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# Determination of crop rows by image analysis without segmentation

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**Abstract**

A method based on computer vision for detection and localisation of crop rows, especially of small-grain crops, is described. The method is intended for use in a system for automatic guidance of agricultural implements in selective treatment of rows and/or inter-row spaces, e.g. with an inter-row cultivator. The computer vision system consists of a colour video camera and a computer. The camera is focussed on the field surface from an inclined angle to obtain images that cover up to about five rows simultaneously. New images are continuously transferred to the computer, which processes them and calculates the necessary lateral movements of the implement. The processing method does not include a segmentation step, which is found in most other methods for plant detection. The segmentation step has been replaced by computation of centres of gravity for row segments in the image. This approach has proven to reduce the computational burden of the image processing software. The estimation of the orientation and the lateral position of the centre lines of the rows is accomplished by weighted linear regression. The accuracy of the estimation was determined by comparing the calculated row centre line with the position of a reference string, which was placed parallel to the row along the centre line of an adjacent inter-row space.
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## 1. Introduction

There is a long tradition of growing certain crops in northern Europe, e.g. sugar beets, in rows spaced at a considerable distance. Although wide spacing was used because of the space required by fully developed plants, this method also made it possible to control the weeds mechanically, at least in early stages of crop development and especially in the inter-row space.

With the recent concern about the content of pesticides in both crops and groundwater resources, the idea emerged that it might be feasible to grow other crops in rows, thereby gaining the same possibilities for mechanical weed control. Small-grain cereals fall into the category where such a system may be used. Therefore, a project was started at the Danish Institute of Agricultural Sciences with the aim of testing various aspects of applying the described method to cereal crops.

In Scandinavia, cereals are traditionally sown in rows with 0.12 m inter-row spacing. In the project, this spacing was doubled to 0.24 m to provide sufficient space for mechanical tools while still making it possible for the crop to produce a closed canopy within a relatively short time. In addition, this spacing implied other advantages, such as placing the fertiliser close to the crop plants, thereby minimising the supply of nutrients to the weeds. Naturally, the farmer is concerned about a possible lower yield from the field due to the double row spacing. Recent research has shown that the yield depression may amount to 7% (Johansson, 1998).

However, this cultural practice introduces a relatively novel problem, namely the need to guide the implement, e.g. a fertilising machine or a row weeder, along a crop row with an accuracy of about $\pm 20$–40 mm. Formerly, this was performed manually by a person seated on the implement with a direct view of the rows, but this is hardly possible with a modern growing concept like the present one. Firstly, the rather limited row spacing of 0.24 m combined with the wide implements used today would require a very intense observation of the guiding process together with quick reactions by the human operator. Secondly, considering the very large areas grown with cereals, the task would be quite overwhelming.

For this reason, a sub-project was initiated with the goal of developing a system for automatic guidance of implements with respect to crop rows. After some initial considerations of various guidance principles it was decided that the system should rely on video images of the crop rows. The aim is to guide the implement and not the tractor pulling the implement. The task of driving the tractor and supervising the overall process would be left to a human operator.

Typically, once an image has been recorded, it is divided into objects and background. Many workers have addressed this problem and different solutions have been proposed. Thus, some authors report on a method that utilises a lookup table whereby an image pixel is compared with values in the table and consequently classified as plant or background (Slaughter et al., 1997; Tian et al., 1997). A somewhat different approach is reported in a project concerning the construction of a self-steering tractor (Gerrish et al., 1997). Here the operator is required to initiate the system by setting a reference colour, which is subsequently used by the system for detection of living plants. Some authors have worked with infrared images instead of colour images using only the shifts in grey level for segmentation of plants in the images (Marchant and Brivot, 1995; Brivot and Marchant, 1996). Infrared images may also be suited for methods that do not require segmentation (Olsen, 1995). More recently, Åstrand and Baerveldt (1999) developed a system of finding rows in a sugar beet crop that utilises infrared images with a fixed threshold value for segmentation.

Once the plant objects have been isolated a line should in some way be fitted to these objects. This is possible using a Hough transformation technique (Reid and Searcy, 1986; Marchant and Brivot, 1995; Marchant, 1996; Torii et al., 1995). Some workers find the computational load of the Hough transformation method quite high and use other methods instead. Therefore, various statistical estimates of central tendency have been examined, notably the mean, the median, and the mode (Slaughter et al., 1997). Of these, the median was found to produce the best results. Also a least squares method has been used instead of the Hough transform (Torii, 1998).

Detection of crop rows is also described by Tillett and Hague (1999). These workers used a near-infrared filter to enhance contrast between plant and soil. The resulting images were segmented based on a threshold value calculated from the average grey level obtained from a number of sample points in the images. In a later paper (Hague and Tillett, 2001) the authors refined the method of crop row detection by using a bandpass filter for localisation of the rows. This method is also characterised by avoiding to segment the images in order to discriminate green plant material from the soil background.

## 2. Scope

The goal of the present work is to develop a system that—with sufficient accuracy—can guide an implement with respect to crop rows consisting of a nearly continuous crop canopy. The system should be able to work even with newly emerged plants that are in their initial stage of growth. This task should function by use of natural light only, with the exception of possible operation at night. It should, thus, be able to work under a wide range of illumination situations. The accuracy should be within the range of a few centimetres, i.e. $\pm 20$ to $\pm 40$ mm depending on the crop and its degree of development.

## 3. Material

An experimental field of approximately 100 m in length was sown with barley several times during the summer period. Within the bout of the seed-drill the inter-row distance was fixed at 0.24 m. When the plants had developed to a state where they nearly covered the soil surface and thus could no longer be used in the experiment, the field was cleared, harrowed and resown. About mid-summer, water stress appeared at some places along the rows, and images from these areas showed signs of poor emergence and high weed infestation.

The electronic equipment consisted of a JVC KY-F55 colour video camera equipped with three CCD chips for the red, green, and blue channels of the image. The resolution of the images was $720 \times 576$ pixels. For the initial experiments the video signal was fed to a Targa 2000 PCI frame grabber mounted in a standard PC on which the image stream was stored on a hard disk at a rate of 25 frames per second each frame compressed according to the Motion JPEG Codec Architecture. The disc storage rate was 5 MB/s and the size of one image was 200 KB, which proved fully sufficient to recognise the crop-row structure. An optical system with a focal length of 25 mm was used to obtain oblique images with the camera pointing forwards and downwards.

The camera and electronics were mounted on a light hand-operated carrier (Fig. 1). This arrangement allowed successive records of the same rows to be collected during their development, as the carrier left almost no tracks or other disturbances in the field. Of course, the disadvantage of the hand-operated carrier was that the forward velocity could not be kept very constant. We attempted, however, to keep the forward speed at a rate of approximately 0.5 m/s.

For the later experiments, that concerned measurements of the precision with which the rows could be located, the camera was mounted on the frame of a row weeder. For these tests an ordinary frame grabber (IC-PCI from Imaging Technology) was used where the images was transferred directly to the program. Here the image transfer rate was determined by the program and amounted to approximately 3 images/s.

Fig. 1. The hand-operated vehicle carrying the camera and computer, with a battery for power supply.

## 4. Method

### *4.1. Image recording*

Prior to the recording in the field, the camera was calibrated. The procedure of calibration was performed by simply recording an image of two circular plates with marked centre points. One was placed at the top and the other at the bottom of the image field on the ground and the distance between their centres was recorded. The resulting calibration image allowed transformation of co-ordinates between the image plane and the ground plane. The transformation was based on three distances, which were measured on the ground as well as in the image: the plate diameters parallel to the image's top- and bottom-border and their centre distance.

Finally, the camera's white balance was set by means of a white paper. Thereafter, when a track of approximately 70 m had been recorded, the image stream was saved onto a disk file. A number of tracks were recorded with the camera tilted so that the image centre at the ground was located 4 m behind the camera, which was mounted 1.10 m above the ground.

During post-processing, the individual images were extracted from the recorded streams. Only every tenth image was saved which corresponds to one image for approximately every 0.2 m of track length. After extraction, the images were transferred to CD disks for permanent storage.

After the initial work with constructing the algorithm for detection of the rows' centre lines the precision of the calculated row centre lines was estimated by placing a white rope of 7 mm thickness in the middle of the inter-row space over an 80 m long distance. For each metre along the rope its position midways between the two adjacent crop rows was adjusted so that the distance to the centre of the target row was 120 mm which was equal to half the inter-row distance. Then the tractor with implement and camera was run along the rope and images obtained and stored for later analysis. The tractor was run at a speed of 0.4 m/s at which speed the images were contiguous to each other. Fig. 2 shows the left end of the row weeder with the camera attached. The camera was placed 1.73 m behind the midpoint of the image field and at an elevation of 1.15 m. Thus, the camera was tilted forward at an angle of $56^\circ$ from a vertical orientation. Each run with the equipment resulted in approximately 80 images and a total of 10 runs were made at various stages of crop development. The crop was barley sown with an inter-row distance of 0.24 m. The amount of weed in the test area varied along with the development of the crop and for some images the weed density was somewhat higher than normally acceptable for practical farming.

The rope was clearly detectable on the images and it was verified that it did not influence the calculation of the row centre lines. By means of a special program the images were treated so that only the rope was present. The rope's position in the field domain was calculated and the parameters for a line parallel to the rope but positioned half an inter-row width toward the target row whereby it should ideally end up in the centre of this row. This line was taken as the correct row centre line and compared to the estimated centre line based on the image data.

Fig. 2. The experimental set-up, showing the camera in the upper part of the image pointing forward-downward to the left of the tractor's left rear wheel.

The experiment aimed at measuring the performance characteristics of the image analysis algorithm. Therefore, the hydraulics for the lateral movement of the frame was disabled so that the camera's position was fixed in relation to the tractor. The tractor was driven as parallel to the crop rows as possible so that, ideally, the calculated lateral offset, i.e. the lateral distance between the row and the image vertical centre line, should have a constant value.

The test runs were performed at various amounts of green plant material between the crop rows. This material consisted partly of weeds and partly of crop leaves extending into the inter-row space. However, the unfavourable effect on the determination of the row centre line is independent of the nature of the inter-row green material.

### 4.2. Image analysis

The process of detecting the plant rows in an image consists of a number of distinct steps, each of which may consist of one or more program routines. This design implies that it is relatively easy to replace one of these steps if another routine is found to work better. Some of these steps make use of empirical methods and constants that are found to work reasonably well for the present image material. Thus, even if it is easy to show that they will not work under all circumstances, it is experienced that most practical situations and conditions are covered. However, if better methods are found, the actual routine may easily be replaced.

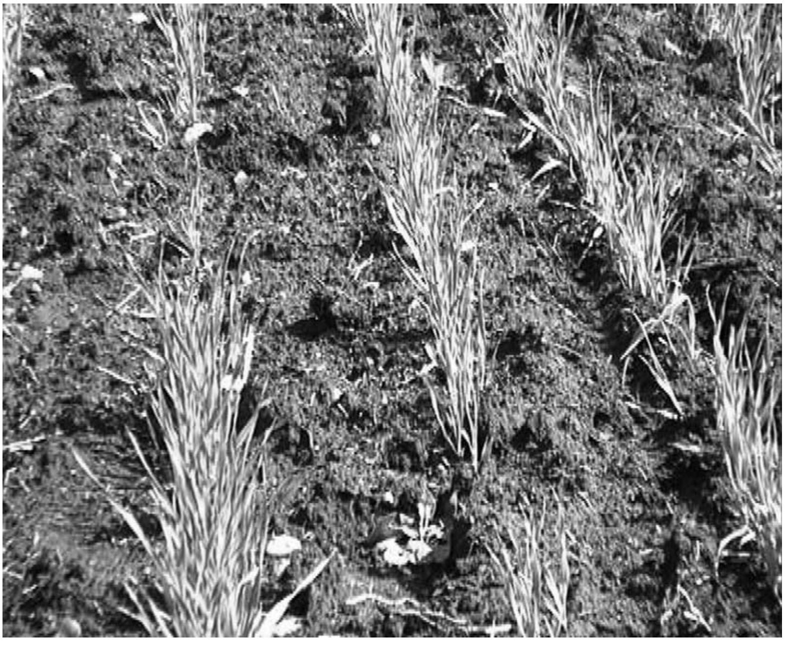

Fig. 3. Original colour image from the video camera (changed to its greyscale representation for typographical reasons).

The method described here was used for images recorded with the camera focussed onto the field from an inclined angle, such as the image shown in Fig. 3. Prior to analysis, the image size was reduced to 1/3 of the original size, i.e. the amount of pixels was reduced to 1/9 of the original amount. This data reduction was done only to reduce the computational load, and it was found that the smaller images work well for row detection. In the following sections, each step of locating the crop rows is described in detail.

#### *4.2.1. Colour to greyscale image*

The first step is to manipulate the image in such a way that the living plant tissue is emphasised in comparison with all other objects in the image. This is done by first dividing the colour image into its red, green, and blue channels. Subsequently, an indicator value for living plant tissue is computed as

$$\text{Indicator} = 2\times\text{Green}-\text{Red}-\text{Blue}$$

Apparently, the indicator value may be negative. This has, however, no influence for the subsequent calculations. However, to visualise the indicator values as a greyscale image, they may be mapped to the range of 0–255 by simple linear mapping. In the resulting image the green plants appear bright in contrast to a dark, almost uniform background where the soil surface, including shadows, stones, straw,

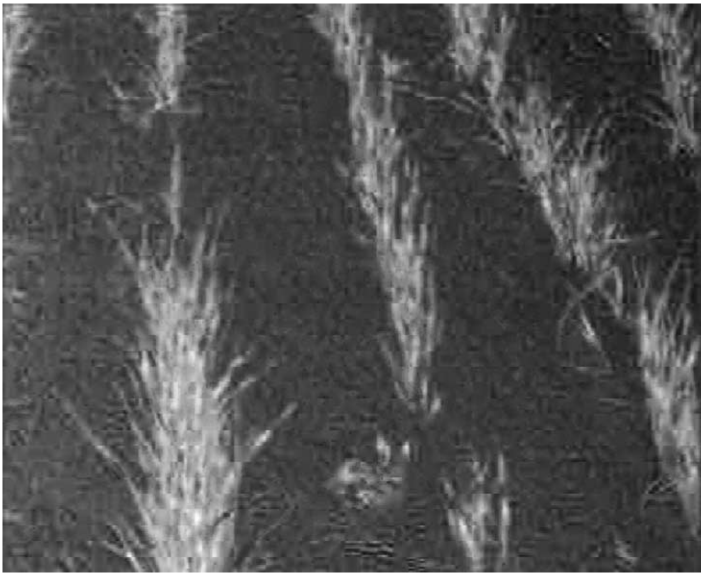

Fig. 4. Resulting greyscale image after linear combination of the colour channels of the image in Fig. 3.

and other debris, has disappeared. This image (Fig. 4) is well suited for identification of crop rows.

Compared with other possible colour channel combinations this method is reported to yield good results (Woebbecke et al., 1995), and has proved to work well for the present images. It has functioned well for a wide range of illumination conditions, ranging from bright sunlight to a totally overcast sky, and even when the camera vehicle was moved from bright sunlight into a fully shaded area.

#### 4.2.2. Estimation of points indicating the centre lines of the rows

Prior to the estimation of the row positions, a number of points indicating the centres of the rows are determined. In order to obtain such points, the greyscale image resulting from colour combination is divided into a number of horizontal strips as shown in Fig. 5 and subsequently it is estimated where the rows intersect each individual strip. In principle, the number of strips may be equal to the number of pixel rows in the image but in order to reduce the amount of subsequent computations it may be feasible to let each strip consist of more than one pixel row.

Thus, the number of strips should be kept at a reasonably low value. Practical experience has shown that division of the image into approximately 15 strips is suitable when working with a camera tilt angle of about 55° from the vertical.

Each image strip is processed as illustrated in Fig. 6. Mathematically, the process can be described as follows:

(1) Let $V_{i,j}$ be the grey value of the pixel in position $(i, j)$ of the image strip (corresponding to Fig. 6a). The indices $i$ and $j$ denote the pixel row and the pixel column, respectively, ($i = 1,\ldots,N$ and $j = 1,\ldots,M$).

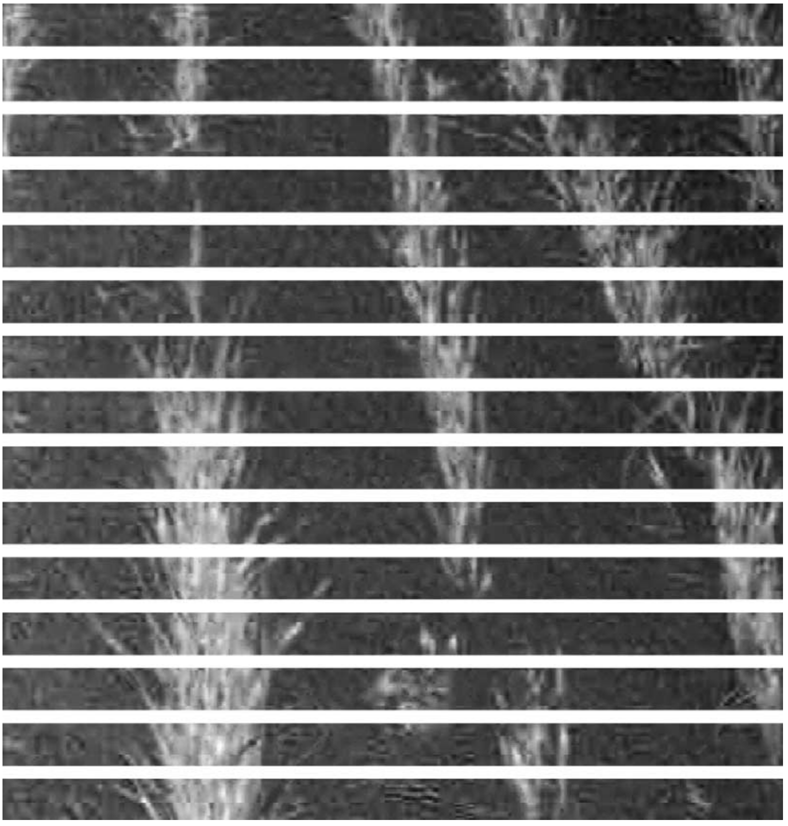

Fig. 5. Greyscale image in Fig. 4 divided into horizontal strips.

(2) Let $\mathbf{v} = (v_1 \ldots v_M)$ be a row vector resulting from summing the array $\mathbf{V}$ over the index $i$:

$$v_j = \sum_{i=1}^{N} V_{i,j}, \quad j = 1, \ldots, M$$

The result of this summation is illustrated by the curve in Fig. 6b. The vector $\mathbf{v}$ is now split up into sub-vectors, of which the lengths correspond to the nominal inter-row spacing in the middle pixel row of the image strip. The division starts from $j = 1$ (from the left in Fig. 6b). The proper length, $m$, of the sub-vectors can be found from the parameters describing the perspective relationship between world co-ordinates and image co-ordinates as is described in, e.g. Hague and Tillett (2001). Note that $M$, which is the length of vector $\mathbf{v}$, will generally not be an integral multiple of the sub-vector length, $m$. As a consequence, the length of the last sub-vector may be less than $m$. Assume that the number of sub-vectors is $P$ and let $\mathbf{w}^{\langle k \rangle}$ denote sub-vector number $k$ $(k = 1, \ldots, P)$

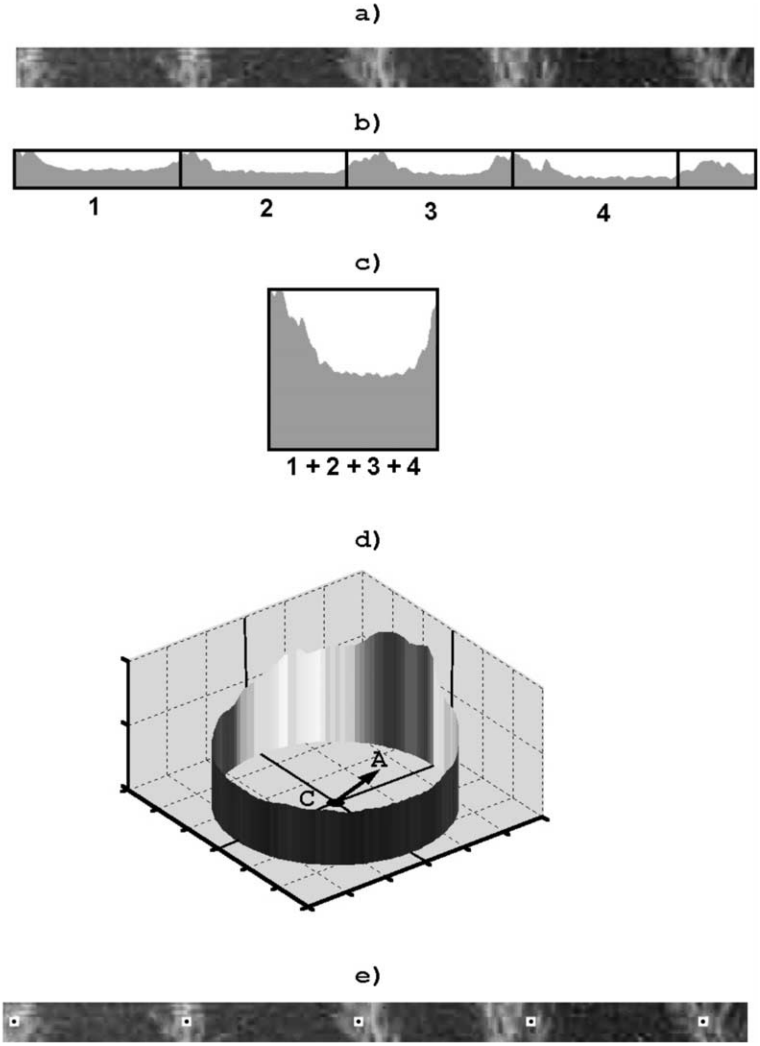


Fig. 6. Estimation of the points where the rows intersect a particular strip from the greyscale image. (a) Strip from greyscale image. (b) Vertical sum of grey values in the strip. (c) Sum of strip sections. (d) Circular representation of the sum curve and determination of the centre of gravity, A. (e) Projection of the estimated row positions back into the image strip.

(3) In principle, each sub-vector will be 'intersected' by the centre line of exactly one row. The presence of a row intersection will be indicated by vector elements with high values. In order to get a combined estimate of the positions where the centre lines of the rows intersect the sub-vectors, the average of all the full length sub-vectors is calculated:

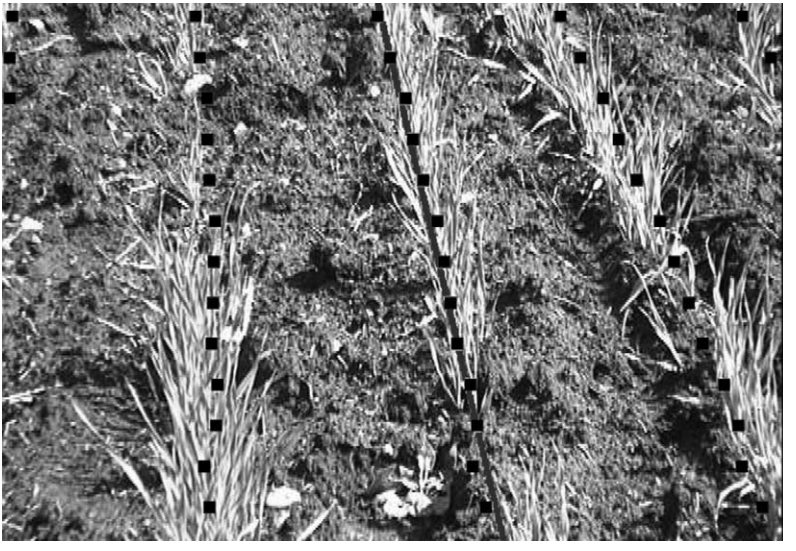

Fig. 7. Image from Fig. 3 overlaid with the calculated points from each image strip of Fig. 5. Also the line from the least squares regression is shown, indicating the guiding row.

$$\mathbf{W} = \frac{1}{P-1}\sum_{\mathbf{k}=\mathbf{1}}^{P=1}\mathbf{w}^{\langle k\rangle}$$

The vector $\mathbf{W} = (W_1 \ldots W_m)$ is illustrated as a curve in Fig. 6c.

The above formula for computation of vector **W** can easily be modified so that the last sub-vector, $\mathbf{w}^{\langle P\rangle}$, is also taken into account. If the length of $\mathbf{w}^{\langle P\rangle}$ is $m'$, each of the vectors $\mathbf{w}^{\langle 1\rangle},\ldots,\mathbf{w}^{\langle P-1\rangle}$ are divided into to two vectors, $\mathbf{w}'^{\langle k\rangle}$ and $\mathbf{w}''^{\langle k\rangle}$ ($k = 1,\ldots,P-1$), where $\mathbf{w}'^{\langle k\rangle}$ contains the first m' elements from $\mathbf{w}'^{\langle k\rangle}$ and $\mathbf{w}''^{\langle k\rangle}$ contains the remaining elements, i.e. $\mathbf{w}^{\langle k\rangle} = (\mathbf{w}'^{\langle k\rangle}\mathbf{w}''^{\langle k\rangle})$. Under these assumptions W can be calculated as

$$\mathbf{W} = \left(\frac{1}{P}\sum_{k=1}^{P}\mathbf{w}'^{\langle k\rangle}\ \frac{1}{P-1}\sum_{k=1}^{P-1}\mathbf{w}''^{\langle k\rangle}\right)$$

(4) The elements of vector **W** will now be arranged evenly distributed on a unit circle as illustrated by the cut cylinder in Fig. 6d. As the number of elements in **W** is $m$, the angular distance between two consecutive elements on the circle will be $2\pi/m$, and in a plane rectangular co-ordinate system with origin in the circle's centre, the position, $(x_l, y_l)$, of element $l$ ($l = 1,\ldots,m$) can be defined as

$$x_l = \cos\left(2\pi\frac{l-\frac{1}{2}}{m}\right) \text{ and } y_l = \sin\left(2\pi\frac{l-\frac{1}{2}}{m}\right), \quad l = 1,\ldots,m$$

Regarding the elements as point masses with masses $W_l$ the centre of gravity, $A(x_A, y_A)$, of the circular arrangement will be given as

$$x_A = \frac{\sum_{l=1}^{m} W_l x_l}{\sum_{l=1}^{m} W_l} \quad \text{and} \quad y_A = \frac{\sum_{l=1}^{m} W_l y_l}{\sum_{l=1}^{m} W_l}$$

(5) The direction angle, $\varphi$ ($0 \leqslant \varphi < 2\pi$), of the vector CA from the circle centre, $C$, to the centre of gravity, $A$, is defined as

$$\varphi = \begin{cases} \tan^{-1}\frac{y_A}{x_A} & \text{if } x_A > 0 \text{ and } y_A \geqslant 0 \\ 2\pi + \tan^{-1}\frac{y_A}{x_A} & \text{if } x_A > 0 \text{ and } y_A < 0 \\ \pi + \tan^{-1}\frac{y_A}{x_A} & \text{if } x_A < 0 \\ \frac{1}{2}\pi & \text{if } x_A = 0 \text{ and } y_A > 0 \\ \frac{3}{2}\pi & \text{if } x_A = 0 \text{ and } y_A < 0 \\ \text{undefined} & \text{if } x_A = 0 \text{ and } y_A = 0 \end{cases}$$

From the angle $\varphi$ the index, $l^*$, in vector **W** corresponding to the centre of the rows can be computed as

$$l^* = \text{round}\left(\frac{\varphi}{2\pi} m\right)$$

where round indicates rounding to the nearest integer in the interval from 1 to $m$. In the original image strip, this corresponds to the following column indices:

$$j = l^*, \; l^* + m, \; l^* + 2m, \ldots, \; l^* + Pm$$

which have been indicated by squares in Fig. 6e.

The length of the vector CA is defined as

$$d = \sqrt{x_A^2 + y_A^2}$$

and will take a value between 0 and 1. The value of $d$ indicates how clearly the expected row structure has been identified in the image strip: $d = 0$ indicates no rows and $d = 1$ indicates very distinct and concentrated rows. Therefore $d$ will be referred to as the relative accuracy of the estimated row positions in that image strip.

When the row positions have been estimated in all image strips they can be represented by points in the image (Fig. 7). The next step is to find the points (one from each image strip) that represent the guiding row.

For the very first image, i.e. when the row tracking process is started from the headland, the point closest to the horizontal centre at the bottom strip of the image is taken as the point determining the line. In the following, this point is called the anchor point and the centre line of the guidance row should, ideally, pass through this point. For subsequent images, the guiding row is taken as starting from the point in the bottom strip that is closest to the anchor point of the previous image.

The next problem is to determine which of the points in the strips upward in the image belongs to the same row as the anchor point. This is done by a method somewhat similar to the one utilised in the Hough transform. The slope of all lines connecting the anchor point with the other points is calculated, and the distribution of the slope values is estimated based on a histogram with a bin width of 2°. The bin with the highest count gives an initial estimate of the slope of the centre line of the guiding row which, at this stage, is assumed to pass through the anchor point. Points where the horizontal distance to this line is less than half the inter-row distance are identified as points belonging to the guiding row. The co-ordinates for these points are then entered into a weighted least squares regression analysis using their relative accuracy values mentioned above as weights.

The regression analysis will result in estimates of the slope and intercept of the centre line of the guiding row as shown in Fig. 7. The analysis will also provide the variance and covariance values for the slope and the intercept. Using this information, it will be possible to extend the line beyond the borders of the field of view and calculate a confidence interval for the point of interest, i.e. for the point closest to the working location for the weeding tools.

## 5. Results

Testing of the system's accuracy is not very straight-forward because there exists no true position and direction for the centre line of a crop row due to the natural variation in the plant growth. Thus, Olsen (1995) found that the width of the row measured at the emergence points at the soil surface amounted to $30 \pm 6$ mm and viewed from above this width and variation of the canopy will be even higher as the leaves extend laterally. Simultaneously, a row may locally develop more on one side than the other and, therefore, the apparent row direction, considered at this location, may be quite different from the overall row direction.

In order to obtain a measure for the in-row versus inter-row conditions a 40 mm wide band was placed over the calculated row line in the images and the ratio of the area of green leaves in this band to the total area of the band was calculated. Likewise a similar band was placed over the centre line of the inter-row space and the corresponding ratio was calculated. Fig. 8 shows the relation between these two ratios. It is noted that the amount of inter-row green material increases almost exponentially as the crop rows develop. The relation between the amount of inter-row green material and the crop height was estimated by means of a least squares regression. Using a straight line model the $R^2$ statistic attained a value of 0.90. The top $x$-axis of the diagram indicates the approximate height of the crop. One must, however, bear in mind that measurement of the crop height is difficult and associated with a great uncertainty.

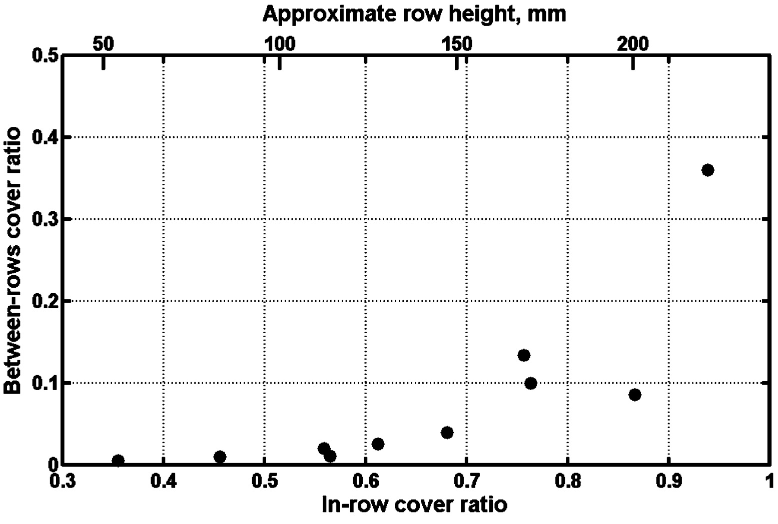


Fig. 8. Cover ratio of green material in the crop row versus the cover ratio in the inter-row space. See text for details of the calculations.

The performance of the row detecting algorithm was tested by comparing the position of the calculated row centre line to the position of the white rope in the middle of the adjacent inter-row space. This comparison was made for each of the images along the 80-m long distance.

The distances between the calculated and the manually determined row centre line were computed for each of the ten 80 m test runs. The distances were calculated both at the centre of the image field and vertically below the camera (outside the image field). The mean distances were the calculated for each of the 10 runs, but none of them were significantly different from zero at the 5% significance level, neither for those measured at the centre of the image field, nor for those measured below the camera.

In order to get a measure for the distance variations the standard deviation of the distance between the manually and the automatically determined row line was calculated for each run, i.e. for each development stage of the crop. The result is shown in Fig. 9. Two lines are shown in this diagram, one for the variation at the centre point of the image field and another for the case where the centre line is extended outside the image field to the point immediately below the camera, i.e. 1.73 m behind the centre point of the image field. This extension of the line is done in order to find out what the result will be close to the point at which an implement tool will work. It is noted that the extension of the line makes the variation more susceptible to the development of the crop.

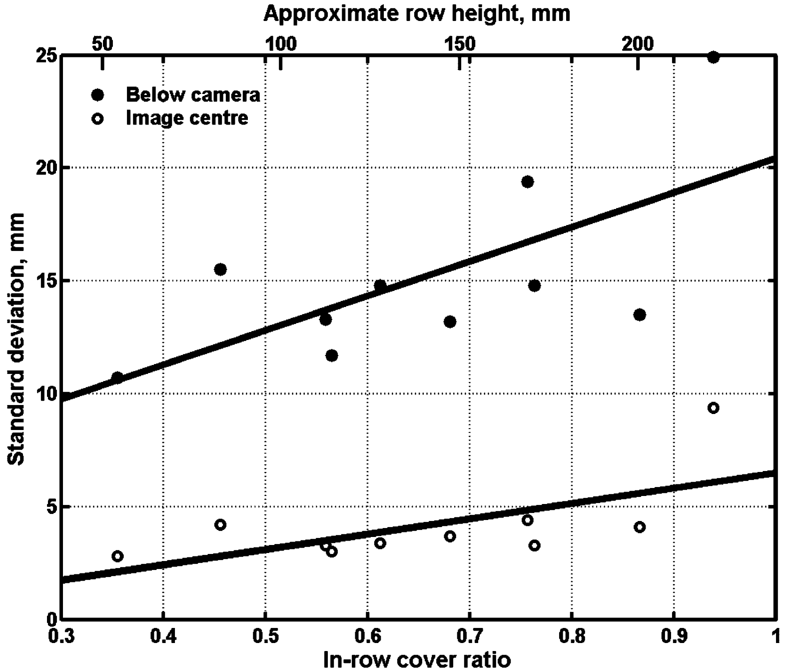


Fig. 9. Variation of the distance between the manually and automatically determined row centre line as a function of the crop development measured as the cover ratio of green leaves in the row.

## 6. Discussion

The accuracy of the described method for detection of crop rows will increase with the number of crop rows covered by each image. If only one row is present in each image the approach may, under unfavourable conditions, produce mediocre results. In this case, if a weed is growing beside the row, the points in the image strip containing the weed will be offset from their correct position. Still, the estimated quality of the points, i.e. length of vector CA in Fig. 6d, may be rather high leading to a poor estimate of the line parameters. Under these circumstances the Hough transformation method may perform better than the method described in this paper.

It is obvious that a great amount of weeds in between the crop rows will disturb the row detection algorithm, as most of the image field will be covered by green plants in this situation. Good farm management practise will, however, ensure that the weeds are always behind the crop in their development. Thus, there should always be relatively large areas of soil visible in between the weed plants. Furthermore, the weeds seldom grow in rows over greater distances. It may, therefore, be expected that inter-row weeds will seldom be a large problem. Of course, the inter-row space may also be covered by green leaves due to the development of the crop. However, in this situation it is hardly necessary to perform row weeding.

Even if the field under treatment is only moderately infested by weeds there may be areas or patches where weeds occur denser, which may cause the row detection to be less reliable. Under such circumstances, the accuracy derived by the detection algorithm will reveal that the rows are located with increased uncertainty. Thus, the accuracy value may be used to warn the operator that greater care should be exercised in the steering or, possibly, that the guidance of the implement should be totally left to the tractor driver for the moment.

In Fig. 8 it is seen that the row height of the crop for some of the experiments was only about 50 mm corresponding to the one leaf growth stage. At this stage of crop development the leaves are almost vertical resulting in a very low coverage of the soil. This condition might be expected to lead to poor determination of the row positions. However, as seen in Fig. 9, the rows were determined with the highest accuracy under these conditions. This is assumed to be due to the inclination of the camera whereby the row structure becomes very much clearer in the image compared to a situation where the camera points vertically downwards. Furthermore, the fact that the weed infestation is relatively low and the crop leaves do not extend very much into the inter-row space at this stage of development result in concentrated and well-defined rows.

The images were obtained under a wide range of illumination conditions from bright sunlight to fully overcast. It appeared that the initial colour combination of the images made the shadows disappear to such a high degree that the algorithm calculated a good estimate for the row centre line under all illuminations. It was, of course, necessary that the light intensity for all parts of the images was within the dynamic range of the video camera, therefore, this condition was always ensured to be fulfilled.

From Fig. 9 it may be noted that the accuracy with which the rows may be found is well within the desired limits of about $\pm 20$ to $\pm 40$ mm as stated in the scope section especially for the point at the image centre where the standard deviation for the well developed crop with a height of approximately 200 mm corresponds to a 95% confidence interval of about $\pm 12$ mm ($\approx \pm 2 \times$ standard deviation). When the estimated centre line is extrapolated 1.73 m to the point below the camera this interval increases to approximately $\pm 35$ mm. However, when the crop has developed to this stage, the need for precise weeding diminishes.

Based on length of vector CA in Fig. 6d the uncertainty of the estimated row line may be estimated and, for some operations, be used to fine-tune how close the implement is run to the rows. For one-sided operations such as placing fertiliser close to the row, an empirical relation may be established between the desired lateral position of the tool and the uncertainty. Thus, a greater uncertainty in the estimation of the row may be used to increase the lateral distances between the injection knives and the rows in order to keep the probability of damaging the crop at a low level.

As mentioned above, the row found closest to the vertical centre line of the image is taken as the guiding row in the first image upon starting a new bout from the headland. This very row should, of course, be used as guiding row until reaching the other end of the field. However, if the lateral movement of the implement between two consecutive images exceeds half the inter-row distance, the algorithm will select an adjacent row as the guiding row. For the present, this problem is thought to be solved merely by using a fast computer so that the lateral movement of the implement between two consecutive images will always be considerably less than half an inter-row distance. It should be mentioned that other solutions might be imagined. Thus, it is possible to vary the inter-row distance in a manner whereby this distance pattern can be recognised by the image analysis program. Such a scheme may work well for a newly emerged small crop. It may, however, be questioned whether it will work for a more developed crop due to the erratic appearance of the canopy in the images.

## 7. Conclusions

For colour images, simple linear combination of the three colour channels can produce greyscale images with good contrast between green plants and background under a wide range of natural illumination conditions.

It is possible to avoid the segmentation step in the image analysis when detecting the position and direction of the crop rows.

The row position can be estimated by using a combination of point estimation and weighted linear regression.

Experiments indicate that the row position can be estimated with an accuracy of about $\pm 6$ mm to approximately $\pm 12$ mm depending on the crop development for the central point in the imaged area.

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