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Cost-effective weed control in cereals using vision guided inter-row hoeing and band spraying systems

by

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Contents	Page
Abstract	1
Summary	2
Background	2
Experimental Equipment	3
12m Inter-row cereal hoe	3
20m Vegetable band sprayer	5
Results	6
12m Inter-row hoe performance	6
20m Band sprayer performance	8
Economics of operation in organic and conventional systems	9
Conclusions	10

Technical Report

Tillett, ND and Hague, T (submitted 2005), Increasing work rate in vision guided precision banded operations, Biosystems Engineering.

Abstract

Weed control is one of the most economically and agronomically significant problems for both conventional and organic cereal production. This project developed generic precision row guidance technology to benefit cereal producers through better targeting of both chemical and mechanical weed control inputs.

The technology is based on computer vision to detect and dynamically track crop rows. Previous work has been restricted to following only one drill bout, limiting work rate. In this project we overcame technical barriers to tracking multiple bouts and demonstrated this capability on a 12m inter-row hoe spanning three 4m drill bouts. Crop row spacing was increased to 250mm to facilitate passage of 160mm wide hoe blades. The experimental hoe comprised three sections each with its own camera and mechanism for independent lateral movement.

Field trials showed that under normal commercial conditions lateral error should not exceed 25mm (S.D. 10mm) at speeds of up to 10 kph. Performance was reliable under a wide range of crop growth stages and coped well with high levels of weed infestation. Problems that did occur were usually due to inaccuracy of drill bout matching, particularly near headlands, where bouts converge or diverge beyond the lateral stroke (± 250 mm). Strategies were successfully implemented for dealing with these eventualities, though for best performance extra attention should be paid to bout matching.

Two application scenarios were explored, organic and conventional production. For the latter we implemented combined hoeing between rows and band spraying of selective herbicides on the row. This reduced herbicide input by 60%. Unfortunately, as a consequence of the very narrow (100mm) spray band individual nozzle flow rates must be very low (10l/hr). Conventional nozzles with appropriately small orifices are very prone to blockages. Further investigation suggested that twin fluid nozzles would be more suitable for this application as satisfactory spray patterns can be generated at very low volumes (5l/h) potentially leading to overall application rates of 10-20l/ha.

Although project objectives were restricted to the development and physical evaluation of engineering systems the hoe was used to treat approximately 5ha of commercial organic spring wheat in 2004. Results indicated that crop yield was 18% higher than a section of the same field drilled at 125mm row spacing and harrowed. This result was not part of a replicated trial, and cannot be treated as significant in isolation, but it does highlight potential differences that are not well covered by contemporary research. We speculate that the difference in crop yield, appearance and nitrogen levels (up from 12% to 13%) may be connected to mineralization of nitrogen rather than weed control.

As part of the wider scope of this LINK project similar technology was used to guide four band spraying sections from a conventional boom sprayer operating in vegetables. Trial results indicated reliable performance albeit at a lower accuracy (22mm S.D) due to the less stable platform.

Summary

Background

Control of weeds is a major economic factor in both conventional and organic cereal production. In conventional systems herbicides provide the cornerstone of an effective weed control strategy. However, this comes at a cost. UK farmers spent £186.2M in 1999 (equivalent to 12,000 tonnes a.s.) on herbicides (source CPA). With grain prices expected to remain low, costs will need to drop to make farming profitable. In some areas farmers are finding that environmental legislation is limiting their herbicide use. Furthermore, resistance, notably in blackgrass, is making herbicides less effective. Taken together, these factors point towards the need for a range of alternative economically viable techniques that address these issues.

In organic arable crop production weeds remain one of the most significant agronomic problems. Whilst a low weed population may be desirable, they can, above critical population thresholds, significantly reduce crop yield and quality in conventional and organic crops alike. The challenge is to manage weeds to produce a profitable and acceptable crop whilst accommodating their beneficial effects. To achieve this, efficient and predictable techniques are needed for the control of weeds, particularly post-crop emergence. This need is particularly acute for farmers engaged in organic seed production.

One way forward for both conventional and organic systems is increased use of post emergence mechanical weed control. This might be used in conjunction with reduced herbicide for conventional production or as part of an overall strategy involving pre-emergence cultivation and crop rotation for organic systems. The spring-tine harrow is the most popular post-emergence weed control measure at this time, in organic systems at least. Whilst this versatile tool is likely to remain important for some time it suffers from a number of drawbacks. In particular, it treats both crop and weed uniformly, relying on the crop to be more robust than the weed. This requires higher crop seed rates to compensate for physical damage, which has economic implications. Spring-tine weeding is most effective on seedling weeds, whilst control of mature broad-leaved weeds and grasses is poor. On heavy clays, or on soils that tend to cap, the opportunity for spring-tine weeding is much reduced and often non-existent due to the difficulty in producing sufficient tilth to bury weeds.

Inter-row cultivation overcomes many of these problems. Damage to the crop is minimised through spatial selectivity, i.e. only the inter-rows are cultivated. Also, it has been shown that, due to its more robust nature, inter-row hoeing can control weeds at a wide range of growth stages and under a wide range of soil conditions. In conventional cereals control within the row can be achieved with herbicide applied in bands over crop rows at the same time as inter-row cultivation.

The main practical problem with banded treatments such as inter-row cultivation and band spraying is the relatively low work rate, stemming from a need to span single drill bouts and manually maintain very high levels of precision. In this project we set out to address these issues developing a generic guidance technology based on computer vision that can guide equipment spanning multiple drill bouts. Our primary

technology demonstrator was a 12m inter-row cultivator for cereals spanning three 4m drill bouts. We also investigated issues associated with guiding band spray nozzles from the rather less stable platform of a 20m boom sprayer. The latter was demonstrated in a vegetable crop.

Experimental Equipment

12m Inter-row cereal hoe

The experimental hoe illustrated in Figure 1 was constructed specially for the project by Garford Farm Machinery. Where possible standard commercial parts were employed, particularly those concerned with depth control and soil engagement. The trial cereal crops were drilled at a row spacing of 250mm with tramlines at 12m. The nominal row spacing at the interface between bouts was increased to 325mm to provide some tolerance to inaccurate drill bout matching. Soil engaging blades were 160mm wide flat A-blade angled down at approximately 5° to the horizontal. Each blade was attached to its own parallelogram depth control wheel linkage via a spring.



Figure 1 Experimental vision guided hoe spanning 12m with three independently controlled 4m wide sections.

The hoe 4m central section was front mounted on a passive linear slide that allows +/- 150mm of lateral movement independent of tractor position. This section was steered by two soil engaging disks whose angular alignment was controlled by a hydraulic cylinder. The unit had two linear potentiometers one to measure disk steer angle and the other to record slide position. The two outer 4m sections were attached via slides to either end of frame mounted on the tractor's rear three point linkage. To increase lateral stiffness two soil engaging disks were attached to this frame behind the tractor wheels. The outer sections were positioned by hydraulic cylinders providing +/-250mm of lateral movement to accommodate variability in bout matching and tractor lateral misalignment. The position of each slide was sensed by a potentiometer. Each of the three 4m hoe sections was equipped with a CCD camera mounted centrally at a height of 1.4m

and viewing down at 40° to the vertical. For convenience both front and rear frames folded to facilitate road travel (Figure 2).



Figure 2 Experimental hoe folded for road transport with band spraying tank fitted

Crop row location was achieved by analysing digital colour images from cameras mounted on each section. The field of view of these cameras placed approximately a 2m length of the four central crop rows into the image. The colour images were converted to mono-chrome based on a ratio of red green and blue that both enhanced contrast between green plant material and background, and minimised the effects of shadows. The subsequent process of row location could be thought of as one of template matching, in which a template with the expected row pattern was positioned to give a best fit over the rows as they appeared in the image. The relatively large area of ground in view increases robustness to local areas of missing crop. The system makes no distinction between weed and crop plants. It relies on plant density being greatest within crop rows. This condition was normally satisfied even when weed pressures were high.

Estimates of crop row location were obtained from a new image 20 times a second and analysed on a PC based computing system that allowed live video images and a user interface to be displayed in the tractor cab. Rather than start looking for the crop rows in each image afresh it was better to have a rolling estimate of crop row location that was updated every time new information became available. That information included side shift movement and forward speed and was linked to a kinematic model of tractor motion. Indeed if for any reason there was no information available from a sequence of images it continued to operate based on dead reckoning. Uncertainty in position would increase over the period that vision data was not available, but previous experience suggests that gaps where crop had failed of the order of 4m can be bridged in this way.

In conventional cereal production inter-row cultivation in isolation is unlikely to provide adequate weed control due to weeds within the crop row. A system of combined inter-row cultivation and on-row band

spraying was therefore devised and fitted to a 4m vision guided hoe operated on Unilever's experimental farm. The nozzles were flat fans (Lermark 005F 65) orientated parallel with rows to provide a 10cm band. To facilitate spraying at more advanced crop growth stages, two nozzles were fitted for each row, one each side, directed towards its base. At early growth stages adequate coverage was thought to be provided by only one of the two nozzles. The second nozzle was employed when the crop was large enough to block spray penetration to the other side of the row.

20m Vegetable band sprayer

The sprayer illustrated in Figure 3 was based on a conventional 20m trailed boom sprayer. The trial crop was broccoli transplanted in 4m bouts at a 1m row spacing. For demonstration purposes downward pointing nozzles were mounted on drop legs aligned over crop rows. Alternative drop leg positions or nozzle arrangements could however be accommodated.



Figure 3 Experimental vision guided band sprayer spanning 20m with one fixed and four independently controlled 4m wide sections

It was assumed that the tractor driver would position the central 4m section with adequate accuracy and so nozzles on that section were fixed. The remaining four sections were each mounted on side shifting sub frames mounted within the boom. Side shift movement was via a DC motor driving a toothed belt with position feedback provided by a multi-turn potentiometer. Each sub frame was equipped with four drop legs. The design of the sub frames was such that normal boom folding was uninhibited.

One CCD camera was mounted on each side shifting frame at a height of 2m looking forward and down at an angle of 40° to the vertical. This created a field of view of approximately 2m wide by 3m forward from which two rows were tracked. The computer system was similar to that used on the hoe.

Results

12m Inter-row hoe performance

Assessment of lateral accuracy was performed using a procedure in which a cultivation blade was replaced by a nozzle issuing a pulsed dye trace onto the soil. Dye trace position relative to crop rows was a measure of lateral error and trace length a measure of speed. Crop row position was determined using a manually positioned template spanning the same four crop rows that had been tracked by the vision system. There was a subjective element to template positioning and so some variability could be ascribed to measurement error.

Sample results of dye traces for the front and left rear units obtained in flat fields are given in Figures 4 and 5 respectively. They indicate that standard deviation in lateral error for the front unit was 8mm with an overall bias of less than 1mm. This result was obtained at 6.6kph (1.8 ms^{-1}). The rear unit is shown as having achieved a standard deviation of 9mm with a 4mm bias at 10.2kph (2.8 ms^{-1}). These figures are within our target performance specification (S.D. 10mm) and indicate that the 160mm wide blades should leave a 40mm margin to allow for crop root zone width and any lateral bias in machine set up (based on a maximum error of 2.5 standard deviations).

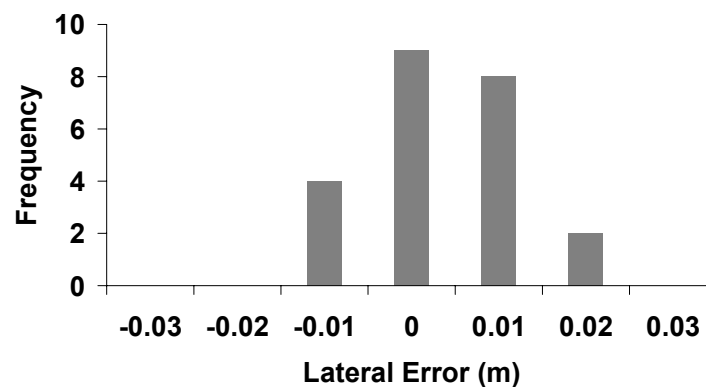


Figure 4 Lateral error between crop rows and soil dye trace for the central front unit operating at 6.6kph.

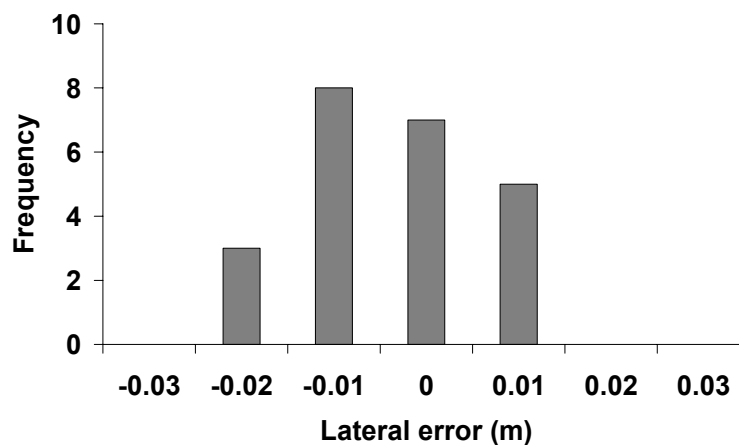


Figure 5 Lateral error between crop rows and soil dye trace for the left rear unit operating at 10.2kph.

Trials on side slopes of approximately 5° indicated that a downhill lateral bias of 15mm can be expected on both front and rear mounted units. Some of this bias was probably due to mechanical slack in the cultivator depth control mechanism. Alignment of the tractor up hill to compensate for side slope would have resulted in implement heading misalignment which may have also contributed to lateral error. The magnitude of this error is not sufficient to cause problems under normal operating conditions, though it would be possible to compensate manually using an offset function already available on the console.

Practical experience over two seasons and three trial sites demonstrated the robustness of the guidance to normal field conditions. Crop damage occurred rarely and was usually due to the side shift reaching its travel limit, an event that triggered a recorded warning message. By far the most common source of these driver warnings was associated with poor drill bout matching. This most frequently occurred over short distances near the headland. However, on occasions where the manual disk-based bout marker did not produce a clear mark, poor matching sometimes persisted into the field. Under these circumstances the driver had the option to stop work, lift the implement, causing it to centralise, and lower it again so that it locked onto the closest set of rows.

In an attempt to improve work rate and reduce driver workload an automatic system was developed to detect when such a jump from one set of rows to another was necessary and to conduct that side shift movement as quickly as possible whilst still in work. This inevitably resulted in crop damage, but if the driver had heeded warnings and slowed down only a small area was affected. The driver was able to decide on the correct strategy based on the value of the crop and desired work rate. The options were to briefly slow down and allow an automatic row jump to take place damaging a small area of crop, or stop, re-centre and continue with no damage.

Whilst strategies outlined above proved effective it is clear that more care needs to be taken at crop establishment than is traditional in arable systems. Inexperienced tractor drivers were used to establish our trial crops and it is likely that professional drivers would perform better. Use of a GPS guidance system during drilling that restricted maximum deviations to within 15cm would complement the vision based guidance and relieve the driver of the need for special care.

Combined hoeing and on-row banded herbicide application was successful at substantially reducing herbicide leaching. However, regular blockages in the small nozzle orifices require to achieve low volumes (10l/h per nozzle) led to poor reliability and limited trial work. Subsequent investigation indicated that a practical system with very low spray volumes (10-20l/ha) could be achieved with twin fluid nozzles. These nozzles use air flow to achieve droplet formation and can be fed at much lower liquid pressures using larger metering orifices than is the case with conventional hydraulic nozzles. Twin fluid nozzles are well suited to banded treatment and their inherent system of air assistance would improve penetration between crop stems, facilitating treatment from one side of a crop row only. Further work is required to establish performance of a system based on twin fluid nozzles, but initial indications are promising.

As an addition to formal project work both Sheepdrove Organic Farm and Unilever Colworth did some agronomic and environmental evaluation. Organic spring wheat drilled at a row spacing of 25cm and hoed once was compared to a crop grown on 12.5cm rows and harrowed. The hoed crop was visually a darker green colour, yielded 18% higher and had a 1% higher nitrogen level. Weed pressure was low in both crops. It has been suggested that the differences may be due in part at least to soil mineralization. Combined hoeing and band spraying was conducted from a 4m hoe in conventional wheat in a high weed pressure situation and compared to a conventional herbicide programme. Pesticide leaching was reduced by more than the reduction in application rate, but weed control was poor. It is likely that the difficulties with band spraying described above contributed to this lack of efficacy. These results provide interesting insights into the opportunities and challenges associated with implementing this technology, but as both trials were based on one season's results without replication they should not be treated as definitive.

Fuel use during inter-row cultivation was typically 1.8L/ha, equivalent to an energy input of 68MJ/ha. This is comparable with harrowing but lower than many herbicide treatments due to high energy of manufacture. To take an extreme example, IPU has an energy of manufacture of 324MJ/Kg which for a dose of 2.5Kg/ha equates to 810MJ/ha.

20m Band sprayer performance

Lateral accuracy was assessed using a similar method described for the hoe except that the pulsed dye nozzle was attached to one of the drop legs. The measured error therefore included any movement in the drop leg itself. The trial crop was broccoli that had been transplanted 3 weeks earlier. The plant spacing in-the-row was 0.39m with row spacing of 1.02m.

Accuracy assessment was conducted at 12kmh⁻¹ (3.3ms⁻¹) which, due to spray boom stability, represents an upper speed limit for band spraying as currently practised commercially. The results are illustrated in Figure 6. Overall the standard deviation in lateral position was 22.4mm. To ensure full coverage of 99% of plants the spray band width should cover +/- 2.5 standard deviations plus the width of the plants. Assuming the plant width to have been 0.1m in this case the required spray pattern was 0.21m wide, 21% of total area.

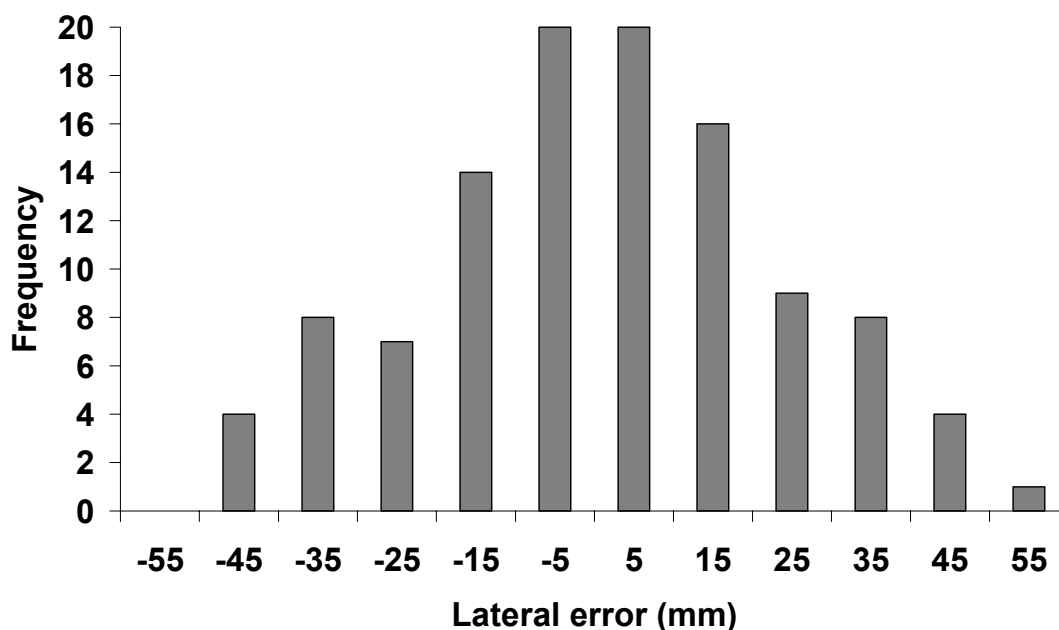


Figure 6. Hand measured lateral error between crop rows and soil dye trace for the drop leg sprayer's right inner unit operating at 12kmh⁻¹

Economics of operation in organic and conventional systems

An analysis of economics comparing a 4m manually guided hoe with a 12m vision guided machine in organic cereals suggested that the later would reduce treatment cost by £6/ha. However, to achieve payback within 2.5 years it would be necessary to operate close to capacity which is 2600ha. This analysis takes no account of the increased efficiency due to higher precision or greater workable hours from reduced fatigue. No comparison was made with the rather more common organic weed control technique of harrowing as insufficient data is available on relative agronomic performance.

Operating the same hoe equipped with on-row herbicide band spraying was compared to conventional overall spraying from a 24m boom. On the assumption that yields would be unchanged, the hoe reduces costs by £4/ha, which when treating 2300ha leads to a payback period of 5 years. In isolation this might not represent an attractive investment, but when other potential benefits are taken into account the case improves. Examples of other potential benefits include band spraying insecticides with herbicides, reduced leaching allowing farming in environmentally sensitive areas and, perhaps more speculatively, use as a tool to assist with herbicide resistance management.

Application of this technology to banded application of crop protection chemicals in horticultural crops looks attractive when compared to overall spraying at the same 20m width. The benefit was calculated to be £128/ha giving a payback of six months.

Conclusions

- Multiple bout spanning using vision guidance techniques was reliable under field conditions.
- Lateral hoe blade position for both front and rear sections of the 12m hoe had standard deviations within 10mm at speeds up to 10kph.
- Ergonomic user display, error warnings and some automatic error recovery strategies were found to reduce driver workload.
- Poor drill bout matching, particularly near headlands, was the largest cause of driver warnings when hoeing cereals.
- Combined inter-row cultivation with precision delivery of agro-chemicals has enormous potential for environmental and economic benefit, but there are some issues regarding nozzle selection that should be addressed before further agronomic trials take place.
- Lateral spray nozzle position for the 20m band sprayer was within 25mm at speeds of up to 12kmh⁻¹
- Further field trails with agronomic and environmental assessment are needed to evaluate potential opportunities presented by this technology.

Technical Report

INCREASING WORK RATE IN VISION GUIDED PRECISION BANDED OPERATIONS

(Submitted 2005) Biosystems Engineering

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Abstract

Concerns over the economic and environmental sustainability of farming are increasing interest in techniques to reduce inputs by better targeting. One way to improve targeting is through physically aligning treatment devices with crop rows. Manual guidance is a difficult and stressful task due to the high concentration required to maintain acceptable tolerances, typically $\pm 25\text{mm}$. Under normal farm conditions GPS based technologies are unable to reliably offer this performance. Commercial implement guidance systems based on computer vision have demonstrated that the required accuracy can be achieved. However, working width is limited due to the need to match implements with drill or transplanter width in order to avoid misalignment at the interface between bouts.

This paper describes an integrated vision based system for tracking multiple bouts that has been tested in two example applications. The first was an inter-row hoe for use in cereals with three independently guided 4m wide sections, each with its own camera, operating on 12m tramlines. Trials showed that standard deviation in lateral position was 10mm at 10 kmh^{-1} . The second exemplar based on a conventional boom sprayer was a precision band sprayer for vegetables spanning five 4m wide beds. Trials indicated the standard deviation in lateral position was 22mm at 12 kmh^{-1} .

1. Introduction

Banded operations such as inter-row cultivation and band spraying can reduce inputs with economic and environmental benefits. However, to achieve the full benefit it is necessary to maintain high precision over long periods, something that is difficult to achieve manually. The importance of automatic precision guidance for agriculture has been recognised for many years (Tillett 1991), but recent innovations have introduced new practical and cost effective technologies.

In the Americas and Australia Real Time Kinematic (RTK) GPS linked with local base stations has been used to guide implements and tractors for the purposes of banded treatment and to improve general efficiency. The precision with which GPS aerial position is known is dependant on a number of factors such as distance from the base station, speed and straightness of path. Manufacturers often quote nominal

accuracy as Circular Error Probable (CEP) which is defined as a radius within which 50% of position readings will lie. Typical figures for RTK systems are 20mm under favourable conditions within 10km of the base station. This figure increases significantly as distance from the base station exceeds 10km. Dynamic correspondence between aerial position and drill coulter position during crop establishment will be dependant on detailed design considerations and field topography. Typically control error will often exceed GPS measurement errors and contribute an additional standard deviation of approximately 50mm to overall error (Bell, 2000). Taking both position sensing and controller accuracy into account one might expect drilled row position to be known (in global coordinates) to be in the region of 70 mm 75% of the time. Subsequent operations such as inter-row cultivation and banded spraying will be conducted relative to recorded global plant position, but will be subject to their own sensor and control errors of a similar magnitude. Overall, a well engineered system operating in straight lines might achieve a lateral accuracy relative to the plant row to be in the region +/- 100mm. Performance along curved paths is likely to be inferior.

For reasons related to smaller farm and field sizes and less regular field shapes RTK GPS guidance systems are less popular within Europe. A high population of trees on European field boundaries also causes reliability problems due to absorption of GPS microwave signals by water within the trees. Where precision guidance is required European farmers are more likely to guide manually, or to use local sensors following crop rows or soil furrows. Traditional crop sensors such as mechanical feelers are now being replaced by systems using computer vision. This non-contact technique (Hague et al, 2000) is versatile covering a wide range of crops, growth stages and planting geometry. The main advantages of computer vision over both manual and GPS based guidance relate to improved accuracy, typically a standard deviation of 10mm relative to the plants (Home et al., 2002). Computer vision is able to follow crop rows with smooth curves without significant loss of accuracy.

Computer vision has proved popular for guiding hoe blades between rows of high value crops for which herbicide options are either limited or non-existent. Inter-row cultivation based on vision guidance relies on the rows used for guidance being parallel with all those rows to be hoed in that pass, a condition that is only satisfied within a drill bout width, typically 4m in European arable cropping. This limitation severely restricts work rate and makes existing commercial vision guidance technology less attractive for inter-row cultivation in arable systems. Similar arguments can be applied to band spraying for which the restricted working width is even more significant in comparison to the span, typically 24m, of conventional broadcast spray systems. The single bout width barrier could be broken if sections of an implement spanning multiple bouts could be made to move independently, each guided by its own camera.

2. Objectives

This work addressed the technical challenges of robustly tracking multiple bouts and sought to demonstrate the technology under field conditions. We placed particular emphasis on achieving high reliability under difficult conditions.

3. Method

Colour images from each camera were converted to grey scale using a ratio of red green and blue that exhibited good contrast between live plant material and background, but reduced illumination effects (Marchant and Onyango 2002). The mono-chrome image was then divided into eight horizontal bands in which parallel crop rows appeared as a periodic variation in grey level according to row position. This periodic amplitude variation was extracted by the application of a digital band pass filter to each horizontal band in turn. The filter was derived to match the frequency of the crop rows whilst attenuating the lower frequency effects of shadows and spurious higher frequency features such as weeds. The derivation of that filter $f(x)$, which can be considered as a template for matching crop rows, was given by Hague and Tillett (2001) as:

$$f(x) = \frac{127}{\omega_b x} [\cos(\omega_c x) \sin(\omega_b x)] \quad (1)$$

where ω_c is the angular frequency corresponding to the nominal row spacing (radians/pixel)

$\omega_b = 0.05 \omega_c$ a tolerance band to allow for some inaccuracy in row spacing

x is the horizontal distance across the image (pixels)

Observations of row location from each camera were then passed to an extended Kalman filter (EKF), a recursive least squares estimator (Bar-Shalom, Y., Fortmann, T. 1988). The Kalman filter estimated three states for each camera relating to individual sections and one that is a measure of tractor steer rate. Of the three states relating to individual sections the first two, camera lateral offset and heading angle with respect to the crop rows, are the states necessary for dynamic tracking. A third state, the camera steady state angular misalignment, was also estimated so as to avoid the need for very accurate mechanical alignment. It was the estimate of lateral error for each individual section that was used to make lateral control corrections. The advantages of this centralised approach as opposed to multiple independent units include an opportunity for a simplified user interface and reduced component costs. The estimated rate of tractor steering was used to couple each of the sections leading to improved overall tracking.

This combination of approaches enhanced reliability in areas of poor crop and high levels of weed infestation. It was recognised however that all systems will fail at some point and strategies were implemented for automatic error recovery. The most common error situation was associated with poor drill bout matching, which was generally at its worst close to the headland where the driver had not kept the

tractor straight in the final few meters. This was addressed by allowing the system to jump rows once a side shift limit had been reached. This was done in combination with graphical and audible warnings to the driver, so that the tractor could be slowed down and any crop damage that would have occurred in an inter-row cultivation application was minimised. Alternatively, the driver could have stopped on hearing a warning, lift the implement out of work, causing the side shift to automatically centre, then lower the implement again and continue to work. The later strategy might be preferable in very high value crops such as vegetables as there should be no crop damage.

4. Experimental Equipment

Two experimental exemplars were used to test the technology and to demonstrate its capability. The first was a 12m hoe for cereals spanning three 4m drill bouts. The second was a 20m band sprayer for vegetables spanning five 4m transplanter bouts. The former provided a stable platform from which to establish levels of accuracy and the latter tested the ability of the vision system to operate from the less stable platform provided by a spray boom. Both exemplars were used to develop and test strategies for coping with failure conditions and to develop an ergonomic user interface.

4.1. Experimental 12m Hoe

The experimental hoe illustrated in *Fig. 1.* was constructed specially for the project by Garford Farm Machinery and comprised three 4m hoe sections. Where possible standard commercial parts were employed, particularly those concerned with depth control and soil engagement. The experimental cereal crops were drilled at a row spacing of 250mm with tramlines at 12m. Soil engagement was achieved with 160mm wide flat A-blades aligned at approximately 5° to the horizontal. Each blade was attached to its own parallelogram depth control wheel linkage via an adjustable spring that afforded compliance and depth adjustment. Tramlines were cultivated by three blades linked to a single depth wheel.

The nominal row spacing at the interface between bouts, determined by lateral offset of the drill between adjoining passes, was increased to 325mm. This provided a nominal +/- 115mm tolerance to error in drill bout matching due to overlap in cultivated width at the interface. If the row spacing between outer rows in adjoining bouts was less than 210mm then those crop rows were likely to be damaged by hoe blades from the adjoining bout. Where those rows were more than 420mm apart then an uncultivated strip was left between bouts.

The central 4m section was front mounted on a three point linkage. This unit incorporated a passive linear slide that allowed +/- 150mm of lateral movement independent of tractor position. Two soil engaging disks controlled by a double acting hydraulic cylinder steered the section within the stroke of the slide. The unit had two linear potentiometers one to measure disk steer angle and the other to record slide position.

The two outer 4m sections were attached via hydraulically driven lateral slides to a frame mounted on the tractor's rear three point linkage. The assembly was run with check chains tight, but to further increase lateral stiffness two fixed soil engaging discs were attached to the frame behind and in line with the tractor wheels. The pair of single acting hydraulic cylinders that positioned the side shifting frame provided $\pm 250\text{mm}$ of lateral movement to accommodate both variability in bout matching and tractor steering. The position of each slide was sensed by a potentiometer.

Each of the three hoe sections was equipped with a CCD camera mounted centrally at a height of 1.4m and viewing down at 40° to the vertical. The field of view placed approximately a 2m length of the four central crop rows into the image. For convenience both front and rear frames folded to facilitate road travel.



Fig. 1. Experimental vision guided hoe spanning 12m with three independently controlled 4m wide sections

The computer system comprised three Ethernet connected PC's, one for each section. Each PC was connected to an associated micro-controller via a serial link as illustrated in *Fig. 2*. The microcontrollers provided an interface for sensor input and solenoid valve output as well as low level control and counter timers for speed measurement. The host PC was mounted in the tractor cab, providing the operator display and interface as well as image processing for the front camera. The other two PCs were mounted on each of the rear hoe sections processing images from their associated cameras. Information derived from analysis of images from all three cameras was used to update the Kalman filter based tracking algorithm that ran on the host PC. Refined estimates of lateral error were sent to the appropriate micro-controller where a control algorithm drove solenoid operated hydraulic valves in an on-off mode so as to reduce offset error.

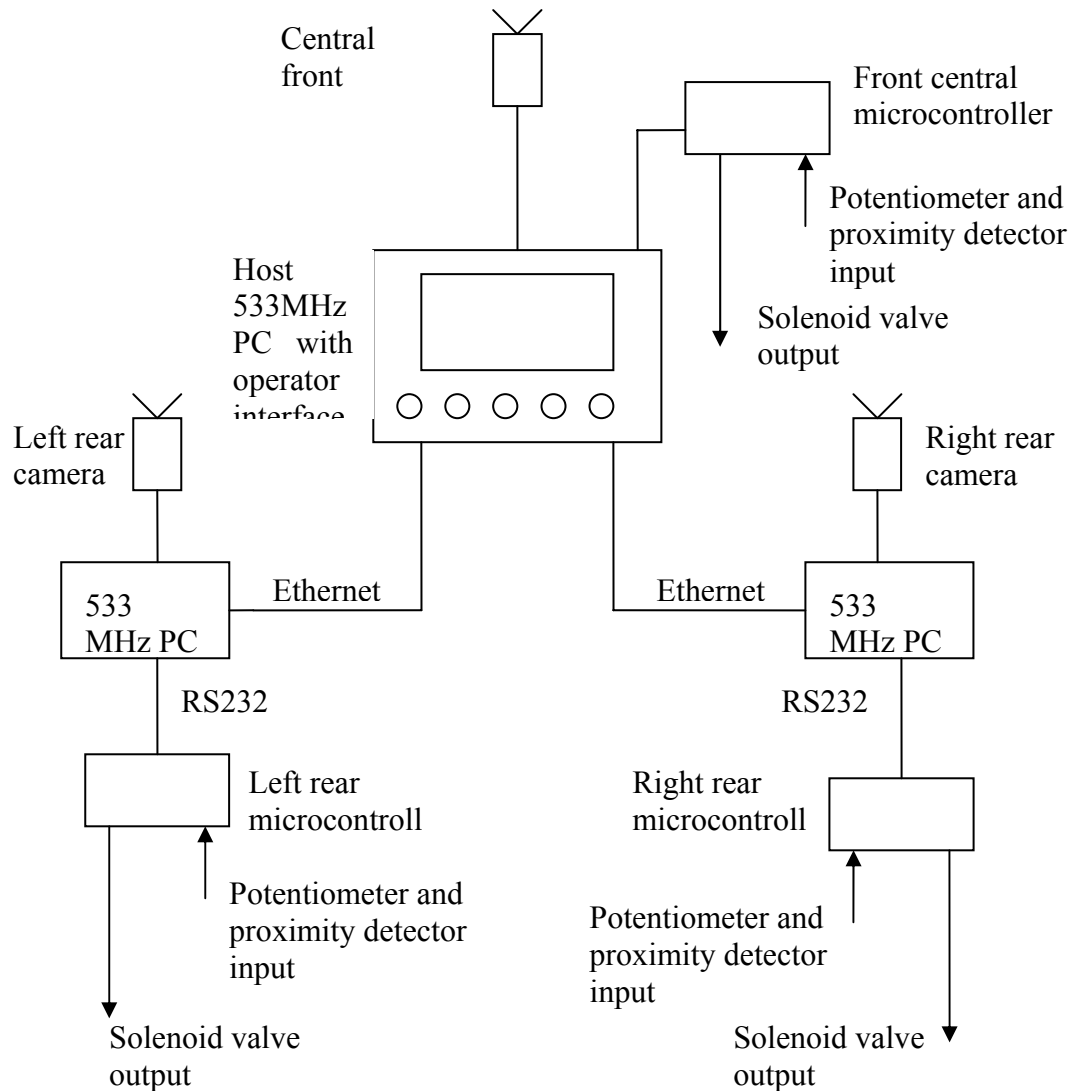


Fig. 2. Schematic of experimental hoe vision guidance computer system

4.2. Experimental 20m band sprayer

The sprayer illustrated in Fig. 3. was based on a conventional 20m trailed boom sprayer. The trial crop was brocolli transplanted in 4m bouts at a 1m row spacing. For demonstration purposes downward pointing nozzles were mounted on drop legs aligned over crop rows as illustrated in Fig. 4. Alternative drop leg positions or nozzle arrangements could however be accommodated.



Fig.3. Experimental vision guided band sprayer spanning 20m with one fixed and four independently controlled 4m wide sections



Fig. 4. Drop legs with flat fan nozzles viewed from behind and aligned over crop rows

It was assumed that the tractor driver would position the central 4m section with adequate accuracy and so nozzles on that section were fixed. The remaining four sections were each mounted on side shifting sub frames mounted within the boom as illustrated in *Fig. 4*. Side shift movement was via a DC motor driving a toothed belt with position feedback provided by a multi-turn potentiometer. Each sub frame was equipped with four drop legs. The design of the sub frames was such that normal boom folding was uninhibited.

One CCD camera was mounted on each side shifting frame at a height of 2m looking forward and down at an angle of 40° to the vertical. This created a field of view of approximately 2m wide by 3m forward from which two rows were tracked.

The computer system was similar to that used on the hoe and described above. However, as there was no central section guidance, the cab mounted host PC did not connect to a camera or micro-controller. Each of the other two computers was connected to two cameras and two microcontrollers each as illustrated in *Fig. 5*. These 800 MHz PCs were mounted at the rear of the spray trailer with Ethernet connections to the host. As a consequence of this arrangement all image processing was done on the rear computers and the Kalman filter ran on the host. The micro-controllers performed the same function as described for the hoe except that they

operated relays controlling DC motors in an on/off mode. For convenience all motors were driven from a common Pulse Width Modulation source that enables side shift speed to be varied. The final side shift rate was chosen to be 0.3 m/s.

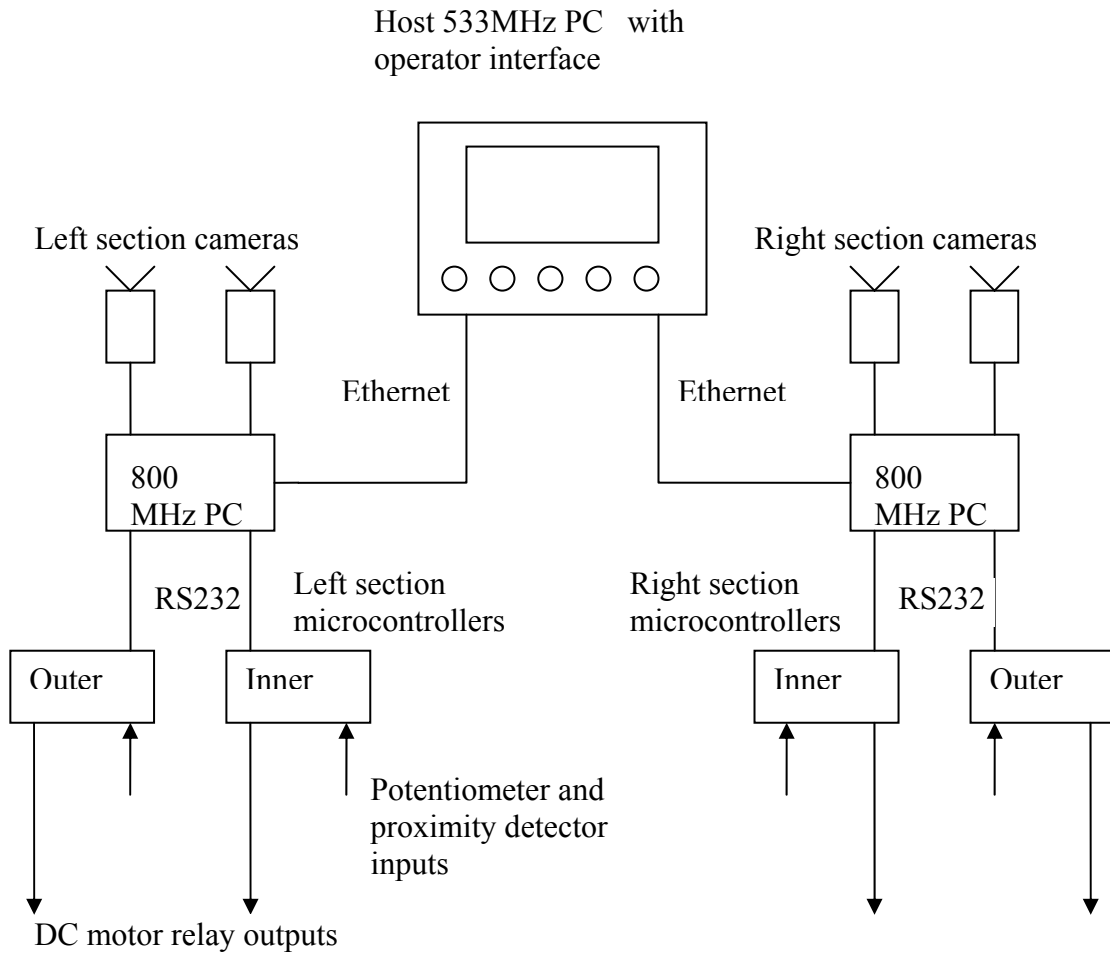


Fig. 5. Schematic of experimental band sprayer vision guidance computer system

5. Experimental system performance

5.1. Hoe

Assessment of lateral accuracy was performed using a procedure described by Home et al (2002) in which a cultivation blade was replaced by a nozzle issuing a pulsed dye trace onto the soil. Dye trace position relative to the crop rows was a measure of lateral error and the length of the pulsed trace a measure of speed. The position of crop rows was determined using a manually positioned template spanning the four crop rows tracked by the vision system. Inevitably there was a subjective element to template positioning and so some variability could be ascribed to measurement error.

Sample results of dye traces for the front and left rear units obtained in flat fields are given in *Figs. 6. and 7.* respectively. They indicate that standard deviation in lateral error for the front unit was 8mm with an overall bias of less than 1mm. This result was obtained at 6.6kmh^{-1} (1.8 ms^{-1}). The rear unit is shown as having achieved a standard deviation of 9mm with a 4mm bias at 10.2kmh^{-1} (2.8 ms^{-1}). These figures were within our performance specification target (S.D. 10mm). If we assume that maximum error due to variability in guidance is 2.5 standard deviations (25mm), then with a hoe bade width of 160mm, a “safe” band of 40mm is left to accommodate the crop. The width of this band is eroded by any systematic bias due for example to mechanical misalignment between camera and blades. However, experience would suggest that such bias is normally less than 10mm leaving an adequate margin.

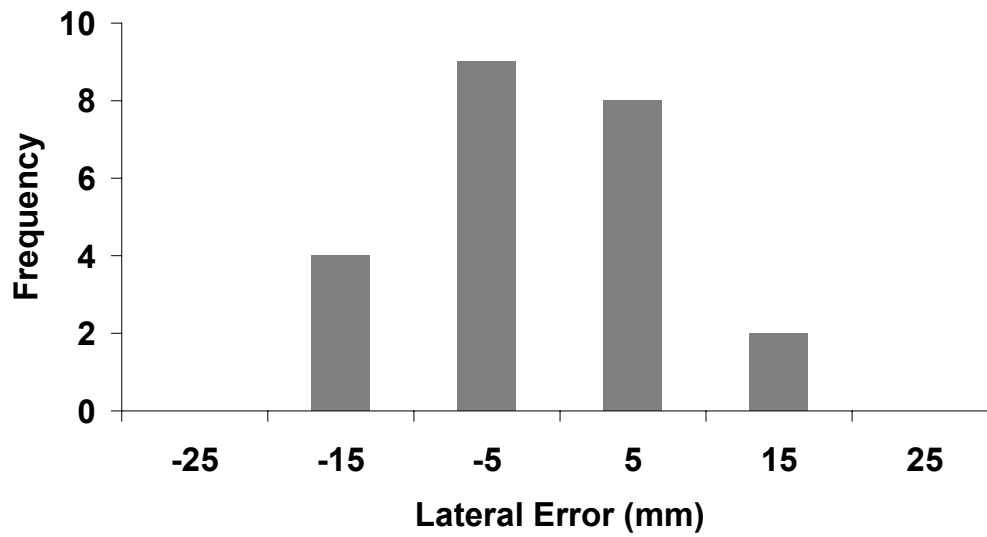


Fig. 6. Hand measured lateral error between crop rows and soil dye trace for the hoe central front unit operating at 6.6kmh^{-1}

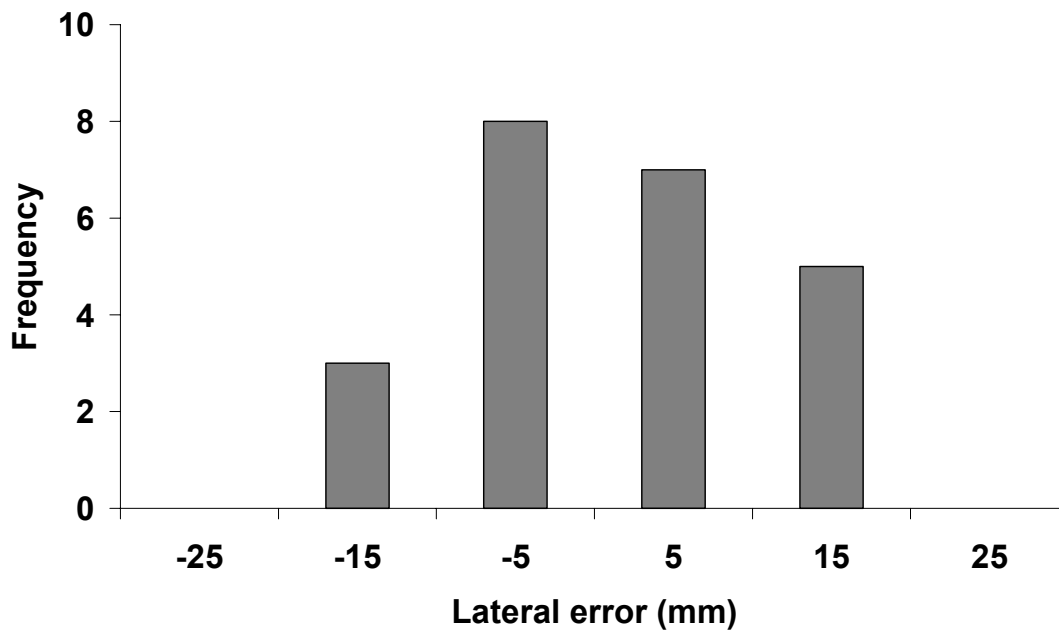


Fig. 7. Hand measured lateral error between crop rows and soil dye trace for the hoe left rear unit operating at 10.2kmh^{-1}

Trials on side slopes of approximately 5° have indicated that a down hill lateral bias of 15mm can be expected on both front and rear mounted units. Some of this bias was probably due to mechanical slack in the cultivator depth control mechanism. Alignment of the tractor up hill to compensate for side slope would

have resulted in implement heading misalignment which would also have contributed to lateral bias down hill. Based on this result and the discussion above, it is unlikely that side slopes of less than 5° would be sufficient to cause problems under normal operating conditions, though good maintenance and set up will improve performance. An existing manual offset function on the console could be used to compensate for down hill bias on side slopes of 5° or greater. However, use of this function is undesirable as the operator must remember to change offset when side slope angle changes.

Practical experience over two seasons and three trial sites demonstrated the robustness of the guidance to normal field conditions. Crop damage occurred rarely and where it did occur the system had generally triggered a warning message. By far the most common source of driver warnings was associated with poor drill bout matching. This most frequently occurred near the headland where, either the tractor had been turned slightly before the drill was lifted, or where at the start of a bout the tractor was not well aligned as the drill was lowered. However, on occasions where the manual disk based bout marker did not produce a clear mark, poor matching did persist into the field. The strategies outlined above for dealing with these problems proved effective, though inevitably reduced overall work rate due to the need to slow down or stop. It is clear that more care needs to be taken with bout matching than is traditional in arable systems.

Inexperienced tractor drivers were used to establish our trial crops and it is likely that professional drivers would perform better. Use of a GPS guidance system during drilling that restricted maximum deviations to within 12cm would complement the vision based guidance and relieve the driver of the need for special care. It would also be possible to increase side shift stroke to further increase tolerance to errors in bout matching.

5.2. Band sprayer

Lateral accuracy was assessed using a similar method described for the hoe except that the pulsed dye nozzle was attached to one of the drop legs. The measured error therefore included any movement in the drop leg itself. The trial crop was broccoli that had been transplanted 3 weeks earlier. The plant spacing in-the-row was 0.39m with a row spacing of 1.02m.

Accuracy assessment was conducted at 12 kmh^{-1} (3.3 ms^{-1}) which, due to spray boom stability, represents an upper speed limit for band spraying as currently practiced commercially. The results illustrated in *Fig. 8*. represent the combination of data from two runs in opposite directions in a flat field. Analysis of the separate data sets revealed that the moderate cross wind present during the trial resulted in only a 1mm difference in bias, suggesting that the dye jet was not significantly deflected. Overall the standard deviation in lateral position was 22.4mm. To ensure full coverage of 99% of plants the spray band width should cover ± 2.5 standard deviations plus the width of the plants. Assuming the plant width to have been 0.1m in this case the required spray pattern was 0.21m wide, 21% of total area.

For the purposes of these trials only water was sprayed onto the plants for the purposes of demonstration. The required spray band width was achieved by fitting flat nozzles that could be rotated on a vertical axis.

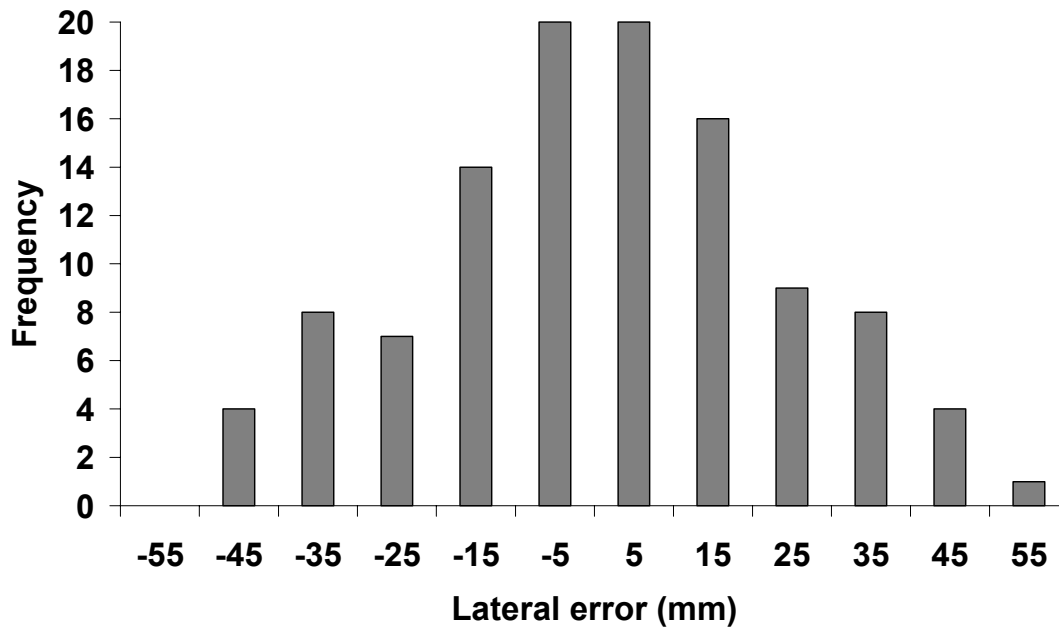


Fig. 8. Hand measured lateral error between crop rows and soil dye trace for the drop leg sprayer's right inner unit operating at 12kmh^{-1}

6. Discussion

An ability to guide field machinery along crop rows at high work rates and accuracy provides a number of new opportunities. These include ability to conduct tasks that were previously impractical, or to improve the economics and therefore the take up of tasks that had hitherto been restricted to niche applications. In this section we discuss some of these opportunities.

The most common form of secondary weed control in organic arable production is the spring tine harrow (Taylor *et al.*, 2001). Cultivation is uniform across the row and so selectivity between weed and crop is on the basis of ease of uprooting (Rasmussen, 1991). Timing is therefore critical and there is normally only a narrow window of opportunity at the early stages of crop establishment. Too early and the crop is uprooted, too late and the weeds are too firmly rooted. Harrows have the advantage of being available in widths up to 12m and operating at high speed, typically 10 kmh^{-1} .

Weed control by inter-row cultivation overcomes timing problems as selection is on the basis of geometry. Vigorous inter-row cultivation can uproot, cut or burry even well established weeds without damaging the

crop (Welsh, 1998). Traditionally the difficulty of maintaining accuracy, low forward speeds and restricted working widths have made inter-row cultivation less popular than harrowing amongst organic arable farmers. The technology described here should overcome these restrictions. However, overall economic viability will depend on the magnitude of the benefits associated with improved weed control as the cost of a vision guided hoe is likely to greatly exceed that of a harrow. Relatively little research is available on agronomic merits of hoeing over harrowing and so further agronomic trials work would be necessary to reliably establish the circumstances under which the new technology might offer financial advantages at a farm level. That research should address the effects of soil mineralization and attempt to quantify workable days as well as looking at weed control.

The very high levels of accuracy demonstrated in this project also open the way for banded application of agro-chemicals in crops grown on relatively narrow rows such as cereals. This could be done as a separate band spraying operation or more likely as a one pass operation combined with inter-row cultivation. In this case band spray mixtures would include selective herbicides with insecticides as is normal practice for overall application. If the cost of agrochemical for such overall treatments is £20/ha, then banded application of only 30% of row width would save £14/ha. If treated area were 2000ha then annual savings would be £28,000. This benefit has to be offset against the increased cost of equipment and working at only half of the conventional 24m span. Analysis of economics suggests that combining inter-row hoeing with band spraying in conventional arable production does produce a net benefit, though with a payback period of approximately 4 years, farmers would be unlikely to purchase on economic grounds alone. Other potential benefits that might make this option attractive include; reduced leaching and management of herbicide resistance. Reduced inter-row application of insecticides may also have ecological advantages, though new research would be required to establish the implications of conducting crop protection operations in this way.

The arguments made for combined inter-row cultivation and banded agrochemical application in arable crops also apply to conventional vegetable production. The constraints and economics are in many ways more favourable to the technology and single bout vision guide hoes are relatively common in this industry. Few of these machines are linked to combined band spraying, though some band spraying of vegetables does take place as a separate operation.

7. Conclusions

Multiple bout spanning using vision guidance was reliable under field conditions. Lateral hoe blade position for both front and rear sections of the 12m hoe had standard deviations within 10mm at speeds up to 10kmh⁻¹. Lateral spray nozzle position for the 20m band sprayer was within 25mm at speeds of up to 12kmh⁻¹. Boom roll and yaw over undulating ground provided the limiting factor in forward speed in sprayer performance.

Ergonomic user display, error warnings and some automatic error recovery strategies were found to reduce driver workload. Poor drill bout matching, particularly near headlands was the largest cause of driver warnings and automatic row jumps when operating the 12m hoe.

Combined inter-row cultivation with precision delivery of agro-chemicals has enormous potential for environmental and economic benefit, but there are some issues regarding nozzle selection.

Field trials with agronomic and environmental assessment are needed to evaluate potential opportunities presented by this technology.

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