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Robotic Weed Control using Machine Vision

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The purpose of this work is to present a non-chemical weed controller for vegetable crops derived from a cooperative French–Spanish project. One of the major efforts of this project is related with working in a natural, complex environment and the similarity between the weeds and the vegetable crop, which makes locating the weeds difficult.

The robotic arm presents a parallel structure with six degrees of freedom, and due to its light structure, it is capable of reaching high accelerations. The end-effector has an electrode powered by a set of batteries and kills the weeds by producing an electrical discharge of 15 000 V. All the subsystems of the machine communicate through a controller area network (CAN) bus.

There are two vision systems mounted on the machine. The first one is placed at the front of the robot to acquire and analyse field images, in order to detect weeds and send their coordinates to the robotic arm control. The second camera is placed close to the electrode, and its mission is to correct inertial perturbations by relocating every individual weed detected by the first vision system.

The successful performance of this new concept of precise non-chemical weeding has been demonstrated in a lettuce crop in Valencia, Spain. © 2001 Silsoe Research Institute. Published by Elsevier Science Ltd. All rights reserved

1. Introduction

Today, consumers increasingly demand natural, quality produce, without any or with limited chemical treatment. At the same time, concern about the ecological impact of agriculture is growing in western countries. In order for farmers to follow the market trend, new methodologies and procedures have to be introduced in agriculture to obtain satisfactory production levels, with sufficient quality, and without damaging the environment. For this reason, the purpose of this work is to present the design of a non-chemical weed controller for vegetable crops.

Several non-chemical weed control methods have been already developed, but most of them are only applicable in specific environments. The approach adapted for this study consists of applying electrical discharges to the weeds, which represents a clean, selective and fast method for weed control (Diprose *et al.*, 1984). However, work has to be done locally, which means that each weed has to be touched individually by an electrode.

The major difficulties of this project are related with working in a natural, complex environment, where operating conditions are permanently changing. Moreover, all the technical choices have been made respecting a low-cost component specification.

2. General description of the robot

The developed weeder eliminated the weeds using electrical discharges. It consisted of a robotic arm, held over a mobile platform trailed by a conventional tractor. Using one vision system, the robot located every weed individually in continuous fieldwork. An inertial control and a secondary vision system helped to compensate the perturbations introduced by the ground irregularities. The end-effector was basically an electrode that produced electrical discharges of 15 kV and 30 mA during 200 ms approximately.

The main components of the system were the mobile platform, the robotic arm, the manipulator, the inertial control and the two vision systems (*Fig. 1*). The high

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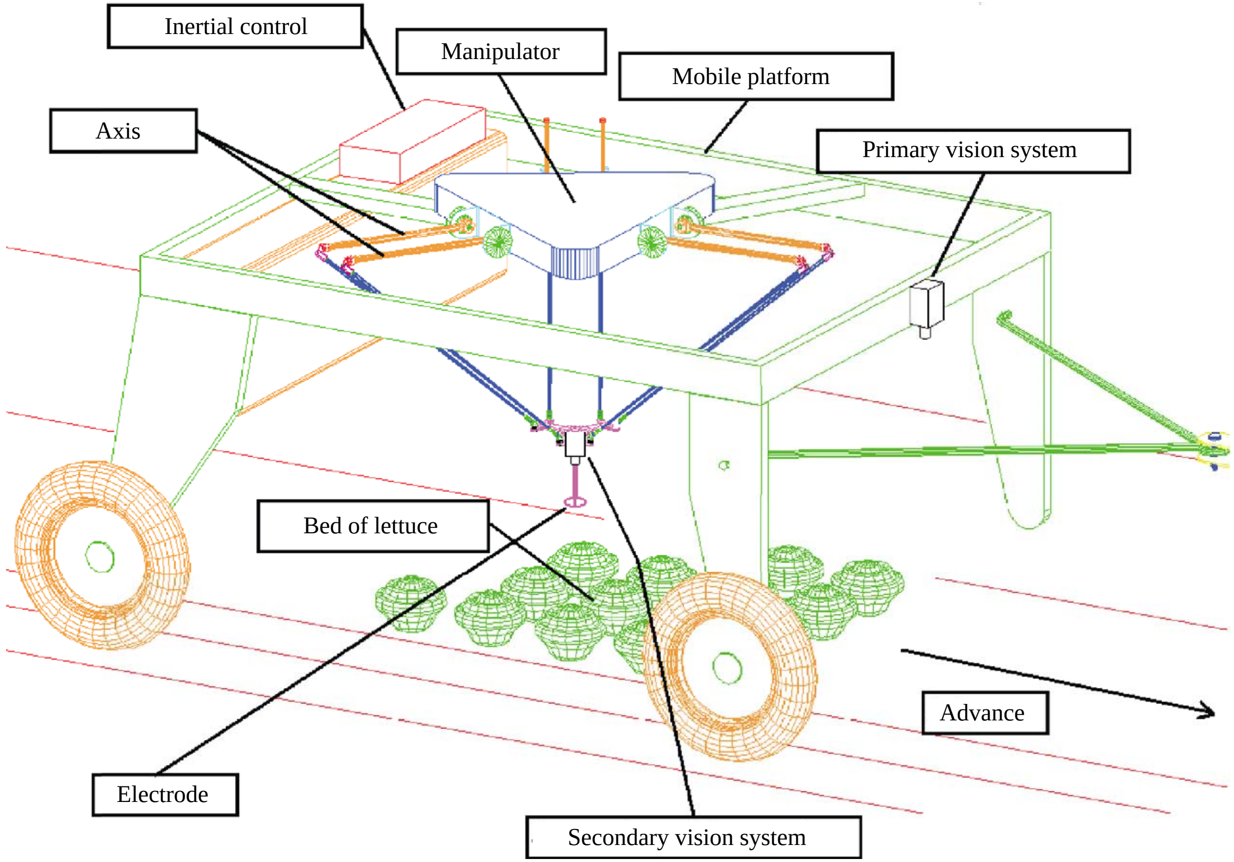

Fig. 1. Scheme of the electrical control weeder

level functions of the machine were split into five parts: general supervision, inertial unit control, arm control, primary vision and secondary vision system, running in parallel on four personal computer (PC) boards (one computer ran the supervision and the arm control tasks). In addition, each of the six axes of the arm was controlled in position by a specially designed board, based on a Phillips 80552 microcontroller, developed at Cemagref. These 11 processors were linked by a controller area network (CAN) bus at $1\,\mathrm{Mb}^{-1}\,\mathrm{s}^{-1}$ (*Fig. 2*). This configuration allowed each part to be independently developed and simplified the integration of the systems that form the prototype.

The machine was powered by a set of four 24 V batteries that provided approximately 40 A. The six degrees of freedom of the robot were implemented by six electrical motors (100 W each).

2.1. *The mobile platform*

The mobile platform is much heavier than the manipulator. As it can move at a speed of $0{\cdot}8\,\mathrm{km\,h}^{-1}$ on agricultural soils, it induces perturbations on the control of the arm position. The frequency of these perturbations can be considered to be of a few hertz, and the amplitude of the displacements of about 10 cm. Various solutions were available to reduce these perturbations, the following three being of particular interest.

(1) Use an active suspension: By using an active suspension, the perturbations introduced by the soil irregularities can be filtered and the platform stabilised, so that the manipulator can work like a classical manipulator (Karnopp & Margolis, 1984).

(2) Use a micro–macromanipulator concept: The idea is to combine two manipulators: one for filtering disturbances and other for executing the task, e.g. a Steward platform (Clavel, 1989) to compensate for the perturbations and a classical manipulator to execute the task.

(3) Integrate sensors: The information provided by the sensors can be used to compensate the perturbations while the robotic arm works. This was the adopted solution, because it seemed to be the less complicated and the less expensive one. Various sensors were used to measure the movements of the mobile platform and to correct the position of the target previously detected by the vision system.

Finally, the platform also made it possible to partially shadow the scenes seen by the cameras using a dark canvas conveniently located on the structure.

2.2. *Manipulator*

Concerning the manipulator, two options were explored: either to use a conventional serial manipulator (where the tool is at the end of a chain of elements) or to use a parallel one (where the tool is held by several elements at the same time). This second solution was adopted, and implemented as the HEXA structure (Pierrot *et al.*, 1991). It was chosen because the project required short cycle times and high accelerations of the end-effector mass, which was less than 500 g. This architecture has the advantage of its mechanical simplicity and it is capable of achieving high accelerations using fixed motors and gears (Merlet, 2000).

2.2.1. *Control of the arm*

The weeds were assumed to be distributed on the ground on a plane, so the system worked with a two dimensional (2D) local axis of coordinates. The origin of coordinates was placed in the stop position of the robotic arm, exactly in the geometrical centre of the manipulator.

As the tractor was continuously advancing, the origin of the coordinates moved in the elapsed time between one image being acquired and everyone of the detected weeds were treated. For this reason, the arm control needed to know the characteristics of the movement of the platform in terms of acceleration, velocity or attitude for correcting the movement of the end-effector (Hootsmans, 1992). Inertial sensors were employed for this purpose (Vaganay, 1993). This method was very sensitive to delays (Corke & Good, 1992), but the accuracy of the inertial measurements was not critical as far as the average speed of the vehicle was known.

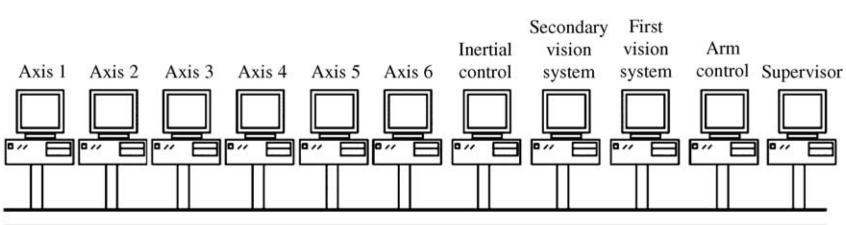

Fig. 2. System architecture

This way of controlling the motion of the arm had the disadvantage that the system only knew the relative position of the weeds with respect to the arm, determined by the primary vision system, at the moment when the image was taken. In order to enhance the accuracy of the movement, a secondary vision system was used in laboratory tests. Together with the location of the individual weeds in an image, the primary vision system sent a time reference and colour details of each weed (known as a signature), that was added to the information provided by the sensors. The secondary vision system used this information to relocate each weed and corrected the trajectory of the end-effector. The combination of these two sources of information improved the precision of the motion control at a relative low cost. The scheme of the whole control process is shown in *Fig. 3*.

3. Description of the machine vision systems

3.1. *Primary vision system*

This vision system was designed to detect the individual weeds (Moltó *et al*., 1996). Its mission was to locate the weeds in real time, while the robot was moving forward. It was composed of a colour camera, placed in the centre of the robot trajectory, 1·0 m ahead of the centre of coordinates of the robot. The camera was connected to a commercial digitising board, inserted on a Pentium 200 based computer. The images had a size of 768 by 576 pixels, with a spatial resolution of approximately 1·5 mm pixel^{-1}. The vision system had to process each image in less than 800 ms, including the acquisition and the data transmission, in order to achieve real-time specifications.

The developed software was divided into three major tasks: image acquisition, image processing and transmission of the location of the weeds to the supervisory system and to the secondary machine vision system. The information transferred to these systems was the position of each weed in the image, the digital signatures of each of the weeds and a time reference.

3.2. *Secondary vision system*

The objective of the secondary vision system was to locate the previous weeds, one at a time, and to provide their actual position, in order to correct the trajectory of the weeding tool, thus compensating for positioning errors generated by the lack of accuracy of the inertial unit.

This system consisted of a monochromatic camera connected to a specific processing unit. The camera was solidly attached to the manipulator and was initially oriented towards one of the weeds detected by the primary vision system. On request of the supervisor, the secondary vision system grabbed an image and located the same weed under its field of view, by comparing its signature with the one provided by the primary vision system. Finally, it transmitted the actual coordinates of the weed to the supervisor, which directed the end-effector to this position.

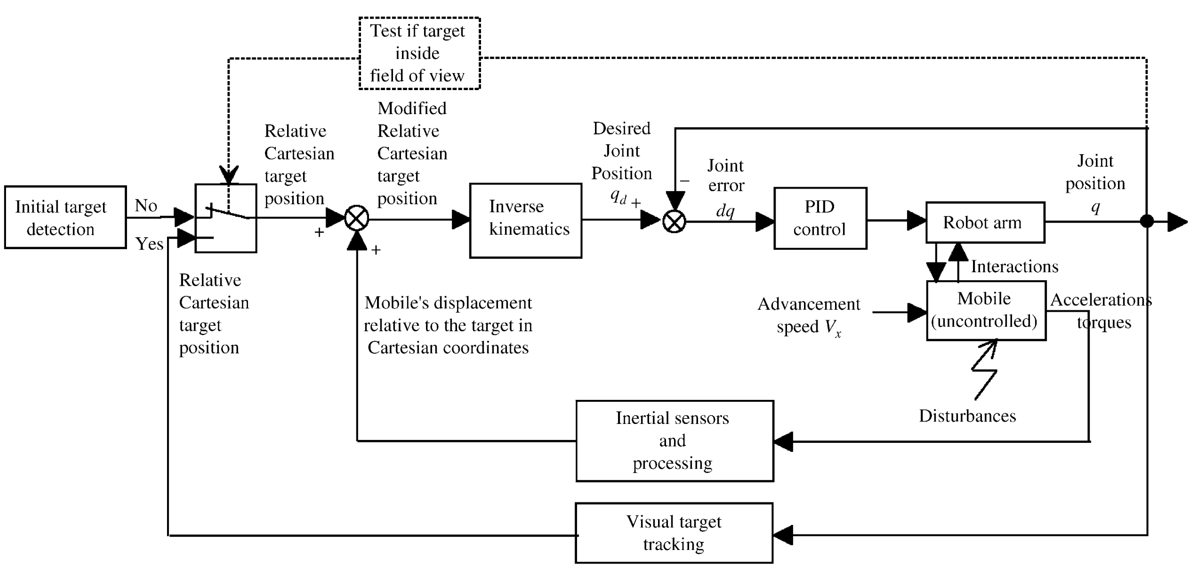

Fig. 3. Combined control scheme; PID, proportional integral differential

3.3. *Weed detection*

Before the fieldwork, two adjustments to the primary vision system were required. The first one was a geometrical calibration, in order to create the transformation matrix that was used to calculate the coordinates of the image with respect to the centre of coordinates of the robot. The second was an off-line training of the segmentation algorithm, to set up a table of data containing the information required by the system for discriminating between plant and soil.

(1) *Calibration*: As a result of image processing, the primary vision system retrieved the position of the weeds in an image in terms of pixel coordinates, that had to be transformed to robot coordinates. The calibration was accomplished by moving the arm to several known positions in the field of view of the camera and obtaining their coordinates both in the image and in the robot coordinate systems, then the transformation matrix was calculated.

(2) *Off-line training of the vision system*: To train the segmentation algorithm, a human expert manually selected different regions on actual field images, taken with different illumination conditions, trying to represent the colour variability of the soil and the plants (weeds and crop). Then, the operator assigned each selected region to a *soil* or *plant* class. At this point, values representing the class and the colour of each pixel in the red, green and blue coordinates (RGB), were stored in the hard disk of the computer. The process was repeated with several images in order to build a statistical model based on non-linear Bayesian discriminant analysis. The results of this step were stored in the form of a data table, that was used during the real-time process. This table associated all the possible RGB values appearing in a image with one or another of the predefined classes.

During real-time operation, the images were scanned and each pixel was automatically assigned to a *plant* or *soil* class, depending on its RGB coordinates. This method was faster enough to achieve the time requirements, but did not separate the weeds from the crop. *Figs. 4 and 5*, show an original field image and the same image segmented with the described method. In a second step, the area, the perimeter and the centroid of each weed were calculated. Objects smaller than a preset threshold were consider as noise and filtered. Objects larger than another preset threshold were considered as crop. Remaining objects were considered as weeds (*Fig. 6*) and the coordinates of their centroid were sent to the supervisor and the secondary vision system. The values of the two abovementioned thresholds were established during the offline training operation. For each detected weed, a digital signature based on its luminance distribution was also sent to the secondary vision system, using a 8 into 8 grey-level grid. This signature was independent of the scale and resolution.

Fig. 4. Original field image showing weeds and lettuces

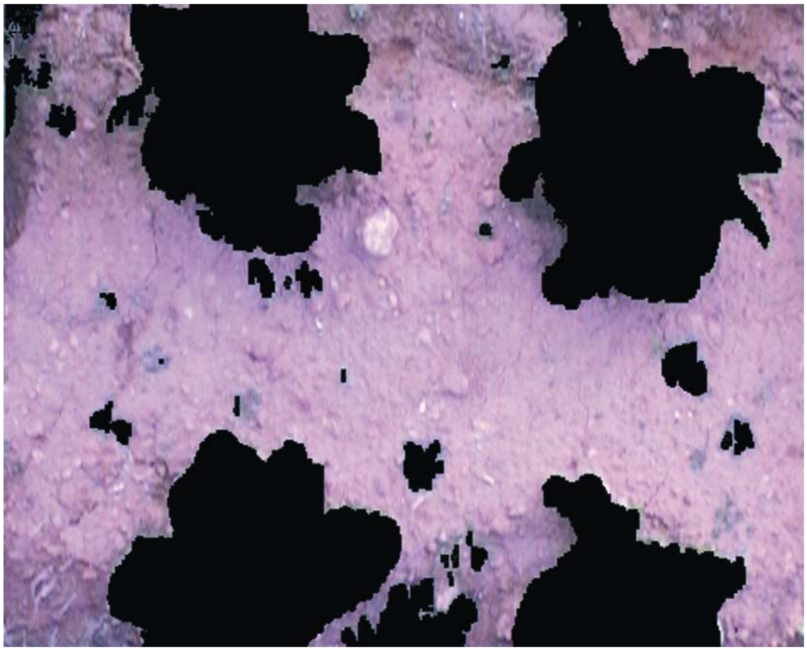

Fig. 5. Plant and soil segmentation

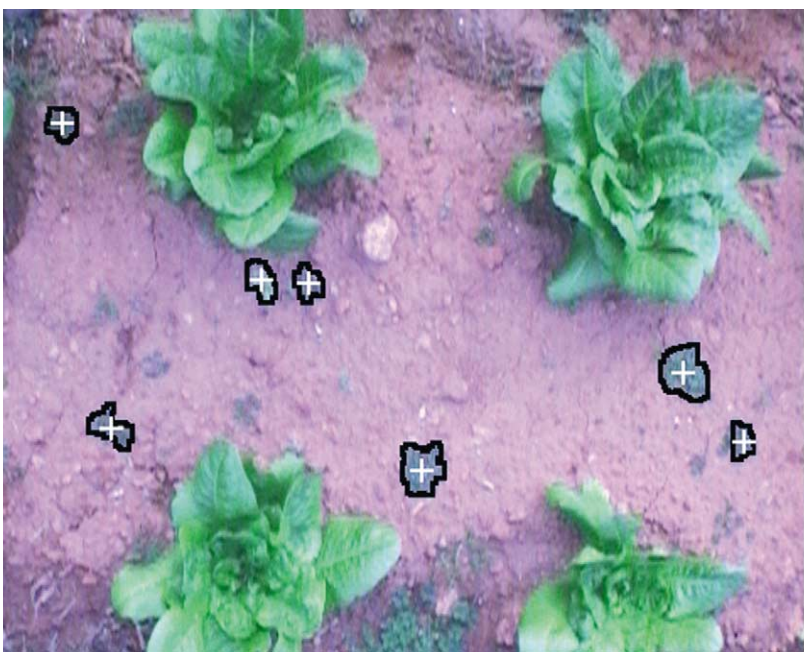

Fig. 6. Detected weeds as a result of the image processing

The supervisor moved the robotic arm towards the position calculated by the primary vision system. When the end-effector was about 30 cm from the theoretical position of the weed, the secondary vision system, using the digital signature, retrieved its actual weed position. In order to accelerate the process, a rough search of areas of interest was made using a grey-level thresholding (to better distinguish the weeds from the ground, the camera was equipped with a green coloured filter). Then, the weed location was determined using the data transmitted by the primary vision system, and adjusted at the correct scale (*Fig. 7*). The coordinates of the actual position of the weed were sent to the supervisor.

Although other authors have conducted some research to distinguish between weed species (Birdsall *et al.*, 1997), discrimination between weed species was irrelevant because in this work weeds were controlled using an electrical discharge.

4. Field tests

The prototype was tested in February 1997 in Valencia, Spain. Tests were conducted for one week in sunny days in a conventional lettuce field (*Fig. 8*). Lettuces were grown on ridges 0·5 m wide. Soil irregularities in the vertical direction varied in the interval ± 5 cm. Considering that the average weed density was 8 weeds m^{-2} and that the weed controller was pulled by a conventional tractor at 0·8 km h^{-1}, the time for treating every single weed had to be less than 1 s (including 0·2 s for electrical discharge).

5. Results and discussion

The electrical discharges induced by the electrode located on the end-effector produced cell plasmolysis on the plants, which could be observed several hours after the treatment. The confirmation of the complete destruction of the affected tissue was observed after several (3–4) days. The system was able to eliminate 100% of small weeds (less than five leaves or less than 20 cm tall). No significant damage was caused to lettuces having more than ten leaves. When the electrode discharged on a lettuce leaf larger than this size, only the affected leaf showed some kind of damage.

The primary vision system was demonstrated to be capable of discriminating between soil and plant pixels using the above-mentioned simple algorithms. Its performance could not be assessed during the operation of the robot, because it induced unnecessary delays in the process. However, experiments with 100 images taken in the same illumination conditions demonstrated a 95% success in the detection of pixels belonging to soil, and 97% success in pixels belonging to plant (Table 1). These results made it possible to properly locate 84% of weeds and 99% of lettuces (Table 2). The average time for the whole process was 482 ms, which is under the requirements of the robot (800 ms). Individual time consumed for each operation is detailed in Table 3.

The major problem for detecting the weeds was related with those that were in contact or close to the crop from the camera point of view. With the current segmentation algorithm, based only on the size of the objects, it is impossible to separate the weeds from the crop, causing the lettuces to appear larger that they really are. As a consequence, the robot did not treat such weeds. In the same sense, this vision system is not able to work in severely infested fields, because weed patches can appear as large objects and be confused with the crop.

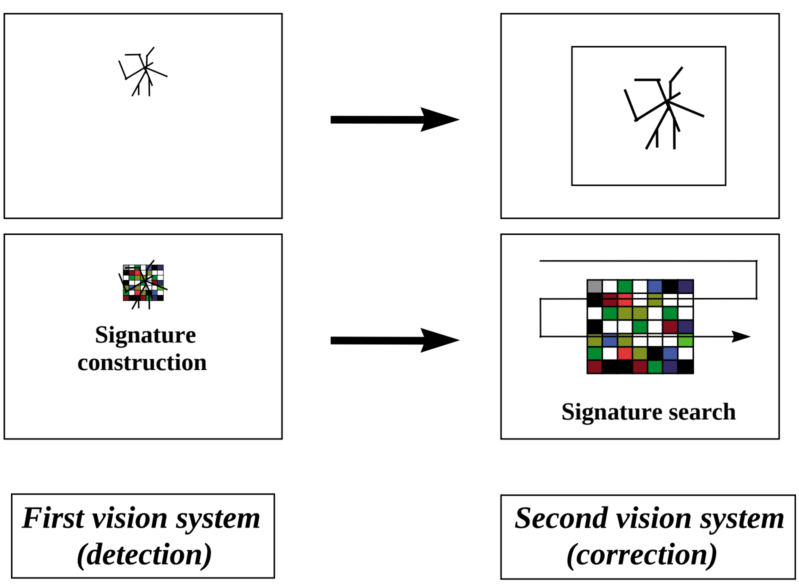

Fig. 7. Digital signature used by the secondary vision system to identify and reallocate the weeds

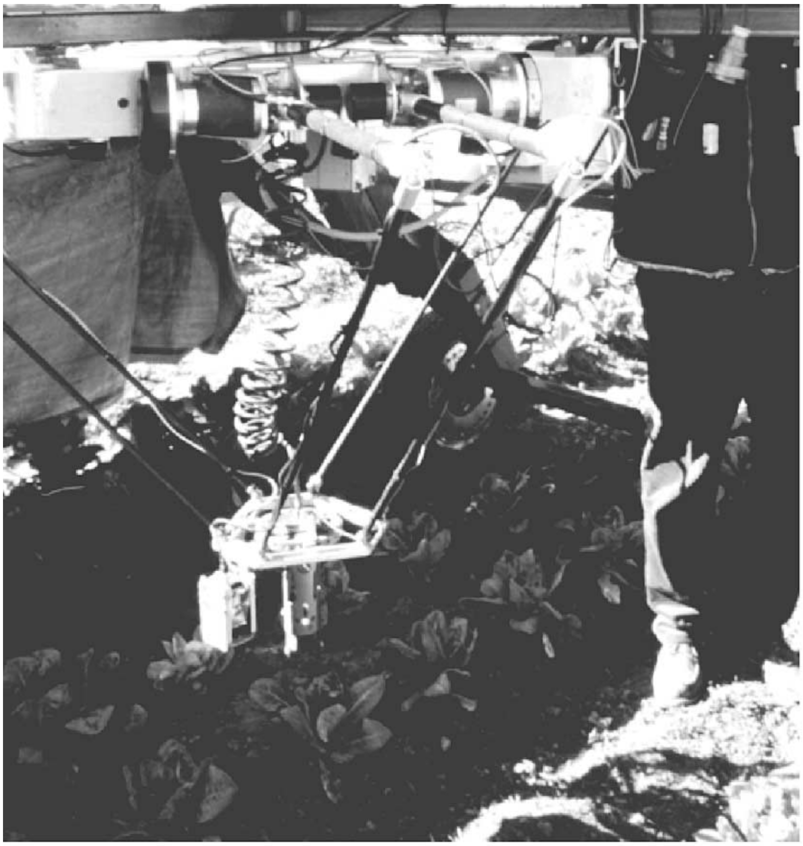

Fig. 8. Mobile platform working during test

Table 1
Segmentation process results

	Classified as soil, %	*Classified as plant, %*
Real soil pixels	95	5
Real plant pixels	3	97

Table 2
Discrimination capability in lettuce cultures

	Detected as weeds, %	*Detected as lettuces, %*
Real weeds	84	16
Real lettuces	1	99

Both problems can be solved by using shape analysis or pattern recognition techniques. These are a very time-consuming processes that could not be implemented with the hardware employed at the time of the tests. On the other hand, it is also important to remark that *a priori* knowledge of the position of the lettuces (*i.e.*, spacing) has not been included as an input to the system.

Table 3
Average results per image

Process	*Time, ms*	*Time, %*
Image acquisition	71	147
Segmentation soil/plant	86	17.9
Filtering	73	15.1
Weed detection	252	52.3
Total	482	100

This information could easily shorten the processing time, and could make possible the allocation of more time for a more accurate detection of weeds. Future effort will be focused on developing fast algorithms to individually analyse all the objects on the image, able to be executed on dedicated hardware like digital signal processors (DSP).

The tracking system based on the secondary vision system could not be used during the field tests, due to its sensibility to the changes in the illumination conditions. However, the positioning errors were lower than expected, which could be explained by the low speed of the machine and the regularity of the ground. The efficiency of this system can be improved by employing a more sophisticated, but more expensive, vision system based on a colour camera and maintaining the global architecture of the machine. Another solution could be to use only one vision system for weed detection and tracking, with the camera placed on the arm end or near the centre of the robot, under a fixed platform. In the first case, each image would be taken from the camera placed at the same position with respect to the centre of coordinates of the arm. In the second case, the arm would be removed from the field of view of the camera during the acquisition of the image, but the delay between the weed detection and the weeding action should be shorter. Besides, since the six degrees of freedom of the arm are mainly needed for placing the second camera in a correct angle of view, this solution would simplify the architecture of the arm.

6. Conclusions

This paper demonstrates the feasibility of robotic, non-chemical weed control in vegetable crops. The described machine has been able to work in a commercial lettuce field, treating the weeds individually with an electrical discharge. Most of the technical choices have been taken in order to reduce the costs of the components.

The robotic system has been implemented in a series of processes, running in different personal computers and electronic boards that are connected in parallel through a controller area network (CAN) bus. The arm has six degrees of freedom, and due to its light structure, it is capable of reaching high accelerations. The end-effector is an electrode powered by a set of batteries and eradicates the weeds by producing an electrical discharge. Two vision systems are mounted on the machine: one for analysing the field images and detecting the weeds, and the other for correcting inertial perturbations induced in the position of the end-effector.

The primary vision system was demonstrated to be capable of properly locating 84% of weeds and 99% of lettuces. The average time was 482 ms, which is under the requirements of the robot. Envisaged improvements of the system are related to the detection of weeds that are in contact or close to the crop. The secondary vision system must be improved to work in field conditions.

Acknowledgement

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