desired position. The system performed well at speeds of up to 3.6 km h^{-1} and was reliable at commercially acceptable weed densities. Even when synchronisation was lost in very high weed densities, it was quickly regained if weed levels dropped. Treatment of larger crop plants (>12cm diameter) resulted in the disc shaft touching the outer leaves. Whilst not quantified, this contact had the potential to cause crop damage. As a result an alternative cranked drive shaft was created to increased clearance between the plant and drive shaft.

Objective 6:
Agronomic assessments were made in both a Brassica crop (Silsoe, September 2006) and a commercial salad crop (Anglia Salads, May 2007).

For the Brassica assessment, the crop (cabbage Elisa) was grown at an atypical time of year (transplanted out in early September 2006), however the trial provided an early opportunity to evaluate performance. Weed pressure on the trial site was judged to be high and with a reasonably representative sample of weed species. Three weeding treatments were conducted at 16 days, 23 days and 33 days after transplanting. All treatments were conducted at 1.8 km h^{-1} using a toolframe equipped with both inter-row and intra-row cultivators. Weed numbers were counted in three annular areas (radii of 0-80mm, 80-160mm and 160-240mm) centred on crop plants. Weed counts were performed immediately before and after each treatment, and again two weeks after treatment.

The efficacy of weed control was at its best during treatments one and two, with initial weed numbers immediately after treatment reduced by 77% and 87% respectively. Subsequent re-growth and new germination in the two weeks after treatment reduced those figures to 74% and 66% of the original weed numbers. By the third treatment overall weed numbers pre treatment were lower, but those that remained had grown to be larger and more robust. This, combined with the difficulty in tracking where ground cover was almost complete, reduced the initial reduction in weed numbers to only 65%. However, there was no significant recovery in weed numbers over the subsequent two weeks possibly due to the late stage in the season not being suitable for further weed germination. Some crop plants were damaged in the final treatment due to the difficulty of tracking in a weed infestation judged to be worse than a commercially acceptable level.

For the commercial (green-leaved) salad assessment, the weed flora at the experimental site was significantly lower than had been experienced in the autumn trial. At the time of the weeding operation (within 3 weeks of transplanting which is typical for that crop), weed seedlings were at the cotyledon to first true leaf stage. This was comparable with treatment 1 in the autumn Brassica trial. Good weed removal was achieved with an approximately 60% reduction in weed density in the annular zone < 90 mm from the centre of the crop, whereas the weeding efficacy was almost 90% in the area > 90 mm but < 300 mm from the centre of the crop. This suggested that the initial weed seedling density present at this early weed seedling growth stage, as seen on the two contrasting trial sites, does not impair the efficacy of the tracking system or weed removal. The novel cultivator mechanism coped well with the capped soil found at the commercial site following irrigation and there was negligible soil throw onto the salad crop leaves.

In an additional test of the tracking system in a nearby commercial red-leaved lettuce crop, the in-row weeder was able to cope extremely well with the red-leaved crop even in the presence of harsh light and strong shadow. A remarkably high level of weed removal was observed as a result.

Objective 7:
An initial demonstration of the technology under commercial conditions took place at Anglia Salads on the 29 May 2007. Heavy rain prior to the start of the demonstration unfortunately prevented the weeder from being practically demonstrated in the fields. However, growers attending the event were given an informal presentation followed by extensive question/answer session and were shown video footage taken the previous week in the commercial site.

A Brassica weeding demonstration took place on 3 July at Warwick HRI Kirton. Unfortunately this event was also affected by rain, though the machine was run on transplants laid out on a barn floor to demonstrate the principle of operation. A power point presentation with video of the machine in action preceded the demonstration.

EXPECTED FINANCIAL BENEFITS

An analysis based on field performance and projected capital cost suggests that the operating cost per pass of a 3m machine controlling weeds in Brassicas would be £47/ha. The equivalent figure for a 2m machine working in Salads would be £115/ha. A full breakdown of this analysis are given as a Appendix 2 in the science section of this report.

Organic production

- It is assumed that two passes of the machine are required and that these replace two inter-row cultivation operations. If we assume that a **typical organic Brassica crop** requires £300/ha of hand weeding labour and that use of the machine halves this need for hand weeding, then **payback would be achieved in 1 year**.
- Assuming **an organic salad crop** requires £500/ha of hand weeding labour and that this is also halved then the **payback period would be 1.6 years.**

Conventional production

- **Conventional Brassica producers** do not generally use hand weeding labour. If weed control measures fail the cost is more likely to be experienced as a loss of quality and yield with the worst areas being abandoned completely. For the purposes of this analysis it has been assumed that one pass of the weeder replaces one pass of an inter-row cultivator and results in a 2% higher yield. It is further assumed that herbicide applications costing £45/ha are reduced from three to two applications. **The payback period in this situation has been calculated as 1.6 years.**
- **Conventional salad growers** frequently employ hand weeding labour at an estimated average of £400/ha. It has been assumed that two passes of the machine halves this figure and replaces two inter-row cultivation operations as well as one herbicide application. On this basis **payback is 1.6 years.**

Other benefits

In addition to the direct financial benefits indicated above there should be a number of other benefits which are less easy to quantify in financial terms:

- Environmental benefits resulting from reduced herbicide use

- Improved product quality
- The potential for reducing the number of weeding operations through better targeting may help minimise problems caused by frequent soil disturbance.
- Plant location techniques developed to track individual widely plants may improve existing inter-row guidance, further reducing herbicide use.
- Lower weeding costs outlined above would increase potential for organic production especially where manual labour is scarce

ACTION POINTS FOR GROWERS

Brassica crops:

- The competitive nature of Brassica plants means that it is not necessary to get as close with the weeder as previously anticipated. Observations from the preliminary field trial in autumn 2006 demonstrated that the immediate under-story of the cabbages used in the trial had very few weeds.
- Crop damage was low, but the hooked stems of some Brassica plants might require a larger (50-60mm radius) uncultivated zone to avoid root damage. The competitive nature of the Brassica plants described above would facilitate using a larger radius without compromising the level of weed control achieved.
- Early weeding (1st true leaf through to 5th true leaf) was most successful in the autumn conditions. However, this may change in spring as the soil heats up and weed emergence and weed species may differ in vigour and composition.
- The machine operated reliably in the typical to heavy commercial weed infestation levels experienced on the experimental site.

Salad crops:

- As tested in the commercial salad trial (May 2007), the machine can be fitted with inter as well as the intra row cultivation tool being developed in this project. This enabled a single pass with the new weeder to replace a pass with a conventional inter-row hoe – thus saving time and energy use and providing excellent weeding coverage.
- Speeds approaching 1.6 km hr^{-1} were achieved with very little crop damage or soil throw.
- Red lettuce varieties were successfully tracked and good weed control was achieved over a large test area with weeds at the early growth stage (1st to 2nd true leaf), typical for weed removal timing in this crop. The hoe also coped well with low spreading varieties of salad giving close weed control with little evidence of crop leaf damage.

EXPLOITATION AND FUTURE APPLICATIONS

Exploitation and building confidences:

The main output from this project has been the development of the experimental weeding machine that has been successfully demonstrated to interested parties. These demonstrations have been accompanied by presentations giving technical details and a cost benefit analysis at some HDC and HDRA grower events. The academic partners have also reported their research findings at conferences and in journals.

The consortium will continue to make use of HDC News and the trade press to disseminate information as the opportunities arise in the future. The technical advances made in the project, such as the developments in the tracking system, tracking on red crops and the development of the novel cultivation mechanism will be made available to existing users of that technology via Garford Farm Machinery.

Promising experimental results have encouraged the construction of a first commercial prototype that will be used for further commercial trials starting at the end of July 2007. In addition the experimental machine is being reconfigured for continued commercial trials so that by the end of 2007 significant experience under commercial conditions will have been gained by two machines on two different holdings. It is anticipated that the experience gained by the engineering partners will be sufficient for them to offer commercial machines to UK growers in spring 2008. The electronics and computing components will be manufactured by Robydome Ltd and their system will be fitted to weeding machines manufactured by Garford Farm Machinery. Sales and support for growers will be provided by Garford Farm Machinery.

The Allium and Brassica Centre along with HDC will have the role of advising growers as to the potential benefits and limitations of the technology so that they can make informed choices on how best to apply it to their businesses. The Allium and Brassica Centre have a large membership of Brassica growers who they keep informed with regular technical updates and meetings. HDC use HDC News and grower meetings as a route to keeping their membership informed. Additional information on system performance will be disseminated via Garford Farm Machinery as part of their sales effort.

The grower partners will have the opportunity to gain practical experience with the technology, initially with experimental equipment, and then post project with commercial prototypes. They will be in a good position to use the technology to its best effect and to relate this experience to other growers.

Broadening future applications:

Research from this project could contribute to knowledge and capabilities beyond the confines of in-row mechanical weed control. An ability to locate and track individual plants might be used for spot application of biological or chemical controls opening the way for a radical change in crop protection.

The academic research partners will use the scientific information gained in this work to strengthen their expertise in this area and, it is hoped, build from it into future work in related areas. For example, the in-row weeder could be extended for use in other crops that have a spatial geometry that fall within the tolerances identified in the project. The novel cultivation and control system might also be suitable in the development of an intelligent thinning system. Tillett and Hague Technology are undertaking preliminary work on thinning algorithms that will be tested on one of the consortium grower’s holdings at the end of the 2007 season. Analysis of crop scenes could also be extended to include automatic recording of crop and weed growth and for levels of assessing weed infestation.

Exploitation plan and consortium linkages, timeframes:

Exploitation Activity	What will be on Offer	Target (Audience)	Partner(s) Involved	Timing/ Duration

Development of <u>commercial</u> prototype equipment based on the experimental findings of the project (end July 2007)	Commercial prototype equipment will be available to consortium growers. Subsequently full commercial versions will be available (spring 2008).	Growers and their advisors	Robydome Electonics and Garford Farm Machinery with advice from consortium growers.	Work on prototypes will start directly after the project ends (July 2007)
Development of agronomic information to support the weeder (available via final report August 2007)	Advice that could be provided by the manufacturer to accompany and improve the sophistication of the weeder	Growers and their advisors	All	Work on supporting agronomic information has been collated and is available for incorporation of any guidance documentation to support the weeder.

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Science Section

Introduction

The scientific approach of the project has been to develop fast, two dimensional mathematical template matching techniques, (exploiting periodicity within the planting grid), which enable individual crop plants to be located and can cope with crop spacing variability. Regular observations of plant position are passed to a tracking algorithm that can follow plant location from a moving vehicle. We have ensured that this can be made to work for a typical range of salad and Brassica crop colours, in particular red salad plants. A novel shallow cultivation mechanism has also been developed. This has been synchronised with the plant tracking algorithm enabling weeds to be removed from between crop plants within the row leaving the crop undisturbed. The final phase of the study allowed the performance of the resulting experimental apparatus to be assessed for both physical accuracy and horticultural value in terms of reliability, weed kill and any crop damage.

Progress, Results and Discussion

Objective 1: Quantify variability in plant spacing

- *Hand measurement of in-row spacing in commercial crops*
    - Hand measurements of Brassica and salad crop spacing have been made on several farms. For example, for Brassicas this has included data from four different farms. Therefore, in total we have used a large data set on the position of 528 Brassica plants and 634 salads.

    - Lettuce Spacing 24cm and 29cm S.D 2cm (Figure 1)
    - Brassicas (Commercial site 1) Spacing 37cm S.D 8cm
    - Brassicas (Commercial site 2) Calabrese Spacing 40cm SD 5cm
Cabbage Spacing 69cm SD 5cm
Cauliflower Spacing 48cm SD 4cm
    - Some Brassicas don't grow vertically out of modules therefore variability in foliage is greater than root
    - Data are consistent with transplanter mechanisms

Figure 1: Field assessment of variability in commercial lettuce plant spacing

- *Establishment of safety margins*

  Brassicas:
  - Safety margins must be more tolerant to spatial variability because of greater planting variability
  - Weed control timing -
    - First 4 weeks after transplanting are critical
    - Relatively long life of crop in the ground
    - Competitive, smothering crop (Figure 2). Late emerging weeds in the crop rows rarely cause problems.
    - Weed species identified in the commercial fields visited included shepherd's purse, volunteer potatoes, mayweed, creeping thistle and annual meadow grass. These are typical of this crop
    - Whilst later emerging weeds don't cause problems with competition and yield, they may shed seeds and contaminate the crop (Figure 3).

  Salads:
  - Safety margins can and indeed *need* to be smaller for salads than for Brassicas. This because of their lower tolerance to weeds and closer plant spacing (Figure 4). To achieve the same *proportion* of weeding coverage, it will be necessary for the blade to pass closer to the salad plants. A key factor in achieving this is the relative variability of in-row plant spacing. Of the crops we measured, which we believe to be typical, the standard deviation in plant position along the row for salads was approximately 2 cm. This is half the same figure for Brassicas which were 4-5 cm (see earlier section for details). Hence, the greater planting accuracy will facilitate similarly improved accuracy hence closer cultivation.

  - Weed control timing -
    - Early, good establishment important - early maturing varieties have less weed problems.
    - Critical period for weeding is the first 3 weeks after crop transplanting.
    - Possible damage from later weed control operations.
    - Zero tolerance to weeds, but short-life crop.
    - Weed species identified in commercial fields visited include mayweed, scarlet pimpernel, groundsel and shepherd's purse. These are typical of this crop

Figure 2: Late emerging weeds smothered by competitive Brassica crop

Figure 3: Shepherd's Purse growing <u>between</u> rows of cabbage, unlikely to reduce yield but could cause contamination.

Figure 4: Weeds emerging very close to lettuce and likely to cause yield loss and quality problems. Close, early and accurate weeding is essential for these crops.

Objective 2: Establish crop colours that can be tracked

- *Variety of samples taken for lab testing*

    - A range of representative samples of crops have been supplied by partners for analysis. Importantly, the growers involved in the consortium have specifically selected plants at a range of growth stages appropriate for cultivation. Therefore the plants used for testing in the lab have been relatively young, but having grown on significantly from the transplant stage. Samples were taken from both inner and outer leaves.

- *Lab analysis of spectra to look at scope for future colour based techniques beyond red/green/blue*

    - All crops can be tracked with Near Infrared (NIR), but some lighting conditions require manual adjustments
    - Lab analysis of spectra shows that a three band camera with NIR, red and blue would give good performance on all crops (Figure 5a & 5b).
    - Classification is correct 98% of time on both red and green lettuce.
    - NIR, red and blue cameras are not yet commercially available.
    - Selected alternative (Red Green Blue - RBG) camera with higher band width data connection (to reduce compression effects) and increased controllability (to bring colour handling closer to theoretical assumptions)
    - RGB cameras will provide excellent images for green salad and Brassicas crops.
    - RGB cameras used for red lettuce will need to be fitted with NIR band pass filters so that they can function as monochrome NIR cameras. This will provide good contrast between plant and background but will be subject to some problems under certain lighting conditions

especially direct low sunlight from one side.

- These problems do not represent a serious impediment to take up in red crops, but we will continue to monitor the possibility of obtaining three band cameras that include the NIR. This would provide a technically better solution.

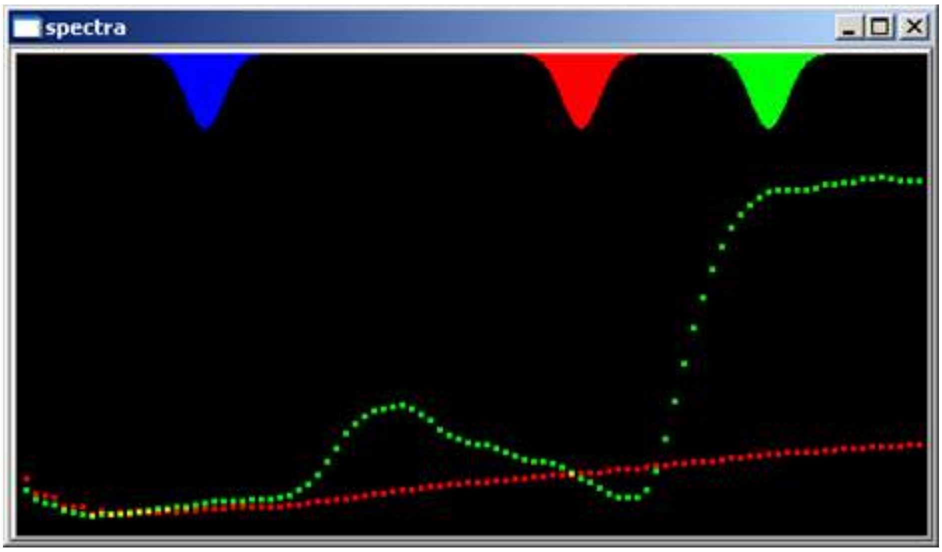

Figure 5a. Reflectance spectra of green lettuce (green line) and soil (red line) with Blue, Red and NIR wavebands indicated above

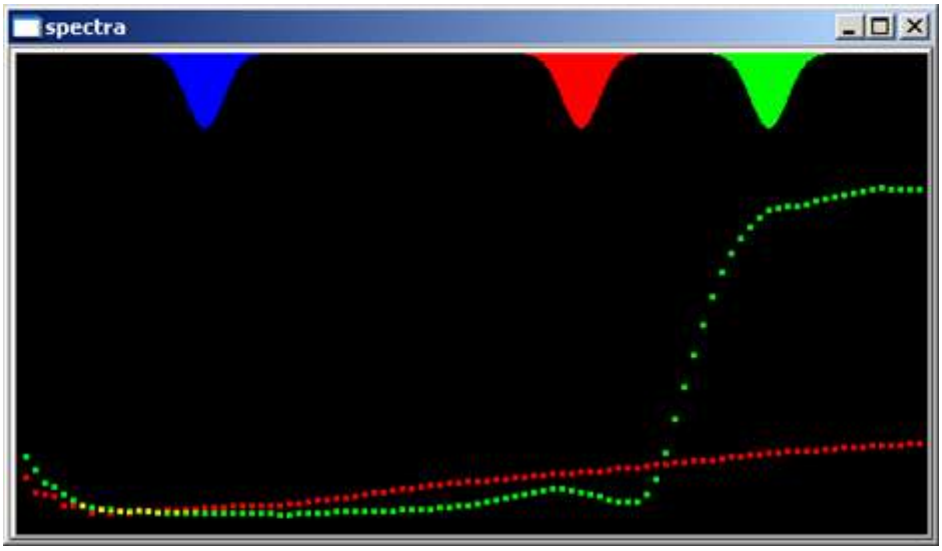

Figure 5b. Reflectance spectra of red lettuce (green line) and soil (red line) with Blue, Red and NIR wavebands indicated above.

<u>Objective 3: Development of two dimensional tracking</u>

- An algorithm based on two dimensional wavelets (Figure 6) has been developed. This provides a spatially localised means of extracting a periodic planting pattern based on individual plants and their near neighbours. Initial placement of the Mexican hat wavelets is based on predicted plant position from a Kalman filter tracking algorithm.

- A Kalman Filter is a recursive least squares estimator that combines information from multiple sources (i.e. vision observations and motion sensors) to continually update an estimate of the parameters being tracked using a kinematic model of the system. In this case the parameters we are tracking are implement heading and offset with respect to crop rows as well as individual plant positions.
- Distortion caused by perspective is taken into account. An adaptive variable step size hill climbing technique is used to locate individual plants which are tracked by the Kalman filter as they proceed down subsequent images.

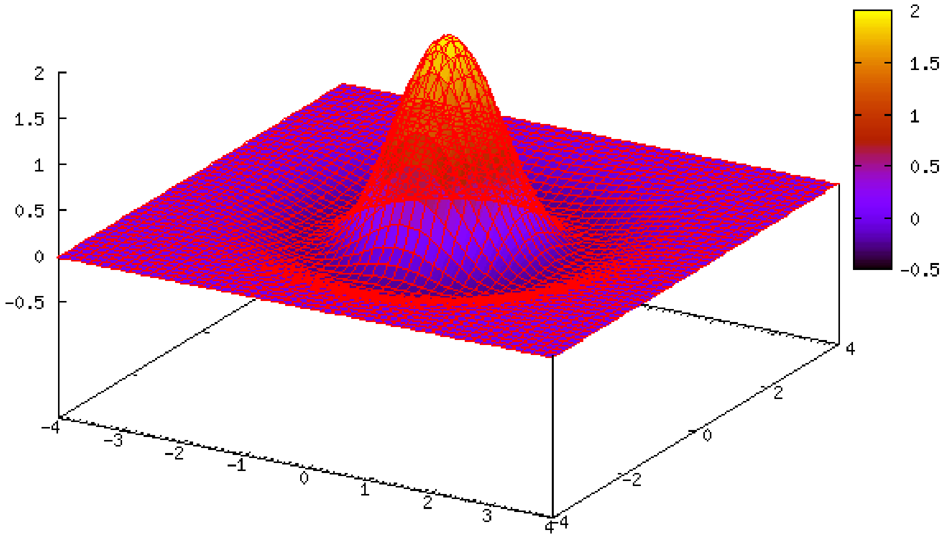

Figure 6 Visualisation of two dimensional Mexican hat wavelet

- Using the technique it is also possible to link small groups of adjoining plants. For example, those in a horizontal line where both planter and cultivator have mechanisms that are geared together across multiple rows for planting and cultivating on the square.
- The software has been successfully tested on sequences of images obtained on the grower partner's holdings under objective 1 (Figure 7).
- The location and tracking algorithm will operate on images as they are generated at 30 Hz.

Figure 7 Sample image of lettuce taken from a sequence. The green crosses indicate Kalman filter predictions and blue crosses indicate the refined position based on application of wavelets

<u>Objective 4</u>: <u>Develop a novel cultivation mechanism</u>

- *Designing the disc*

    - A novel rotating cut out disc has been chosen for this work due to its ability to undertake shallow cultivation without excessive soil throw (Figure 8).
    - The design ensures that the relative motion between the blade and soil in the inter-plant region is low, because disc rotation is synchronised with forward motion. Draft force on the disc is minimised by orientating it forwards (pitch) and into the row (roll) at approximately 5º from the horizontal. The latter has the additional advantage of reducing driving torque as the disc's backward travelling side is placed deeper into the soil.
    - Based on this original concept for a rotating disc by Tillett & Hague Technology, a recent student project (at Cranfield University) is making a complementary contribution to the project by looking into some aspects of the disc design in more detail with "soil bin experiments" (lab-based studies using soil in large bins to track soil movement).

Figure 8 Rotating disc with cut out as used in early field trials

- *Tolerance of the blade design and percentage weed coverage achieved*

    - The plan profile of the blade has been the subject of much detailed design consideration. It is a compromise between maximising cultivated area and providing adequate tolerance to angular misalignment, which if insufficient, might lead to crop damage.
    - The tolerance ultimately required will depend on the dynamic performance of the system as a whole. Trials indicate that angular phase errors, at stages that the disc is fully engaged around a plant, are usually within 10º. A disc designed for lettuce at a 300 mm plant spacing with a tolerance of not less that 10º, typically undercuts 65% of the total area between crop plants that cannot be reached by conventional inter-row cultivation (Figure 9).
    - Taken together with inter-row cultivation, overall coverage would reach 91% of total area. If we assume that the plant requires an uncultivated zone of 4 cm radius around its roots, then this figure increases to 96% of the area available for cultivation. This proportion improves as plant spacing increases and could be improved further by undertaking cultivation from both sides of a row, either using two discs per row, or making two passes.

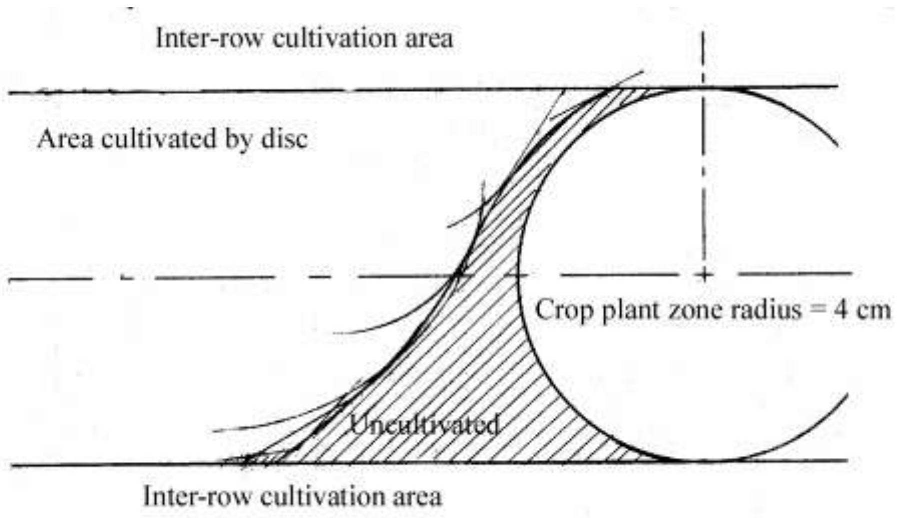

Figure 9 Illustration of uncultivated area (shaded) using a disc with an angular tolerance of not less than 10º operating at an in-row pitch of 30cm.

Objective 5: **System integration & validation**

- *The speed of the system*
  - Fast deployment and retraction are necessary to achieve economic work rates. The target maximum forward speed is 1m/s, which for an in-row plant spacing of 0.5m leads to nominal rotational speed of 2 Hz.
  - Where nominal plant spacing is less than 0.5m we would expect to operate at lower forward speeds maintaining a similar rotational speed.
  - However, variability in plant spacing within the row will require acceleration to higher speeds momentarily to maintain synchronisation. The maximum rotational speed therefore needs to be approximately 3 Hz.

- *Identifying the best choice of drive*
  - Two forms of drive have been considered; electric and hydraulic.
  - Geared electric drive has the advantage of being relatively easy to control using pulse width modulation techniques combined with solid state electronic components.
  - However, the torque that can be delivered, particularly at the 12V commonly available on tractors, is limited. Soil bin studies and practical experience suggest that the torque available electrically (typically 2.5 Nm) will be insufficient under normal field conditions.
  - Initially, an electrically driven rig was built (Figure 10), as it gave us the opportunity to conveniently develop various system components with the blade operating above ground and therefore under no load.

Figure 10: Electrically driven test rig for experimental development above ground

- *Identifying the optimal trajectory profile for the disc*

    - To maximise the area cultivated, the cut out disc is closely engaged around each plant for the majority of a cycle. There is a relatively short period (typically 17% of cycle time) between disengaging with one plant and engaging with the next. During this period the disc can be at any orientation with no risk of crop damage. This period is even shorter if an individual plant spacing is smaller than the nominal value. This fully disengaged period is not normally long enough to accelerate the disc to compensate for variable plant spacing. A compromise is therefore sought in which a smooth trajectory profile is defined with the largest angular correction taking place mid cycle.
    - That trajectory is based on a line in which the gradient at both ends (the plant positions) is defined as the angular velocity appropriate to the actual forward speed and nominal plant spacing. This ensures that phase errors are at a minimum at the point it matters most.
    - The smooth profile avoids rapid accelerations that require large power inputs and lead to increased component wear.
    - The profile is recalculated for every plant according to its position relative to the previous plant and defines the demanded velocity that the motor controller attempts to match. Figure 11 illustrates typical trajectory profiles showing that the velocity (slope) is always the same at the moment a plant is encountered.

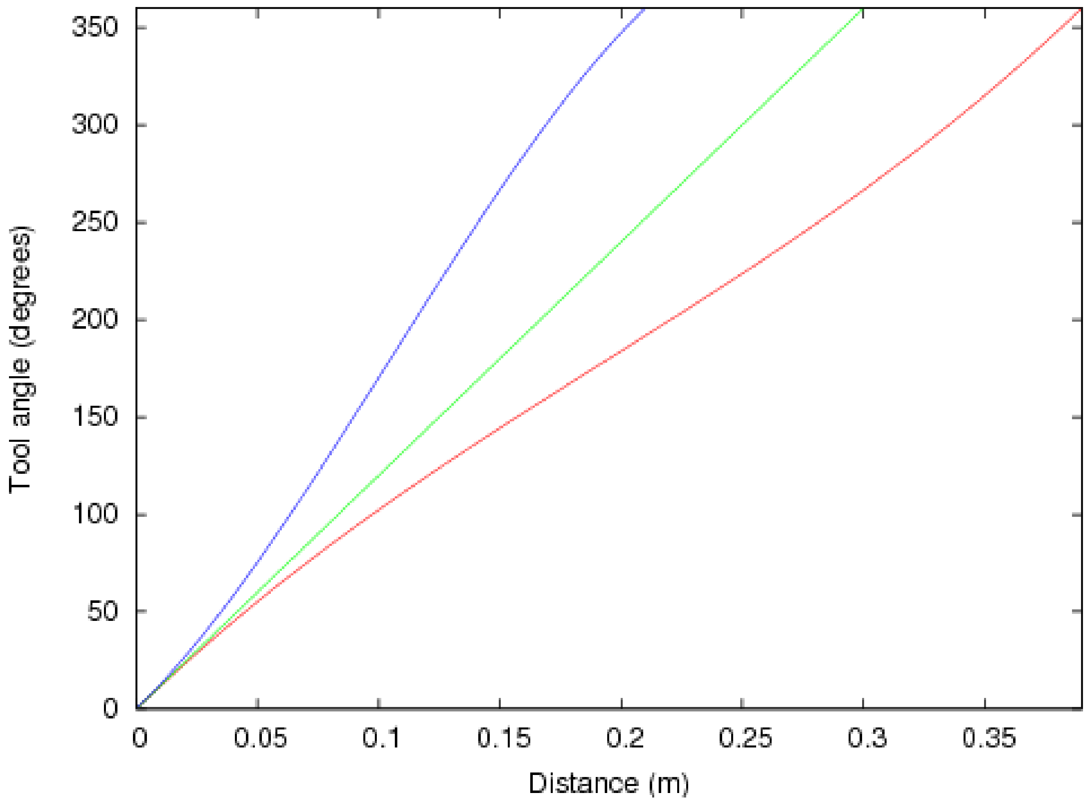

Figure 11 Disc trajectory profiles for a nominal plant spacing of 30 cm, given actual plant spacings of 21 cm (Blue), 30 cm (Green) and 39 cm (Red).

- *Constructing the hydraulically driven rig*

    - Following successful development of control and tracking strategies using electrical drive, a hydraulically driven rig was constructed with accurate depth wheel control. This has allowed field testing on a single row with artificial plants (Figure 12).
    - Initial tests gave satisfactory results (Figure 13) and so a hydraulically driven module was designed based on this rig and described in more detail below.

Figure 12 A single row field test rig with depth control and hydraulic drive shown operating on artificial plants above the soil surface.

Figure 13 Cultivation between artificial plants at a 30 cm pitch

- *Design and construction of a guided toolframe*

    - An experimental toolframe has been constructed by Garford Farm Machinery (Figure 14). The toolframe is based on a commercial disc steered front mounted inter-row cultivator.
    - The 2m wide toolframe has the capacity to accommodate up to five rotary cultivation units.

Figure 14 A 2m wide experimental toolframe designed and constructed by Garford Farm Machinery that was used for field trails and demonstration work.

- *Design and construction of selective disc cultivation modules*

  - The hydraulically driven single row experimental rotary disc cultivation mechanism described above, has been redesigned by Garfords (Figure 15).
  - The new units encapsulate the toothed belt driven encoder and an index sensor within a machined block. The machined block incorporates the shaft bearings and thus provides increased robustness.
  - Each of the disc cultivation modules are fitted to a depth wheel unit. This provides accurate depth control, though their parallelogram linkage mounting provides some compliance in the event of hitting an obstruction.
  - For the trials conducted in September 2006 two disc cultivation modules were mounted on the experimental toolframe and fitted with discs to suit a 0.5m in-row-plant spacing.
  - For the trials conducted in May 2007 four disc cultivation modules were used with discs designed to suit a 300mm in-row spacing.
  - The depth wheel units also provide the mounting point for inter-row cultivation blades.

Figure 15 A hydraulically driven selective disc cultivation module fitted with a flat disc

- *Design and construction of a PC based computer system with a microcontroller machine interface*

    - As anticipated the computing system provided by Robydome based on their inter-row hoe guidance system was unable to cope with the computational load imposed by operation on multiple rows.
    - A new computing system has been developed based on a 1.6 GHz Pentium M processor on a standard commercial single card computer.
    - A custom designed machine interface card has been specially developed to provide low level control of the hydraulic motors and means of reading encoders, proximity detectors and a potentiometer.
    - Both the single card computer and the interface card have been mounted in a metal enclosure on the implement (Figure 16).
    - A user interface is provided by a separate Robydome cab mounted console connected to the main computer via Ethernet.
    - It has been decided not to attempt to provide user information on the tractor console or to integrate with tractor steering as a suitable tractor has not been available.

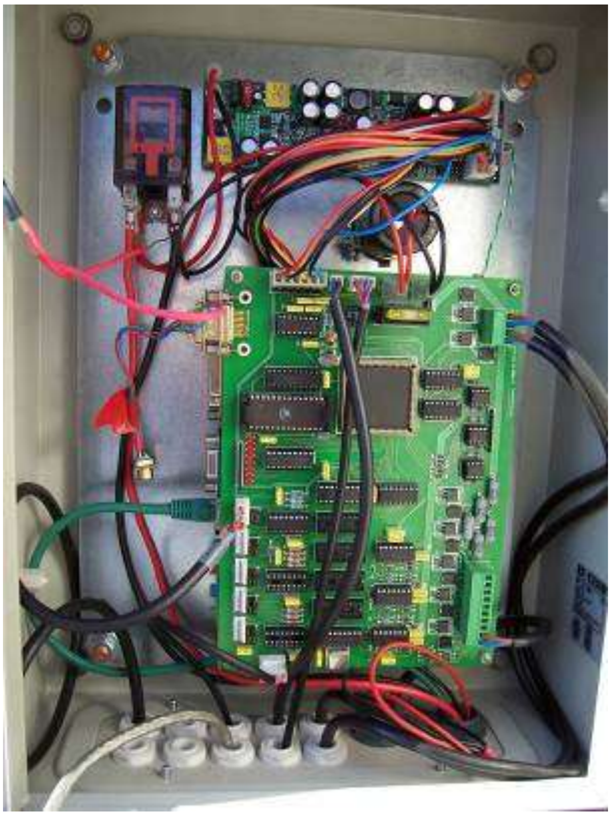

Figure 16 The computing enclosure containing a single card PC (hidden behind) and a custom designed machine interface card (in front)

- *Initial trials of the integrated system*
    - The integrated system was commissioned and field tested on both artificial plants and real transplants (Figure 17).

Figure 17 The integrated system undergoing initial field trials on two rows of cabbages

- The toolframe depth wheel serving as a temporary odometry measuring wheel proved insufficiently accurate on rough ground. It was replaced by a lightly loaded 0.5m diameter wheel running immediately behind a cultivator depth wheel.

- A vision derived measure of forward motion has been combined with odometric information to further reduce the adverse effects of rough ground.
- Tests indicated that a dished intra-row cultivation disc gave a finer tilth than a flat disc that had a tendency to create larger clods under some soil conditions. A dished disc was therefore selected for the agronomic trials on cabbage in Sept 2006. This was not felt to be of sufficient benefit for the relatively small disc required for lettuce grown at 300mm in-row and so a flat disc was used for the May 2007 trial
- Results indicated that the control system was maintaining disc angle to within 10° of the desired position which is within the margin for error built into the disc profile.
- The system performed well at speeds of up to two plants a second (equating to 3.6 km h^{-1} for a 0.5m plant pitch) and was reliable at commercially acceptable weed densities. Even when synchronisation was lost in very high weed densities it was quickly regained if weed levels dropped.
- Treatment of larger crop plants (>12cm diameter) resulted in the disc shaft touching the outer leaves. Whilst not quantified, this contact had the potential to cause crop damage, and so an alternative cranked drive shaft was created (Figure 18).

Figure 18 Cranked disc shaft modification to increase plant to shaft clearance

<u>Objective 6</u>: <u>Quantify weeding performance</u>

- *Experimental design for initial agronomic (Brassica) trials September/October 2006*

  - This preliminary assessment was designed to take advantage of a version of the experimental prototype being available in the autumn. As the cabbage crop was grown at a non-typical time of year it was not grown through to harvest – only to assess weeding efficacy at typical weeding times relative to crop and weed growth stages in the early weeks after transplanting
  - Field trial plots were established at Silsoe (Figure 19). The seedbed was power harrowed approximately three weeks prior to transplanting

with no pre-emergence herbicides in order to maximise the potential for the autumn flush of weed emergence to properly test the system.

- The crop was a fast growing cabbage (Elisa) grown at Kirton in “floppy 50s” to produce a large plant quickly (sown 26/7/06)
- Planting was by hand with an inter-row spacing of 0.5m and a nominal intra-row spacing of 0.5m that was made deliberately variable to correspond a commercially planted Brassica crop whose variability was measured under objective 1 (SD 34mm).
- The crop was netted to protect from pest damage.

Figure 19 Netted plots of transplanted cabbage at Silsoe for the September/October agronomic field trial.

- The experimental plan was designed in consultation with a statistician and included the following planned treatments with 3 replications of each treatment:

  1. weedy control (to assess level of background weed infestation)
  2. weed free control (regularly hand weeded) to compare crop for any hoe damage
  3. “early” treatment weeding at approx. 3 weeks after transplanting
  4. “optimum” treatment i.e. weeding at approx. 4 weeks after transplanting
  5. “late” treatment i.e. weeding at approx. 5 weeks after transplanting.

- Crop and weed assessments were made in the trial plots:

  1. shortly after trial establishment as a baseline assessment of emerging weed flora, weed density and potential patchiness over the experimental area
  2. immediately prior to treatment to asses baseline weed infestation at time of treatment
  3. immediately after treatment to assess whether there are any remaining rooted weeds

4. approximately two weeks after treatment (to assess regrowth and any new weed emergence stimulated by the soil disturbance)

- Assessments of the weed flora on each occasion included:

1. weed species present, to identify whether certain species are more sensitive or able to recover from the treatment.
2. growth stage typical of the weed flora
3. the proximity of weeds to the crop and their density was recorded by using a series of concentric rings centred on the crop plant to provide spatial information on weed removal (Figure 20)
4. the growth stage of surviving weeds was be recorded

- *Figure 20 Three concentric rings used as an aid to spatial weed counting laid over a plant prior to treatment timing 1 with diameters of 16 cm, 32 cm and 48 cm.*

- Assessment of the crop included:

:

1. any noticeable crop damage immediately after treatment using a simple grading system.
2. crop growth stage at time of treatment

- *Experimental results for initial agronomic (Brassica) trials September/October 2006*

  - The efficacy of weed control was at its best during treatments one and two with initial weed numbers immediately after treatment reduced by 77% and 87% respectively. The first weeding treatment coincided with the very early seedling 1 to 2 true leaf stage, with many pre-emerging seedlings were still at the "white-thread" stage (Figure 21). The second weeding was at the 4 to 5 true leaf stage

Figure 21 Weed seedlings at treatment 1 were typically at the 1 to 2 true leaf stage or even the "white thread" stage indicating that the flush of weed emergence was still occurring.

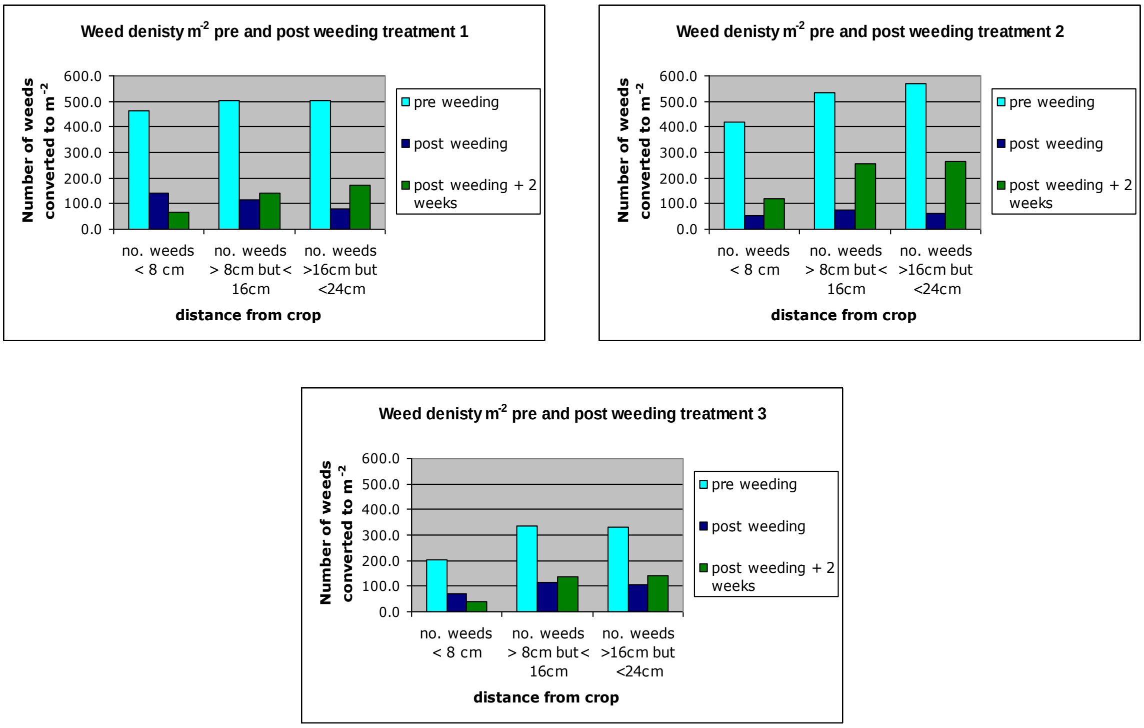

Figure 22 Weed density immediately prior to weeding, immediately after weeding and two weeks after weeding for treatment times one, two and three (the 27 September, 4 October and 17 October respectively).

- Subsequent re-growth and new germination in the two weeks after treatment reduced those figures to 74% and 66% of the original weed numbers (Figure 21). However, even two weeks after weeding, the weed control efficacy compared with the untreated plots was significant (Figure 23)

Figure 23 The bed on the right had been cultivated by the machine two weeks earlier at timing 2. The bed on the left is untreated.

- Whilst rainfall was marginally higher in the two weeks after the second treatment (13 mm) than in the two weeks after the first (9 mm), this is unlikely to have accounted for the higher recovery in weed numbers seen after the second treatment. It is thought that the greater susceptibility of weeds to mechanical damage at the earlier treatment was a more significant factor.

Figure 24 Typical weed levels experienced during treatments one, two and three on the 27 September, 4 October and 17 October respectively.

- By the time the third treatment was conducted weed infestation had reached the point in many places that coverage was complete (Figure 24) and the weeds had themselves started to compete with the crop and indeed themselves as can be seen in the lower weed densities at weeding time 3 (Figure 22). However, despite the lower weed densities at this later treatment time, the weeds themselves were much larger and robust. As the vision system relies on identifying plant material from a soil background, it is not surprising that in some cases tracking was poor or not possible. This combined with the larger better-rooted weeds, reduced the initial reduction in weed numbers to only 65%. However, there was no significant recovery in weed numbers over the subsequent two weeks possibly due to the late stage in the season not being suitable for further weed germination.

- The weeds present on the experimental site were typical of Brassica production including Mayweed (*Tripleurospermum inodorum*), Shepherd's purse (*Capsella bursa-pastoris*) (Figure 25)

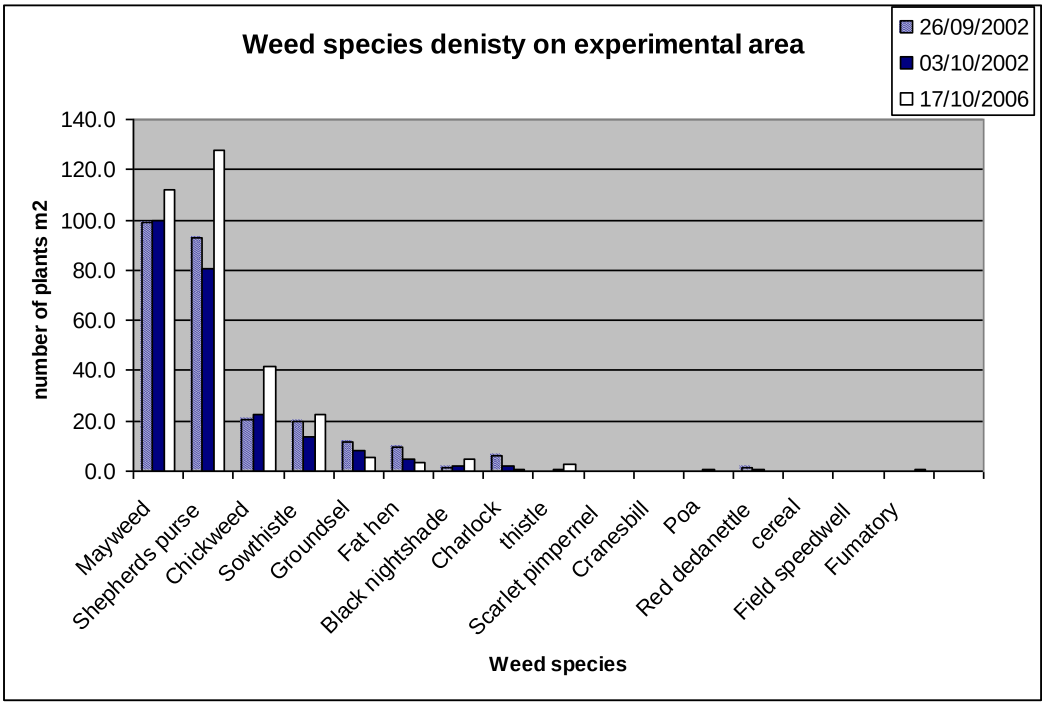

Figure 25 Weed species recorded on unweeded plots during the course of the agronomic assessment at Silsoe.

- Some crop plants were killed in the final treatment due to the difficulty of tracking in a weed infestation judged to worse than a commercially acceptable level. However, the greatest tracking challenge presented by the Brassica crop, was the crooked stem observed on many of the plants which meant that the above-ground foliage and below ground root system were slightly offset and could cause problems with possible root damage (Figure 26). In a few cases (only one or two plants on a couple of the plots) this resulted in root damage and temporary wilting. However the crops quickly recovered in the early weeding treatments with no obvious long-term consequences.

- Possible damage to the crop root could easily be avoided by increasing the radius of the non-weeded zone around the crop and hence allowing a greater margin for clearance of any below ground damage. Increasing the radius of the un-cultivated zone should not present a problem with such a competitive crop. This is because weeds emerging directly under the crop foliage (within an annular radius of 80mm) were severely suppressed by the crop itself. A commercially and acceptable and practically achievable trade off between weeding proximity and crop competitiveness should be feasible.

Figure 26 The crooked stem growth habit of the Brassica crop presented a challenge to the tracking system at later weeding times.

- *Experimental design for commercial agronomic (salad) trial May 2007*
    - The main aim of the commercial salad trial was to increase our experience with
        1. a closer spacing of crop
        2. different coloured foliage
        3. contrasting season
        4. a more sensitive crop to damage and weed competition.
    - We aimed to gain further information on potential weed species selectivity, which will be compared with known gaps in current chemical control and problematic weeds that have been identified for the salad crops.
    - Weeding was carried out on a commercial salad crop that had received a standard pre-emergence herbicide. The weeding operation was made at a time typical for hand-weeding on that particular crop (i.e. within 3 weeks after transplanting).
    - Assessments were based on those reported for the preliminary experiment carried out at the Cranfield/Silsoe site in Autumn 2006. Some modification of the diameter of the concentric rings was necessary to match the different crop planting geometry (i.e. diameters of 18 cm and 30 cm – Figure 27).

Figure 27 Concentric rings used as an aid to spatial weed counting laid over a plant prior to the weeding treatment with diameters of 18 cm and 30 cm..

- *Experimental results for commercial agronomic (salad) trials May 2007*

  - The weed flora on the commercial sire was significantly lower than had been experienced in the autumn trial. Densities were on average approx. 60 weed seedlings m^{-2}, almost a tenth of that observed in the autumn trial. At the time of the weeding operation (typical for that crop) weed seedlings were at the cotyledon of first true leaf stage (comparable with treatment 1 in the autumn Brassica trial) and the salad crop was approx 13 cm across.
  - There was an approximately 60% reduction in weed density (of the plots with weeds present prior to weeding) in the circular zone < 9cm from the centre of the crop, whereas the weeding efficacy was almost 90% in the area >9cm but < 30 cm from the centre of the crop (Figure 28), which were also comparable with the results frond from the autumn Brassica trial. Therefore weed density at this early weed seedling growth stage does not seem to impair the efficacy of the weeding treatment.

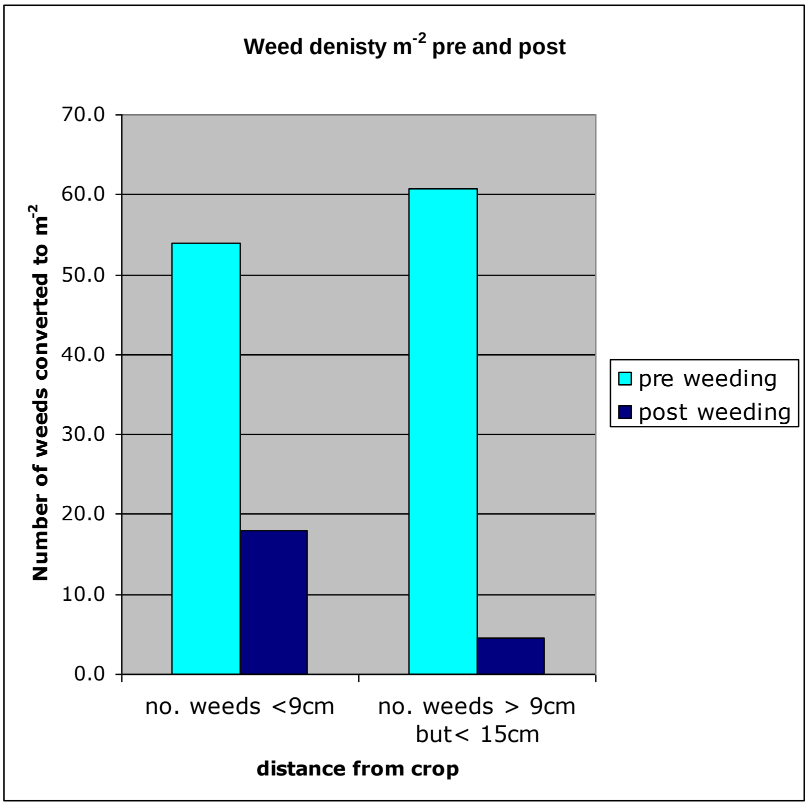

Figure 28 Weed seedling densities immediately prior to weeding and just after weeding

  - The light soils, combined with crop irrigation, had lead to some capping of the seedbed at the trial site. However, the hoe coped well and exposed many weed seedling white threads which subsequently quickly dried out during the course of the day and died (Figure 29).

Figure 29 Capped soil lifted to expose weed seedling roots which quickly dried

- The main species on the trial site were annual nettle and Polygonum spp. However, Mayweeds, Groundsel and Shepherd's purse, all identified as typically problematic weeds of salad crops, were also present and were controlled well at this early growth stage (Figure 30).

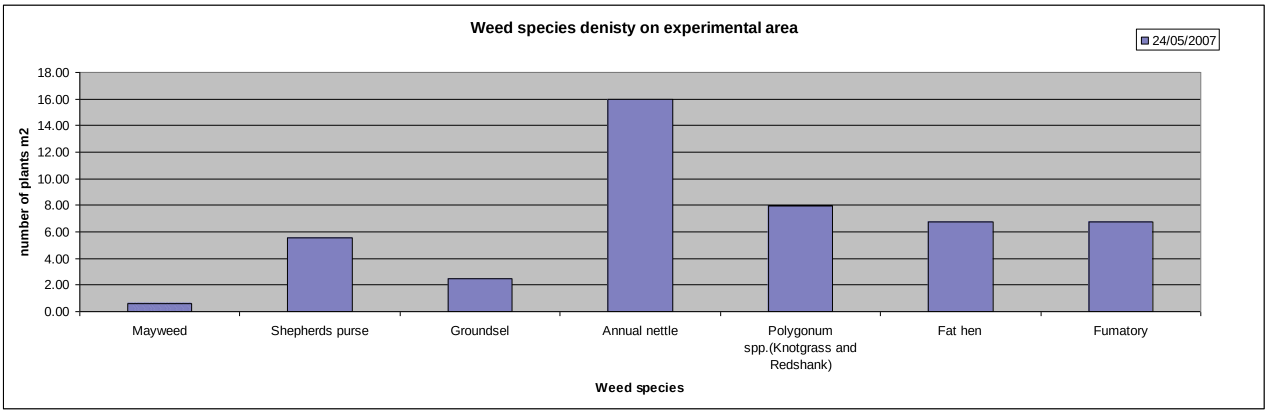

Figure 30 Weed density and composition over the commercial trial area.

Figure 31 A single pass of the in-row weeder fitted with additional conventional within-row hoes, gave good weeding coverage and left a red salad crop virtually weed free

- There was no evidence of any significant soil throw onto the salad crops, which is an important criteria for salad crops and there was only evidence of slight damage in < 5% of the salad crops included in the assessment – caused by slight knocking.
- Following the trial on the green salad crops, an additional test was carried out on a red salad crop (Figure 31). This test was made under harsh daylight conditions casting a significant side shadow, yet the vision guidance coped well following some slight adjustment to cope with the shadow and fitting the RGB camera with a NIR band pass filter.

Figure 32 The tracking system coped well with the strong side shadow and red leaf colour resulting in less than 10 crop plants being damaged in this full-length commercial crop of red lettuce.

- A full-length commercial bed of red lettuce (Figure 32) was weeded leaving virtually no weeds, showing very little evidence of soil throw onto the salad leaves (Figures 33 a and b) and remarkably good crop tracking with < 10 crop plants damaged.

Figures 33a & b Red salad crop showing soil throw after a single pass of the weeder (top) and without mechanical weeding (bottom).

- Finally, the hoe was tested on a neighbouring low spreading salad variety. Despite the growth habit and risk of leaf damage, the hoe coped well, undercutting the leaves to provide close weed control and little evidence of crop leaf damage (Figure 34).

Figures 34 The weeder and tracking system coped well with a commercial low-variety of salad with a contrasting low-spreading growth habit.

- *Economic analysis*

- An analysis (Appendix 2) based on field performance and projected capital cost suggests that the operating cost per pass of a 4m machine controlling weeds in Brassicas would be **£47/ha**. The equivalent figure for a 2m machine working in Salads would be **£115/ha**.

- Organic production

    1. It is assumed that two passes of the new weeder would be required and that these replace two inter-row cultivation operations. If a typical organic Brassica crop requires £300/ha of hand weeding labour and that use of the machine halves this, then payback would be achieved in **1 year**.

    2. If an organic salad crop is assumed to require £500/ha of hand weeding labour and that this would also be halved then the payback period would be **1.6 years**.

- Conventional production

    1. Typically conventional Brassica producers do not use hand weeding labour. If weed control measures fail the cost is more likely to be experienced as a loss of quality and yield with the worst areas being abandoned completely. For the purposes of this analysis it has been assumed that one pass of the weeder replaces one pass of an inter-row cultivator and results in a 2% higher yield. It has also been assumed that the number of herbicide applications costing £45/ha each are reduced from three to two. The payback period in this situation has been calculated as **1.6 years**.

    2. Conventional salad growers do frequently employ hand weeding labour at an estimated average of £400/ha. It has been assumed that two passes of the machine halves this figure and replaces two inter-row cultivation operations as well as one herbicide application. On this basis the payback period is **1.6 years**.

- In addition to the direct financial benefits indicated above there should be a number of other benefits which are less easy to quantify in financial terms

    1. Environmental benefits resulting from reduced herbicide use
    2. Improved product quality
    3. The potential for reducing the number of weeding operations through better targeting may help minimise problems caused by frequent soil disturbance.
    4. Plant location techniques developed to track individual widely plants may improve existing inter-row guidance, further reducing herbicide use.
    5. Lower weeding costs outlined above would increase potential for organic production especially where manual labour is scarce

Objective 7: Demonstration

- The integrated system was demonstrated in a commercial lettuce crop just after the agronomic trial 29 May 2007. Unfortunately, due to heavy rainfall immediately prior to the evening's demonstration it was impossible to take the weeder onto the commercial salad crop. However, an informal presentation was given to the growers who attended along with video footage taken in the salad crop the previous week. Attendees were also free to examine the weeder and ask questions (Figure 32). A further demonstration in Brassicas is planned for 2 July at W HRI Kirton.

Figure 32 An informal presentation was made to interested growers at Anglia salads May 2007.

TECHNOLOGY TRANSFER

- Presentation made on project aims at HDC roadshow (Stockbridge House, February 2005)
- Presentation made at HDC Open Day (Kirton, June 2005)
- Presentation made at the Soil Association Horticulture Symposium (HDRA, June 2005)
- Project webpage
  http://www2.warwick.ac.uk/fac/sci/hri2/research/weedecologyandmanagement/hl0173lfv/
- A4 project summary sheet produced for all Partners
- Presentation made at the East Malling Members Day (East Malling Research 26 January 2006).
- Presentation made at the Horticulture LINK event held in London on 23 February 2006
- A. P. Dedousis, R. J. Godwin, M. J. O'Dogherty , , J.L. Brighton, N.D. Tillett (2005) An investigation into the design and performance of a novel mechanical system for intra-row weed control. British Crop Protection Council Conference, Glasgow

- A. P. Dedousis, M. J. O'Dogherty, R. J. Godwin, N.D. Tillett, J.L. Brighton (2006) A novel approach to precision mechanical weed control with a rotating disc for inter and intra-row weed hoeing. 17th Triennial Conference of the International Soil Tillage Research Organisation Kiel, Germany.
- A. P. Dedousis, R. J. Godwin, M. J. O'Dogherty, N.D. Tillett, J.L. Brighton (2006) Effect of implement geometry and inclination angle on soil failure and forces acting on a shallow rotating disc for inter and intra-row hoeing. 17th Triennial Conference of the International Soil Tillage Research Organisation Kiel, Germany
- Article on the project appeared in the Grower 16 July 2006 (page 16)
- Presentation on the project made to a group of Norwegian and Danish researchers and advisers visiting Warwick HRI on 23 August 2006.
- O'Dogherty, M. J., Godwin, R. J., Dedousis A. P., Brighton, J.L., Tillett N. D. (2006) A mathematical model of the kinematics of a rotating disc for inter and intra-row hoeing. Biosystems Engineering (In Press)
- A. P. Dedousis, R. J. Godwin, M. J. O'Dogherty, N. D. Tillett, A. C. Grundy (2007) Inter and intra-row mechanical weed control with rotating discs. Proceedings of the 6th European Conference in Precision Agriculture, Skiathos, Greece.
- N. D. Tillett, T Hague, A. C. Grundy, A. P. Dedousis (2007) A vision guided system using rotating discs for within-row mechanical weed control. Proceedings of the 6th European Conference in Precision Agriculture, Skiathos, Greece.
- Tillett, N. D., T Hague, T., Grundy, A. C., Dedousis, A. P. (submitted 2007) Mechanical within-row weed control for transplanted crops using computer vision. Biosystems Engineering.
- Presentation on the HortLINK project made as part of the University Department Seminar Series. October 2006.
- Production of official project information leaflet (attached)
- Presentation on the project given at the "Managing Pests, Diseases and Weeds in Organic Vegetable Production stakeholder day (27 March 2007) at HDRA.
- Commercial demonstration in a salad crop (29 May 2007) carried out at Anglia Salads.
- Commercial demonstration in a Brassica crop carried out (3 July 2007) at Warwick HRI Kirton.

APPENDIX 1. Project milestones ■= completed tasks

Activity	Milestone no	Partners (lead first)	Year 1 (April 05-Mar 06)				Year 2 (April 06-Mar 07)				Year 3 (April07-June07)
	Bold = primary		Q1 April-June 05	Q2 July-Sept 05	Q3 Oct-Dec 05	Q4 Jan-Mar 06	Q1 April-June 06	Q2 July-Sept 06	Q3 Oct-Dec 06	Q4 Jan-Mar 07	Q1 April-June 07
Objective 1 Spacing variability		HRI lead									
Quantify planting accuracy within-the-row	1.2	SRI/RM/Edwards	May-05								
Identify appropriate safety margins around crop	1.3	HRI	Jun-05								
Grab image sequences for off line development	1.4	SRI/RM/Edwards	Jun-05								
Identify ideal timings for weed removal	1.5	HRI	Jun-05								
Design specification produced	**1.1**	All		**Jul-05**							
Objective 2 Crop colours		SRI lead									
Establish limitations of existing RGB ratio	2.2	SRI	Apr-05								
Establish limitations of NIR images	2.3	SRI	Apr-05								
Quantify reflectance spectra	2.4	SRI	May-05								
Multi-variate anaysis to select filter combinations	2.5	SRI	Jun-05								
Recommendations completed	**2.1**	SRI	**Jun-05**								
Objective 3 Two dimentional tracking		THT lead									
Develop mathematical templet (wavelet approach)	3.2	THT			Dec-05						
Develop Kalman filter tracking algorithm	3.3	THT			Dec-05						
Test complete tracking on stored image sequences	**3.1**	THT					**Apr-06**				
Objective 4 Cultivation and control		THT lead									
4a) Develop selective cultivation device	**4.1**	THT/Garford			**Oct-05**						
4b) Select actuator and develop phase lock loop control	**4.2**	THT/Garford/Robydome				**Jan-06**					
Objective 5 Systems integration and validation		THT lead									
Design and construct guided toolframe	5.2	Garford/THT					Apr-06				
Construct and fit at least two selective cultivation modules	5.3	Garford/THT					May-06				
Construct PC based console and microcontroller system	5.4	Robydome/THT					May-06				
Integrate vision guidance with tractor steering	5.5	THT/AGCO/Robydome						Jul-06			
Provide some user information on tractor conole	5.6	THT/AGCO/Robydome						Aug-06			
Conduct initial trails	**5.1**	THT/Garford/Robydome/AGCO							**Oct-06**		
Objective 6 Quantify weed control performance		HRI lead									
Assessment in commercial crop	**6.1**	HRI/THT/RM/Edwards									**May-07**
Objective 7 Demonstration		HRI lead									
Field demonstration to interested parties	**7.1**	HRI/All									**May-07**

Appendix 2 Economic analysis

	Intra-row hoe cost benefit	***Organic Brassicas***		***Conventional***		***Organic Salads***		***Conventional***	
		Existing	Proposed	Existing	Proposed	Existing	Proposed	Existing	Propo
	Intra-row weeder								
1	Field efficiency (0-1)		0.75		0.75		0.75		0
2	Working width (m)		3		3		1.8		
3	Forward speed (km/hr)		3.6		3.6		2.1		
4	Spot work rate [**2***3/10] (ha/hr)		1.08		1.08		0.378		0
5	Actual work rate [**1***4] (ha/hr)		0.81		0.81		0.2835		0.2
6	Workable days per season		50		50		60		
7	Capacity based on 8h days [**5***6***8**] (ha/yr)		324		324		136.08		13
8	Capital cost (£)		34000		34000		30000		30
9	Depreciation at 15% of cap cost(£/yr)		5100		5100		4500		4
10	Running cost at 10% of cap cost (£/yr)		3400		3400		3000		3
11	Annual cost of ownership [**9+10**] (£/yr)		8500		8500		7500		7
12	Annual cost of ownership spread over capacity [**11/7**]		26.23		26.23		55.11		5
13	Variable cost, tractor +driver (£/hr)		17		17		17		
14	Variable tractor+driver cost [**13/5**] (£/ha)		20.99		20.99		59.96		5
15	Cost of Intra-row weeding [**12**+**14**] (£/ha)		47.22		47.22		115.08		11
16	Number of intra-row treatments		2		1		2		
17	Total cost of intra-row weeding [**15***16] (£/ha)		94.44		47.22		230.16		23
	Inter-row hoeing								
18	Inter-row hoeing cost (£/ha)	25	25	25	25	60	60	60	
19	No of inter-row hoe passes	2	0	2	1	2	0	2	
20	Total cost of inter-row cultivation [**18***19] (£/ha)	50	0	50	25	120	0	120	
	Conventional spraying								
21	Number of conventional sprayer passes for herbicide			3	2			2	
22	Contract/Farm sprayer charge/cost (£/ha)			10	10			10	
23	Variable cost of herbicide per treatment (£/ha)			35	35			35	
24	Total cost of herbicide spraying [(**22**+**23**)***21**] (£/ha)	0	0	135	90	0	0	90	
	Hand weeding								
25	Variable average cost hand weeding (£/ha)	300	150	0	0	500	250	400	
	Abandoned crop due to weed infestation								
26	Av % of crop expected to be abandoned due to weed	0	0	2	0				
27	Establishment cost (£/ha)	2200	2200	2200	2200				
28	Total average loss due to abandoned crop	0	0	44	0				
27	**Total weed control costs** [**17**+**20**+**24**+**25+28**](£/ha)	**350.00**	**244.44**	**229.00**	**162.22**	**620.00**	**480.16**	**610.00**	**47**
28	**Benefit of proposed strategy over existing**	**105.56**		**66.78**		**139.84**		**134.84**	
	Pay back period if used to capacity [8/(28*7)]	**0.994152**		**1.571455**		**1.576491**		**1.634949**	

Developing mechanical weeding for salad and brassica production

The UK field vegetables industry would save £750K a year if efficient mechanical weeding systems could be developed for in-row weeding

Good weed control is essential in modern salad and brassica production. For bagged salads, contamination with weeds is not tolerated by retailers or consumers. Poor weed control can also lead to other pest and disease contaminants. In brassica crops weed contamination may not be such a problem, but weed competition can have a dramatic effect on crop yields.

However, the range of herbicides available for salad and brassica growers has diminished over recent years as a result of EU and UK pesticides reviews, and the more frequent use of those that remain is leading to increasing problems of tolerance in formerly susceptible weeds.

Added to this, there is growing concern about groundwater contamination from the use of herbicides and customers are pressing for the use of herbicides to be minimised. All this is pushing growers towards greater reliance on hand weeding, but this is costly and a very unattractive job.

Imaging technology has been developed to a point where it can improve inter-row mechanical weed control. Further development to enable machinery to control in-row weeds mechanically would be an enormous benefit to the industry and make a substantial contribution to the competitiveness and profitability of field vegetable growers.

Research aims

The aim is to develop adaptable, cost-effective technology for mechanically controlling weeds, particularly in-row weeds, for a wide range of brassica and salad crops. It is expected that a prototype machine will be developed which can be taken forward by the manufacturing partners.

Research methods

The variability of plant spacing in rows will be quantified on a range of grower holdings to cope with the trade off between acceptable crop damage and weed control for common cropping situations. A mathematical template will be developed that will allow plants to be tracked in a two-dimensional, multiple-row planting pattern.

As the imaging technology uses illumination variant colour segmentation based on the red/green ratio to differentiate between the colour of crop and weed plants, the demand for red foliaged salad crops creates an additional challenge. Using a spectroradiometer, the key discriminating points of the spectrum will be identified.

Manufacturing partners in the consortium will be developing a new cultivation mechanism and synchronised control system to enable the fast deployment and retraction of a shallow undercutting blade to provide in-row mechanical weeding.

Using the technology developed, a steerable toolframe will be constructed equipped with a PC-based computing platform and camera to validate the system. Initially trials will use artificial crops and weeds followed by final field evaluation on commercial holdings.

Benefits for industry

The majority of salad crops are hand weeded once and sometimes twice at a cost of £400 - £1000/ha depending on weed levels. Hand weeding in brassica crops is less common but is expected to increase as further herbicides become unavailable. Costs here are £100 - £250/ha.

Brassica herbicides are expensive – between £45 and £60/ha. One pass of a combined in-row and inter-row weeder will cost £25/ha.

Putting these financial benefits together, the new weeding technology could save the UK industry £750K pa. In addition, there would be environmental benefits from the reduced use of herbicides.

Weeds very close to lettuce, likely to cause yield loss and quality problems (above left). Close, early and accurate weeding is essential for these crops. (Below) Shepherd's Purse between rows of cabbage, unlikely to reduce yield but could cause crop contamination

"This project has the potential to greatly reduce the expensive and monotonous task of hand weeding"

David Edwards
Edwards Brothers

Top: the novel shallow cultivator has been successfully synchronised with a computer programme for the tracking of individual crop plants. Above: An experimental prototype rig in the field

"We aim to develop an experimental prototype for mechanical weeding salad and brassica crops"

Andrea Grundy
Warwick HRI

What is HortLINK?

LINK is the UK Government's principal mechanism for supporting collaborative research partnership between UK industry and the research base.

The aims of the HortLINK programme are:

- To improve the sustainability of the horticultural industry
- To improve knowledge and understanding of processes and factors which determine the performance of the horticultural industry
- To enable access by the horticultural industry to innovative ideas and technology by involving a wide range of research institutes and university departments
- To promote wider industry awareness of the benefits of advanced horticultural techniques/methods.

Further information from the programme co-ordinator.
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Project details
Mechanical weeding for sustainable salad and brassica production in a zero or limited herbicide environment

Reference number
HL0173

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Proof of official project leaflet