Computers and Electronics in Agriculture
33 (2002) 163–177
Computers and electronics in agriculture
www.elsevier.com/locate/compag

Inter-row vision guidance for mechanical weed control in sugar beet

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Received 27 January 2000; received in revised form 18 December 2000; accepted 4 January 2002

Abstract

Despite a general move over the last 20 years towards low volume overall spraying techniques, mechanical weeding using inter-row hoes is still practised by a significant number of UK sugar beet growers. Reasons for this include the control of difficult weeds e.g. volunteer potatoes, thistles and larger weeds surviving herbicide application, as well as the control of weed beet. However, for general weed control, savings in herbicide cost have to be balanced against a relatively low hoeing work rate. Increased use of inter-row hoeing to achieve the potential economic and environmental benefits, can only be accomplished by the introduction of high workrate equipment. This paper describes research, building on earlier work conducted in cereals, which addresses the problems of automatically guiding hoes between rows of sugar beet at high speed. Results indicate that the previously used combination of Kalman filter row tracking and bandpass filter row location provide a sound basis for following rows of larger sugar beet plants. Smaller plants could also be followed if the single pixel scan lines used by the bandpass filter algorithm were replaced by bands formed by merging columns of pixels to increase the information content. The hoe was evaluated at 6 kph under a variety crop conditions ranging from two true leaves with a population of 1700/m^2 newly germinated weeds, through to a relatively clean crop in which crop plants had just started to touch in-the-row. Lighting conditions included diffuse sky and direct sun illumination in which the tractor and hoe cast shadows in the image region. Under this range of conditions standard deviation in hoe lateral error relative to crop rows remained within 16 mm and mean bias never exceeded $\pm$ 10 mm. Additional tests to evaluate the hoe's ability to cross gaps in which all four of the crop rows used for guidance had been removed showed that error did not become unacceptable until gap length exceeded 4 m.

Keywords: Mechanical weed control; Vision guidance; Inter-row guidance

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PII: S0168-1699(02)00005-4

1. Introduction

Agricultural weed control techniques have over the last 20 years become largely reliant on low volume overall spraying of herbicides. However, in a number of minority crops, including sugar beet and many vegetables, mechanical weeding using inter-row hoes is still practised by a significant number of growers. Reasons for this in sugar beet include the control of difficult weeds e.g. volunteer potatoes, thistles and larger weeds surviving herbicide application, as well as the control of weed beet. Herbicide manufacturers are reluctant to spend the large development and approval costs associated with new herbicides in this relatively small market and so the situation is unlikely to improve and may well get worse as older formulations loose approval. Savings in herbicide costs are also a motivation for mechanical methods. However, as Palmer and May (1986) reported, the 50–60% cost savings from inter-row hoeing/band spraying systems over overall spraying have to be balanced against a low work rate and the risk of being unable to complete treatments in the time available.

Weed control in sugar beet by overall harrowing has been investigated by Westerdijk et al. (1997). Their best results were obtained at the six leaf stage when it was possible to replace a late herbicide application with a harrowing treatment without loss to yield. However, herbicides were still required to control weeds at earlier crop growth stages. Harrowing also causes excessive crop damage at latter stages and so the technique can only be a partial control measure.

A widespread return to inter-row hoeing to achieve the potential economic and environmental benefits of reduced herbicide usage, can only be accomplished by the introduction of high workrate equipment. This paper describes research addressing the problem of automatically guiding hoes between crop rows that will allow higher forward speeds to be achieved with the potential to span multiple drill bouts at one pass. A further objective is to maximise workable hours by increasing the range of conditions in terms of lighting, soil type and crop growth stage in which the system can operate, thus providing an efficient and practical mechanical weeding option.

A number of attempts have been made to guide inter-row cultivators using machine vision. Many of these (e.g. Reid and Searcy, 1988) relied on the production of a binary image through a thresholding process. Unfortunately under direct lighting conditions shadows cast by the tractor or hoe lead to poor results using thresholding. Slaughter et al. (1997) overcame this limitation by shading the entire image region, a solution that is not practical under all circumstances. Olsen (1995) proposed a method that was largely unaffected by partial shadowing. In his technique the image was reduced to a single line by the vertical summation of pixel intensities in each column of the image. A Butterworth low pass filter was applied to smooth the summed intensities; local maxima in the filtered intensity were then taken to be the location of the crop rows. His technique was successfully tested on video taped images of cereal rows, but proved unsuccessful with young sugar beet.

Our first work in guiding inter-row hoes was also conducted in a cereal crop (Tillett and Hague, 1999). Unlike previous workers we used a Kalman filter to track crop rows. This has several advantages including: an ability to predict row location, reducing search time for image features; vision observations can be weighted according to confidence in them; the correct central row or rows can be consistently identified. Our initial row location algorithm used a binary threshold to extract row location. Under diffuse lighting reliable performance with standard errors of 16 mm at 1.6 m/s were obtained. Predictably the system was not reliable with partial shadows in the field of view. In subsequent work (Hague and Tillett, 2001) a bandpass filter was used to extract lateral crop row location at eight evenly spaced horizontally scan lines in the image. These eight observations were used directly by the Kalman filter to derive both heading and offset at the hoe blades. Using this approach we maintained our accuracy but widened our operating conditions to include those with shadows. However, in common with Olsen, early experience on sugar beet showed the technique to be unreliable when plants were small.

This paper describes guidance and control aspects of research aimed at extending the operating range of our row tracking system to sugar beet. Agronomic effectiveness is being evaluated under a collaborative project and will be reported in due course.

2. Experimental equipment

2.1. Steerage hoe

The hoe is a 6 m span standard design built commercially by Garford Farm Machinery Ltd (Frognall, Deeping St. James, Peterborough, PE6 8RR). It consists of two frames, the first of which is rear mounted on a tractor three-point linkage with check chains tight. Further lateral stability is provided by two flanged wheels that also control depth. An additional side-shifting frame is attached behind the fixed frame via two sliding bearings as illustrated in Fig. 1. Relative lateral movement is provided by two antagonistically arranged 0.3 m stroke single acting hydraulic cylinders. A Linearly Variable Differential Transformer (LVDT) mounted in parallel with the cylinders provides feedback of side shift position. The cultivator units are attached to the sliding frame at a 0.5 m pitch corresponding to the row spacing. Each cultivator unit has an independent depth wheel with a frame capable of mounting a variety of cultivator and crop protection side guards. In these trials each unit was equipped with three 'A' blades and two side guards. One of the depth wheels is equipped with 12 studs on a circumference, which are detected by an inductive proximity switch to provide an odometric measure of speed. For ease of road transport the outer sections of the side-shifting frame fold vertically.

It should be noted that the guidance technology described in this paper could also be applied to a variety of other implements and mechanical steering arrangements. This would include systems in which the guidance information was used to steer a tractor to which implements were rigidly attached.

2.2. Lateral position control

Lateral position is controlled by regulating the rate of flow of oil into the hydraulic cylinders. For reasons of economy and robustness a low cost, solenoid-operated, closed centre tandem spool valve regulates flow. Thus, in the same manner as that previously reported for our cereal hoe, control acts in three states, shifting left, shifting right and stationary. In a refinement to the earlier system the

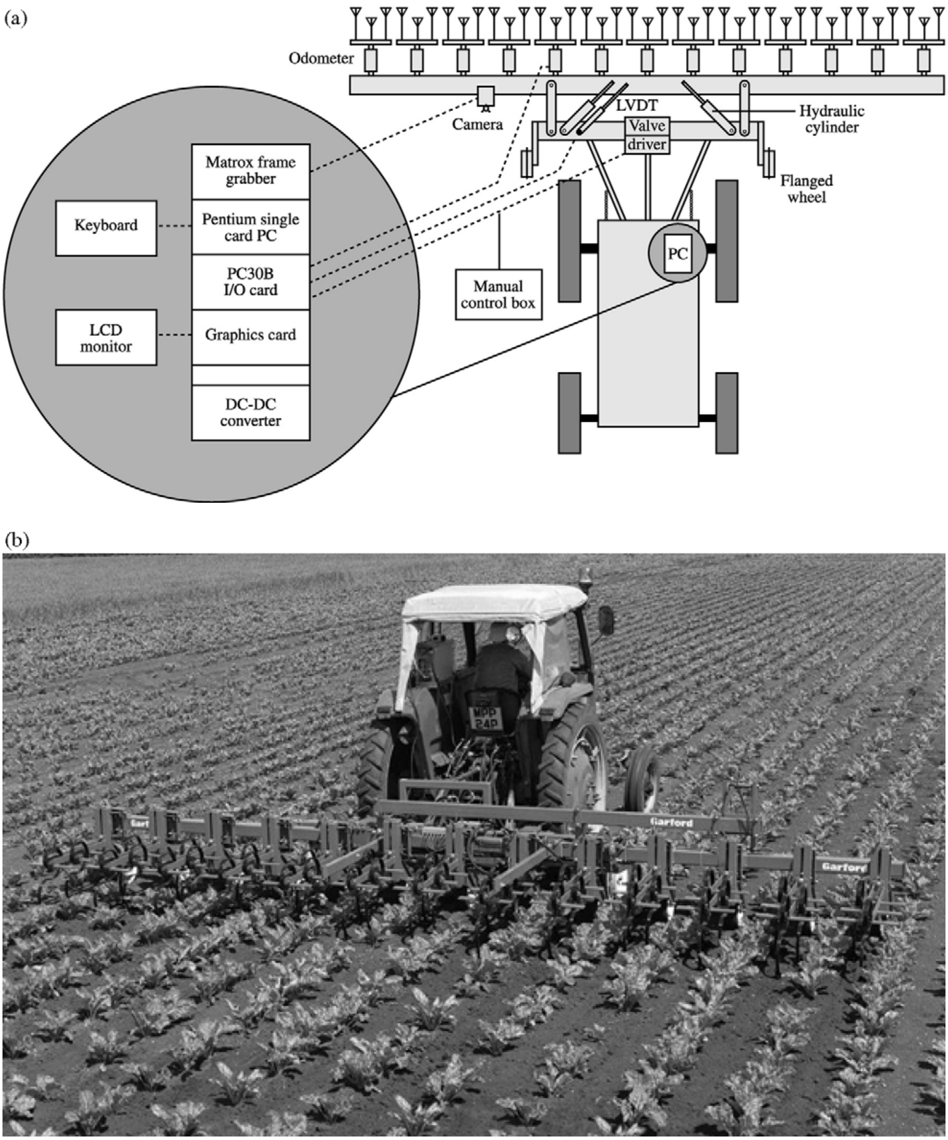


Fig. 1. (a) Schematic of steerage hoe. (b) Steerage hoe.

hydraulic supply to the spool valve is delivered via a variable rate flow divider. This valve ensures that within normal operating conditions side shift rate is independent of both external load and the tractor hydraulic pump speed. Flow rate is adjusted manually to provide a side shift rate matched to the maximum expected rate of change of offset between the hoe and crop rows. In the work described here side shift rate was approximately 0.08 m/s. The response time of the valve was measured at approximately 0.1 s. Accordingly a dead band of ± 9 mm was set in order to prevent overshoot-induced valve chatter.

2.3. Camera and computer

A standard mono-chrome CCD camera is mounted on the side shifting part of the frame such that it is central to the rows being followed when lateral error is zero. Contrast between plant and soil is enhanced by placing a near infrared bandpass filter (Wratten 89B) behind the lens. A number of camera heights and angles were considered. In general, a low mounting, angled closer to horizontal, produces images with the most distinct crop rows. However, that information relates to crop some distance ahead of the hoe. It is particularly important that lateral offset information is available in the area immediately ahead of the cultivators. After some experimentation a compromise height of 1.14 m above ground level looking forward and inclined downward at 40° to the vertical was selected. A 4.8 mm focal length lens was chosen, to provide an adequate view of the four crop rows being tracked without causing significant image distortion. Equations relating ground co-ordinates to the image plane, derived from the optical arrangement, are given in Hague and Tillett (2001).

The IBM PC-based computing platform is identical to that used in earlier work. It comprises a 200 MHz MMX Pentium with a frame grabber card configured to produce 8 bit grey scale images at a resolution of 384 by 288 pixels. A general purpose interface card provides additional input/output.

3. Row following

3.1. Image acquisition

Images are acquired at standard video rate (25 Hz). Camera aperture is set manually and CCD integration period (‘silicon shutter’) is set automatically in such a way that contrast between crop plants and the soil background is maximised and saturation avoided. The method previously used for cereal crops was to set shutter speed so as to maintain the mean grey level of the image close to mid range. This was accomplished by reducing the shutter period if the mean image intensity fell in the upper quartile of the scale, or vice-versa. This method functions well where the features of interest (the crop) occupy a significant portion of the image as is the case for cereals and large sugar beet plants. However, in the early stages of growth sugar beet plant material accounts for a small proportion of the image area, and hence control of mean grey level gives good exposure to the soil, but the small (bright) beet plants become saturated reducing plant/soil contrast. To avoid this problem saturation is detected by the presence of a peak in the histogram of pixel intensities at the top of the grey scale. When such a peak is present the need to reduce exposure time to avoid saturation overrides control of average grey level.

3.2. Bandpass filter and image manipulation

In our initial work on guiding a cereal hoe (Tillett and Hague, 1999) row features were extracted from a thresholded image and tracked using a Kalman filter. In a refinement to this system (Hague and Tillett, 2001) the feature extraction process was replaced by a bandpass filter approach to crop row location. The bandpass filter method is not reliant on the premise that plant material may be discriminated from the background on the basis of a brightness or colour threshold. Instead, we exploit the periodic amplitude variation of horizontal scan lines due to the parallel crop rows. In the cereal hoe version eight evenly spaced scan lines in image space are filtered in this way. Given the geometry, a filter is derived which allows the frequency of the crop rows to be extracted 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, is given by Hague and Tillett (2001) and is given here for completeness:

$$f(x) = \frac{127}{\omega \mathrm{b} x}[\cos(\omega \mathrm{c} x)\sin(\omega \mathrm{b} x)]$$

where ωc is the angular frequency corresponding to the nominal row spacing (radians/pixel), $\omega \mathrm{b} = \omega \mathrm{c} \cdot 0.15$ a tolerance band to allow for some inaccuracy in row spacing, x is the horizontal distance across the image (pixels).

The bandpass filter technique as described above requires that most scan lines contain enough information about individual rows to provide an estimate of overall crop row position, or phase along a scan line. This condition is satisfied in a cereal crop which, from an early stage, forms a virtually continuous row feature due to the high seed density and significant vertical growth. In contrast, sugar beet is precision drilled such that plants are spaced at 190 mm intervals within a row. This combined with a prostrate habit means that at an early crop growth stage any single horizontal scan line is unlikely to intersect more than one or two plants. In order to increase the information content of each horizontal line a number of scan lines are merged vertically to form bands. The image is split into eight bands with additional unused half bands at the top and bottom to minimise edge effects such as blank scan lines and radial distortion. Each band has a width in ground co-ordinates of not less than the in-the-row plant spacing, thus ensuring that every band should contain part of a plant at each individual row position. The number of bands is also limited by computation time.

Merging scan lines to form bands has the potentially undesirable effect of smoothing data to the extent that contrast is reduced. Consequently, for small crops in which vegetation covers only a small part of the total image, contrast is enhanced by taking the brightest value of all pixels within a column. Larger crops use a simple linear average. It is therefore necessary for the operator to specify if the plants are small, arbitrarily defined as those covering less than half the scene, or large.

The derivation of the bandpass filter or template used in our earlier work (Hague and Tillett, 2001) and illustrated in Fig. 2a was based on an idealised periodic variation in grey level across scan lines. This is a reasonable approximation in relatively closely spaced cereal rows, whose density and height create dark inter-row spaces. Thus, in cereal crops there is information in both the bright crop rows and the dark inter-row spaces. However, at the early stages of sugar beet growth this is not the case. Inter-row spaces are not shaded and therefore relatively bright. The inter-row spaces may also include weeds or other bright features that reduce the quality of template match to the true crop rows. Our experimentation showed that a better approximation could be achieved by truncating the negative parts to create a template as illustrated in Fig. 2b. This truncation reduces sensitivity to variations in background brightness between rows. Thus for large plants, as defined above, the original linear filter is used and for small plants the truncated version is applied.

Factors such as weed growth or areas of missing crop result in some image bands that do not convey accurate or reliable information about row position. To obtain a measure of confidence that should be placed on each image band the quality of template match is obtained. This is achieved by comparing the result of applying the template $\pm 90°$ out of phase with its position of best fit with the best fit value using the following relationship:

$$1-\frac{(\text{match at}+90°+\text{match at}\;-90°)}{2(\text{match at best fit})}$$

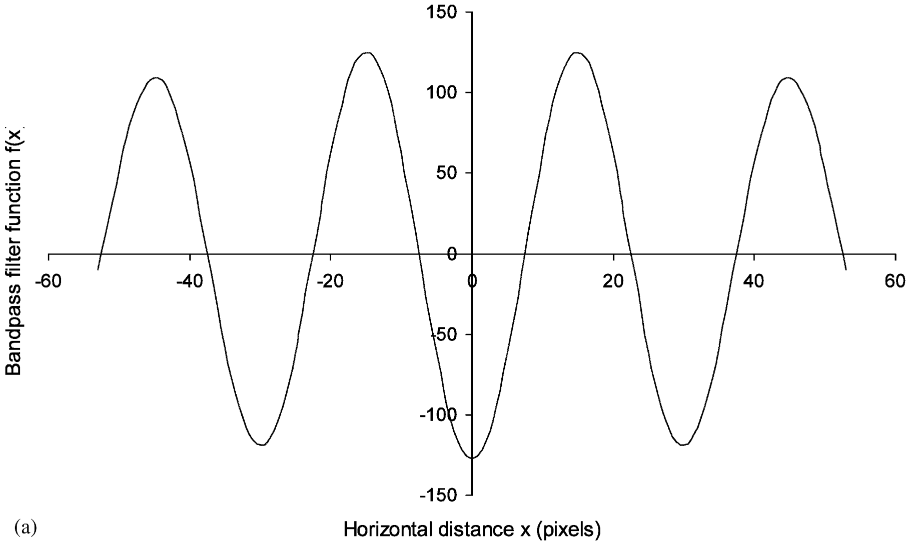
This confidence term has a value between one, indicating a good fit, and zero, indicating a poor template match.

3.3. Kalman filter tracking

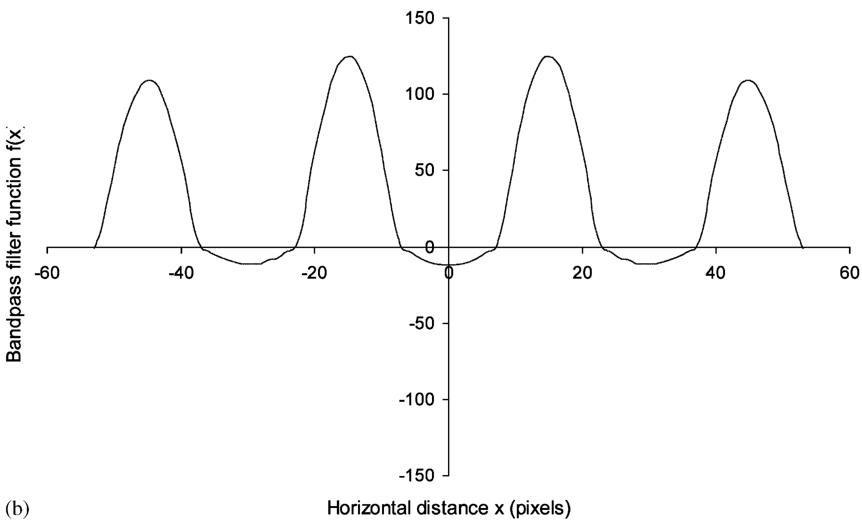
To track hoe position with respect to crop rows we make use of the extended Kalman filter (EKF), a recursive linear estimator, which is covered in a number of texts (Bar-Shalom and Fortmann, 1988; Maybeck, 1979). In our application the Kalman filter takes an observation of row position from each band in an image and calculates an estimate of current hoe position based on all the observations, combined with a predicted position based on previous position and side shift and odometrically measured movement.

Our Kalman filter estimates a three element state vector. Two states, hoe lateral offset and heading angle with respect to the crop rows, are the minimum required to describe the kinematic situation. A third state, a correction for camera angular misalignment, is added due to the practical difficulty in achieving adequate accuracy mechanically.

The Kalman filter operates in a predict/correct cycle. The prediction step is based on a process model that exploits the kinematic constraints of the tractor/hoe



(a)



(b)

Fig. 2. (a) Template used on large plants (Hague and Tillett, 2001). (b) Truncated template for small plants.

combination and uses odometrically measured travel distance and hoe side shift movement. The correction step uses an observation model based on a pin-hole camera representation of the optics and the predicted state to calculate expected row position in image co-ordinates for a particular band. That expected position is compared with the observed value to determine an error term. If the error exceeds a preset value that observation fails a validation test and is ignored. Otherwise that innovation is incorporated into the state estimate using the standard first order EKF equations. These equations update the state estimate in such a way that appropriate weighting is attached to predicted and observed positions according to our relative confidence in the two values. Each of the eight bands from an image is treated sequentially in this way so that at the end of a Kalman filter iteration the revised state estimate has taken all observations into account. The revised state estimate is then used in the calculation of the next prediction and so the cycle continues. The side shift control algorithm uses the latest estimate of lateral offset and runs synchronously with the Kalman filter at 25 Hz.

A more detailed mathematical explanation of our implementation of the Kalman filter can be found in Hague and Tillett (2001).

4. Experimental procedure

To record hoe path one cultivator unit was removed and replaced with a nozzle dispensing white emulsion paint. The position of this trace relative to the crop rows was then manually recorded at one metre intervals using a template. The template consisted of a metric ruler with four marks corresponding to the four crop rows used for guidance. With the template laid over the crop to give a best fit, paint trace position was measured to the nearest 5 mm.

Key row tracking parameters were logged at 25 Hz during all experimental runs. Images were also stored at one second intervals, samples of which have been enhanced for clarity of display and presented in Fig. 3. In order to plot both paint trace and logged data on the same scale odometry based speed has been integrated to provide a forward distance measurement.

Tractor speed was approximately 6 km/h in all runs. The crop rows were all nominally straight.

5. Results

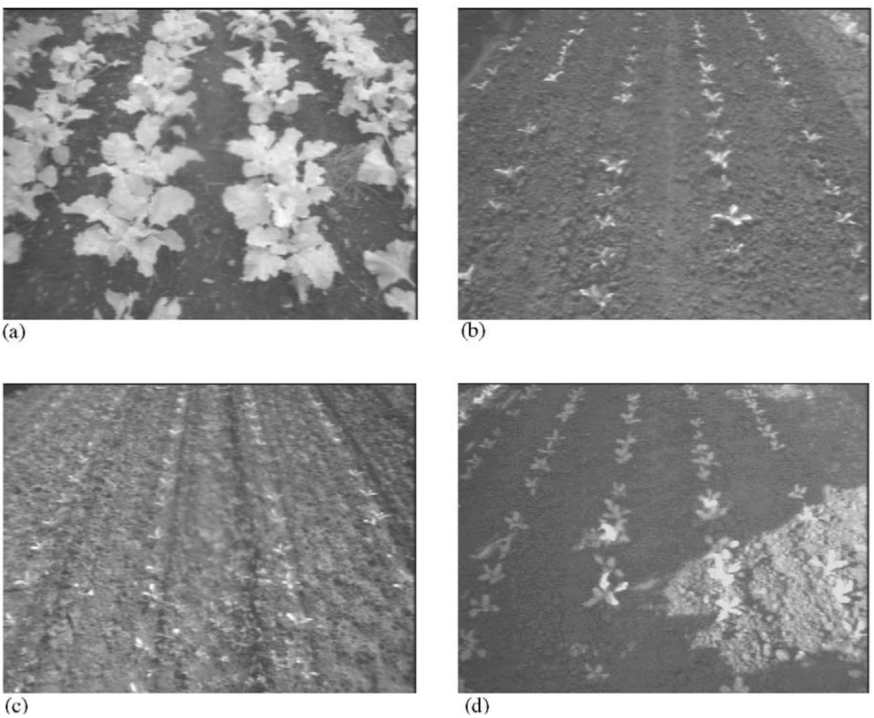
5.1. Performance on large plants

The hoe was run under a diffuse sky in a relatively weed free crop at an advanced stage of growth such that plants formed a continuous feature within the row but left typically a 0.1 m gap clear of leaves between rows. This growth stage is the latest at which commercial hoeing is likely to take place. Experimental runs in this crop were 110 m long though only a 40 m section is plotted in Fig. 4 for consistency with other Figures. Analysis of performance over the full run length gave a mean offset of -5 mm and standard error about the mean of 16 mm. A typical image is given in Fig. 3a.

To obtain a measure of likely performance without a guidance system the logged LVDT data has been added to the paint trace position and displayed in Fig. 4. Analysis of the derived unguided trace gives a mean bias of -74 mm and a standard deviation of 25 mm. Whilst better performance might be achieved by an experienced driver the results clearly indicate the advantages of independent automatic guidance.

5.2. Performance on small plants

Results from two small plant scenarios are presented here. Both were obtained in direct sun with no shadow in the image region. The first, illustrated in Fig. 3b, represents a typical first hoeing of a crop at the four true leaf stage in which weeds are under control and are not a significant factor in row detection. Fig. 5 shows performance in this crop which produced a mean bias of -5 mm and a standard



(a) (b) (c) (d)

Fig. 3. (a) Enhanced image of large plants. (b) Enhanced image of plants with four true leaves. (c) Enhanced image of plants with two true leaves and a significant weed population. (d) Enhanced image partially in shadow of plants with for true leaves.

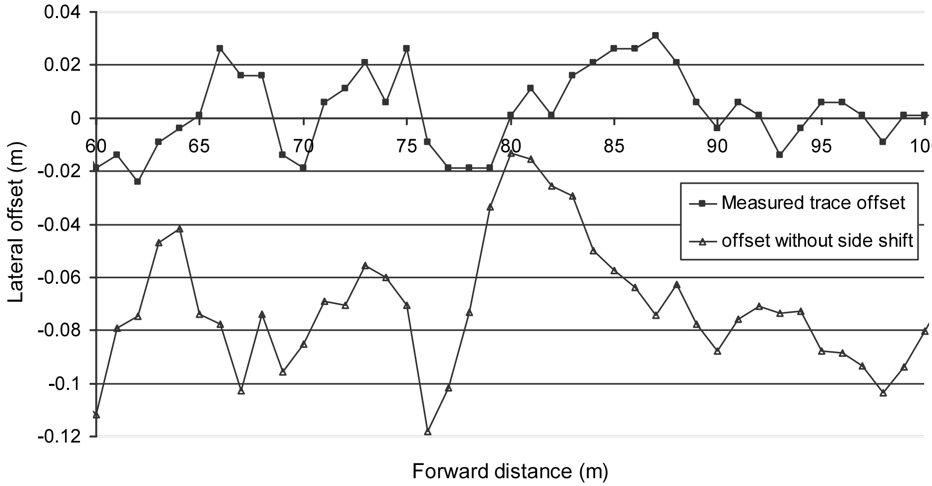


Fig. 4. Row following performance with large sugar beet.

error of 12 mm. The apparently improved performance over larger plants reported above was possibly due to the greater precision with which manual measurements can be made on smaller plants.

The second was a more challenging situation in a crop with only two true leaves and a carpet of very small newly germinated weeds at an approximate density of $1700/m^2$. This represented a situation in terms of plant size and weed population

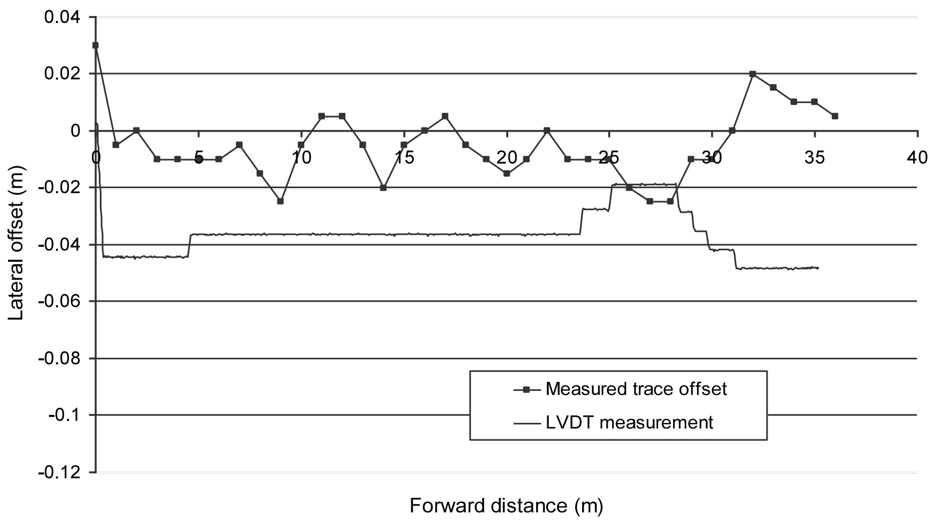


Fig. 5. Row following performance in sugar beet with four true leaves.

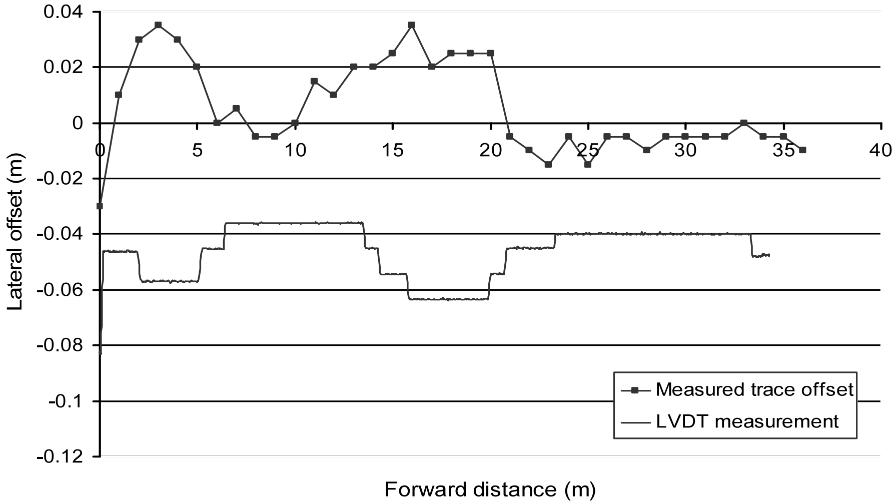


Fig. 6. Row following performance in sugar beet with two true leaves and a significant weed population.

that commercial growers would hope to avoid. Fig. 6 shows hoe performance that produced a mean bias of $+5$ mm and a standard error of 16 mm. Off line examination of individual images such as that illustrated in Fig. 3c indicated that the quality of vision data was poor. It is therefore likely that in this situation a number of observations were either failing the validation gate or being assigned a low confidence. From this we conclude that the system was operating close to its limit.

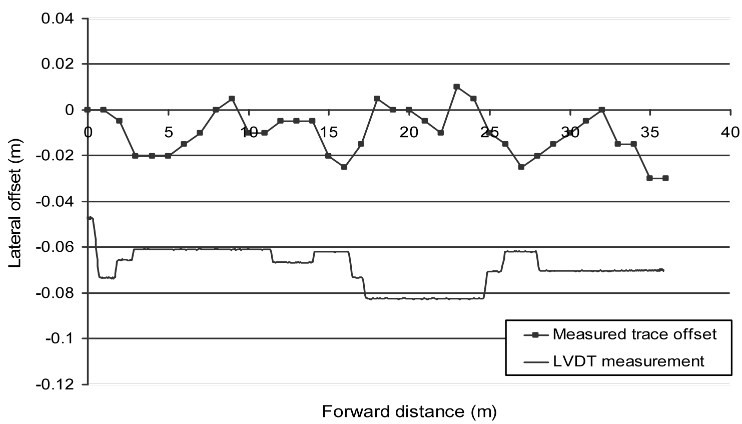


Fig. 7. Row following performance in sugar beet with four true leaves and a partial tractor shadow in the image.

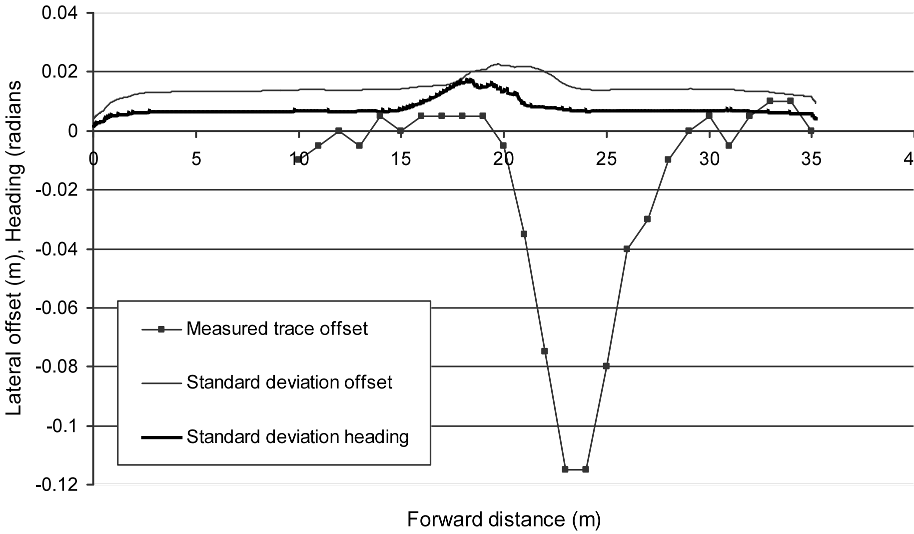


Fig. 8. Gap crossing performance in sugar beet with four true leaves.

5.3. Effect of tractor shadow in the image region

A number of runs have been made in which the tractor and hoe cast shadows in the image region. These, of which Fig. 7 is a typical result, confirm our earlier result in cereals (Hague and Tillett, 2001) that the technique is robust to a range of shadow shapes. In this example mean bias was -10 mm and standard error was 10 mm. A typical image of the crop, which was at the four true leaf stage, is given in Fig. 3d.

The experiment described did not attempt to measure any potential bias in offset due to variations in lighting direction. This will be the subject of future work.

5.4. Behaviour at gaps in the crop

An experiment was devised to evaluate how the system behaved in situations in which crop data is temporarily not available, due for example to a patch of total crop failure, patches of weed infestation or, as happens routinely, a headland is encountered. To simulate this a section of crop was cleared completely over all four rows used for guidance. The length of that section, which started at 18 m along the bed, was increased in steps to 1, 2, 4 and 6 m. All runs were conducted in direct sun with no shadow in the image region. Up to and including the 4 m gap, the hoe path as measured from the paint trace showed no apparent increase in error as the gap was traversed. Once the gap was extended to 6 m the hoe suffered a significant excursion peaking at -115 mm as illustrated in Fig. 8. However, once the gap was crossed and crop became visible again, the hoe quickly locked back onto the correct set of rows. Behaviour when encountering sections of missing crop significantly longer than the 3 m field of view depends upon the particular value of heading obtained as the last valid observations were made.

In addition to showing offset information Fig. 8 also displays the logged estimated standard deviation of the heading angle. When a loss of crop is encountered it is the heading estimate that is affected first as it is heavily dependent on features at the top of the image. Consequently, at approximately 15 m along the bed as the area of missing crop comes into the top of the image, estimated standard deviation in heading increases from what is normally a very stable value of approximately 0.007 rad to a peak of 0.017 rad. This increase might be used to detect a condition in which the vision information was becoming unreliable and implement a strategy to avoid consequential erratic behaviour. Such a strategy might, in addition to warning the driver, set estimated heading angle to zero on the assumption that the tractor will remain generally aligned with the crop rows. A similar strategy might use an excessively large estimated standard deviation in offset to trigger a centralising of the hoe side shift mechanism. Thus, even in total failure it might be possible to achieve performance equivalent to an unguided hoe.

6. Conclusions

1. The merging of horizontal scan lines into bands to enhance the row structure of young sugar beet plants was successful in creating features that could be located and tracked using the previously reported bandpass and Kalman filtering algorithms.
2. Under field conditions the minimum crop growth stage for hoe guidance was two true leaves.
3. Under typical field conditions operating at 6 kph standard deviation in hoe lateral error relative to crop rows was within 16 mm with a mean bias of not more than 10 mm.
4. Performance was not significantly affected by partial occlusion of the image area by shadow.

Acknowledgements

This work was funded by the British Beet Research Organisation with additional support from Garford Farm Machinery. The programme of work is being conducted jointly with ADAS Arthur Rickwood.

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