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Robotics for Improving Quality, Safety and Productivity in Intensive Agriculture: Challenges and Opportunities

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1. Introduction

Despite the large diffusion of robotic and automated solutions that took place during the last decades in most production processes, the agricultural sector only marginally benefited from automated solutions (such as the control of climatic parameters in greenhouses). Robotic applications have been confined so far almost only to research studies with few particular and specific applications made available for farmers.

This lack of advanced robotic solutions in agriculture and particularly in intensive farming cannot be motivated claiming a lack of interest for the latest results of technology and research in this sector. The use of latest results of genetics for the production of hybrid flower plants is one of the many examples that contradicts this kind of argument and shows how much the agricultural sector is keen to exploit the opportunities offered by modern technology and research.

However, from the automation point of view, agriculture remains mainly labour intensive not only in those countries where manpower is relatively cheap, but also for those enterprises which enthusiastically embrace latest technologies in an effort to improve their competitiveness and to ensure top quality products.

The motivation for the little development that robotic solutions deserved so far in the agricultural sector lies elsewhere. On one side it is related to some particularities of the specific sector, like the fact that farming is usually performed in an unstructured environment that is therefore less friendly for robotic solutions than a well structured industrial environment (Kassler, 2001). On the other side a consistent share of the research effort conducted so far, mainly tried to use standard industrial robotic solutions adapting them to the intensive farming sector instead of developing brand new solutions that exploit the specific features of the agricultural sector. Finally the focus of most research was so far on single specific activities or tasks and less frequently on the whole production process or on a consistent share of it. In our opinion the approach should be revised looking for new specific robotic solutions that take advantage of peculiarities and needs encountered in the agricultural sector that are different from those of the industry. In this context, beside overcoming specific constraints encountered in the farming context, the important challenge is to find solutions and develop technology to automatize consistent shares of the agricultural process. From a business point of view it is important to stress that, for the

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robotic industry, the agricultural sector represents a new important market which is ripe for adopting robotic solutions that can be very effective in increasing the quality of products, in improving the safety for the workers of the sector, in reducing pollution and environmental impact, and in ensuring higher productivity.
In this paper the state of the art of robotic research and of available robotic solutions in intensive agriculture is presented first. The particular features that valuable robotic solutions should deserve for agricultural applications are then outlined discussing also which are, in the authors' opinion, the most promising research directions for the next years. Such research should address different problems to develop competences and build new knowledge needed for developing valuable practical solutions suited for the specific agricultural sector. Finally some research results attained by the authors along some of the lines previously described are illustrated.

2. State of the art of robotic studies in agriculture

In order to understand which are the research opportunities at hand in the sector of robotic automation for agricultural processes, it is convenient to review the main research studies carried on in the last years. As remarked before agriculture is still labour intensive also in those countries in which the cost of manpower is very high and robotic automation solutions are widely used in other industrial sectors. Some applications are indeed available as illustrated in Kondo and Ting (1998), but most solutions which have been developed so far mainly focus on specific problems trying to automatize single operations. The available studies can be grouped, for an easier understanding, in two main classes depending on whether they deal with applications in field or in greenhouses. The reason for this grouping is related to the fact that, although many operations must be conducted in both environments, nonetheless there are some important differences in the two settings that are related to the available infrastructures and to the expected productivity (and economic return) per unit surface that sets constraints to acceptable investments. All this ends up in remarkable differences between solutions that can be considered satisfactory in the two different conditions.
The most important lines of study, for what concerns automated solutions for application in greenhouses, are related to specific cultural operations, to harvesting of different crops, and to guidance problems. In Tillet (1993) an excellent overview on robotic applications in horticulture is presented. Transplanting and seeding are some of the cultural operations whose automation has been specifically studied in the works of Ryu et al. (2001) and of Tai et al. (1994). In the wide chapter of automated harvesting Kondo and Monta (1999) introduce a strawberry harvesting robot, while Reed et al. (2001) address the automatic harvesting of cultivated mushrooms. Cho et al. (2002) consider a lettuce harvesting robot equipped with a computer vision system, while an automated cucumber picking by a robot was studied by Van Henten et al. (2002) and (2003). Finally Mandow et al. (1996) and Sandini et al. (1990) discuss guidance topics for robots in greenhouses.
For what concerns applications in the field, automatic guidance has attracted consistent research efforts. Automatic guidance systems for tractors and for other specific machines such as harvesters, transplanters, etc. have been implemented based on different technological solutions. Some systems make use of artificial vision as in the works of Hague and Tillet (1996), Hague et al. (2000), Marchant et al. (1997), Åstrand and Baerveldt (2002), and Tillet (1991). A particular section is represented by studies which use stereoscopic vision

as in the works of Kise et al. (2005) and Rovida Màs et al. (2004). The second technological solution which was studied in more recent years is based on the use of global navigation satellite systems (GNSS) presently represented by the American global positioning system (GPS) (see e.g. Thuilot et al., 2001, and Bak & Jakobsen, 2004). The joint use of GPS and artificial vision has been proposed by Benson et al. (2003) and Chen et al. (2003), while solutions based on lasers (Jimenez et al., 1999), (Château et al., 2000) and ultrasonic sensing (Harper & Mc Kerrow, 2001) have been also investigated.
Other automated solutions studied for specific cultural operations are represented by the work of (Tillet & Hague, 1999) for the automatic hoe control; the works of (Tillet et al., 2002; Åstrand & Baerveldt, 2002) for the inter-row raking and tilling for weed control in sugar beet; the works of Tian et al. (1999), Paice et al. (1995), Tillet et al. (1998) for precision spraying devoted to weed control and crop treatment; the work of Blasco et al. (2002) for weed control implemented with electrical discharges.
Final fields of study for automated applications in the field are represented by robotic solutions for harvesting, as illustrated by the works of Monta et al. (1995), Sarig (1993), Sanders (2005) and Peterson et al. (1999), and mapping yield and fruit quality (Quiao et al., 2005).
It is worth noting that most studies in literature deal with one specific agricultural operation for which automated solutions are studied and presented. This ends up in most cases with the design and testing of a dedicated machine that is often even quite sophisticated, but can perform only one operation. The case of multipurpose robots that can perform different tasks is usually an exception although some studies in this category (Monta et al. 1995, Van Henten et al. 2002, 2003, and 2006) are also available.

3. Desired features for agricultural robots

In order to analyze which are the desirable features for robots to be used in agriculture and therefore which are the most promising lines for research as well as for engineering and product development it is informative to reconsider some of the relevant features of currently available robots and to understand how some of them have impaired the diffusion of robotic solutions in agriculture.
One important aspect is that robots are in general quite expensive and sophisticated. They require manpower with specific skills that are usually not available in agricultural workers and need specific infrastructures (power supply, systems for their movement throughout the crop, etc.). Particularly relevant is the fact that currently available robots developed for factory applications usually have precisions in the range of tenths or hundredths of millimeter. Such precision is about two to three order of magnitude greater than the precisions required in most agricultural operations where errors in the range of some millimeters are usually satisfactory. Remark that the higher is the required precision the higher is the weight of the robot, since its structure must be rigid to avoid deformations, and this ends up with higher power consumption and higher costs.
From these simple considerations it follows a first very important guideline for research and product development related to robotic solutions in agriculture: it is important to design specific robots with mild precision (in the range of millimeters) and therefore much less expensive than typical industrial robots.
Although the cost of robots for agricultural operations can be consistently reduced according to the previous guideline, however it cannot become negligible. To be appealing robotic solutions must offer a significant improvement in productivity with a reduction of costs that justifies their

use with respect to standard solutions involving human labour. This obvious consideration leads to other two new guidelines. One concerns the type of cultures for which robotic solutions should be studied first. In fact, when automatizing intensive and highly remunerative cultures it is more easy to ensure an economic return that compensates higher investments. Remark that all cultures in greenhouses are of this kind and note also that greenhouses offer infrastructures (such as power supply, artificial illumination, plinths to which rails can be hooked, etc.) and represent an environment that is usually partially structured or can be partially structured (pots/plants are regularly displaced on benches or on the earth, obstacles are in known positions, etc.).
The second guideline for research and product development concerning robotic solutions in agriculture is then to focus on applications in greenhouses.
The third guideline steaming from the need to ensure significant improvement over the standard use of human manpower indicates that valuable robotic solutions should be versatile and cover different tasks usually performed by human operators. This in order to reduce the amount of labour needed. If ideally all the tasks to be performed throughout the growth of one crop (planting, irrigating, fertilizing, spraying, weed control, etc.) could be managed by a robot, then human operators could just perform supervising tasks. In connection with this guideline it is important to note that the option of several dedicated robots each one specialized in one specific task does not seem a convenient strategy. In fact the different tasks are usually performed in different periods for only a few times per year, so that the robots would work one at a time while the other would remain idle. Moreover sharing the machine with other farmers in order to reduce costs would not be a feasible solution in most cases because neighbourhood properties usually follow the same calendar and need the machine at the same time. The third guideline is then to look for versatile multitask robots that ideally can manage all the operations needed in the production cycle of different crops.
The forth and last guideline concerns the development of new applications and tasks that can be performed only by a robot and are aimed to improve the crop quality, to improve safety and to reduce pollution and costs. A nice example of such a task is offered by precision spraying for cyclamens. This crop frequently needs treatment. Since the pests to be targeted live under the leaves, the spraying should occur under the leaf canopy in order to be really useful. The cyclamens should then be sprayed one by one, properly positioning the spraying nozzle. This indeed is practically impossible with human operators when the number of plants to be processed is huge as it is usually in dedicated enterprises. The task, however, can be done by robots that do not lose concentration during the operations and can work indefinitely day and night. Another field in this line is represented by the operations involving vision and image processing. Beside surveillance for pest and illnesses detection, image processing can be used to control the growth of each single plant/flower/fruit as well as to identify the level of ripeness in order to plan optimal harvesting time.

4. Structure of robot systems for greenhouses

Different robotic solutions for greenhouses are presented and analyzed in this section. A first important choice is related to the robot structure. Among the different possible solutions (anthropomorphic, scara, Cartesian, etc.) the most convenient one seems to be a Cartesian configuration. Actually the working space in which the robot must move to operate on plants in greenhouses is orthotopic since plants are positioned on rectangular benches (or rectangular portion of soil) so that their position (or the position of their parts) can be easily identified in a three coordinate Cartesian reference. Knowing the position of the plants or retrieving it from video images, convenient trajectories can be easily defined in a Cartesian reference and are immediately translated (without inverse kinematics problems) into commands to the robot if its structure is also Cartesian. It must be noted that the width of benches is in many cases in the range of 3000 mm so that a working space in the range of 3000 1500 1000 mm can be representative of several practical situations.

Drawbacks of a non cartesian structure were experimented by the authors in studies and experiments executed using a robot with pantographic structure (Belforte et al. 2006). It was practically noticed that its non-Cartesian structure consistently increased the required computation for trajectory evaluation and motion control, because the commercially available industrial axis controllers that were used are designed for driving motions along linear axes, therefore they can be easily integrated into cartesian robots while they require more or less complex customization for non-cartesian structures. Last but not least mechanical components and technical solutions available on the market allow fast assembling of relatively low cost Cartesian robots with a wide range of dimensions while their accuracy remains higher than the one required in agricultural operations. Such flexibility in the robot size is of primary importance since greenhouse dimensions are definitely not standardized and new robots should allow adaptation to existing greenhouses if they have to penetrate this new market.

All the above considerations strongly recommend cartesian robot structures. In the following different possible solution of this kind are outlined, however another distinctive characteristic of the robot has to be discussed first: the capability of displacement within the greenhouse. Actually the choice is between fixed robots that operate in a fixed point on mobile benches and mobile robots that operate on the whole surface of the greenhouse.

The fixed robot solution has the advantage that the robotic cell can be highly sophisticated with different equipment that do not need to be moved around and can then be quite heavy. The supply of any required substance/material to the cell for its working needs must be ensured in one single point of the greenhouse and is therefore easier as well as the removal of products/debris. However the fixed point robot requires moving benches that are a quite sophisticated and expensive infrastructure that is available only in relatively few cases.

Moving robots on the other hand can operate on fixed benches or directly on the ground, but require a moving support that adds complexity to the machine and requires some infrastructure in the greenhouse (rails or paths along which the movement can occur). Such kind of robot cannot be very heavy and requires a more careful design for what concerns the feeding/removal of substances/parts required or generated during the robot operations. In general these requirements should not constitute a severe constraint and a moving robot solution seems to be slightly more flexible and definitely less expensive. Here different possible solutions of cartesian robots are introduced.

4.1 Fixed gantry robot with moving benches

In this solution the robot has a gate structure. Its advantage is to be symmetric (especially for loads and forces), while the disadvantage is the requirement of a clear space on both sides of the benches for the supports of the robot.

4.2 Fixed throat depth robot with moving benches

In this solution the robot stands on one side only of the benches. While this solution does not require clear space on both sides of the benches at the same time it is asymmetric and this could require to make it heavier to avoid deformation.

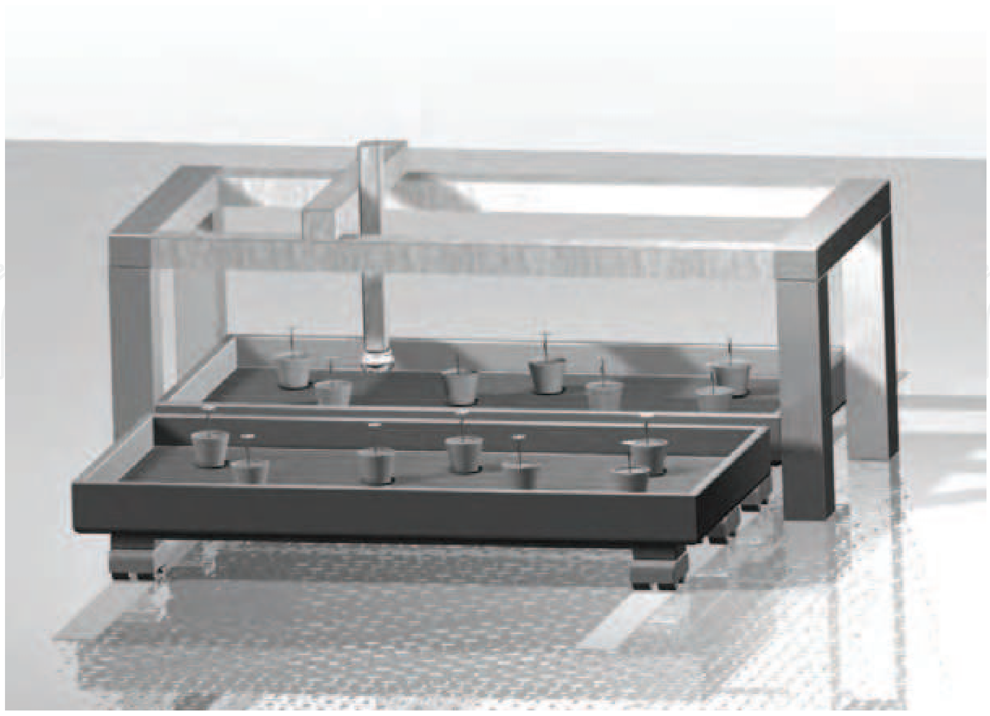

Fig. 1. Fixed gantry robot with moving benches.

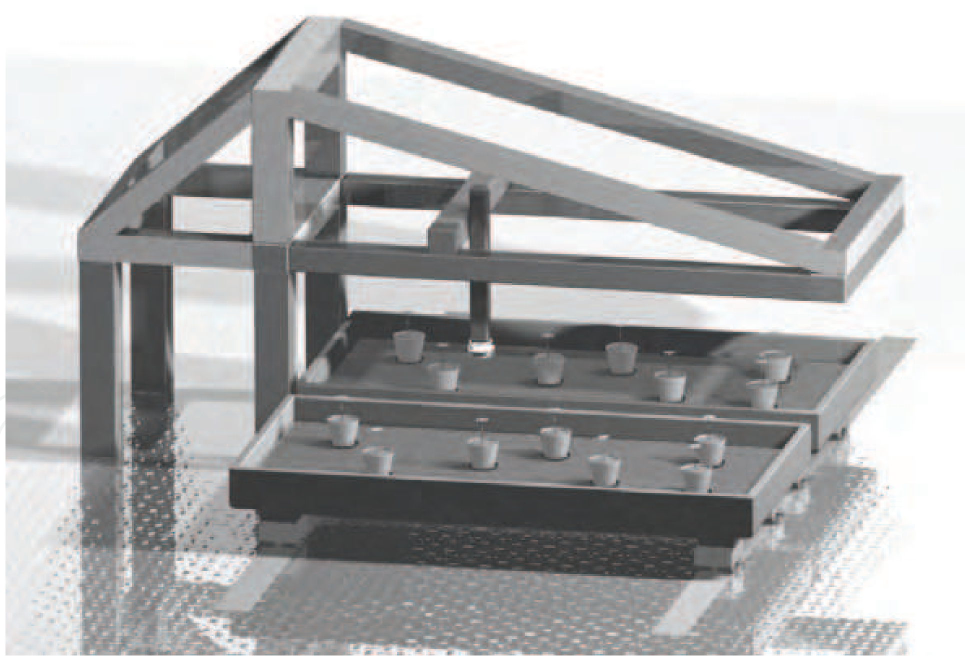

Fig. 2. Fixed throat depth robot.

4.3 Moving gantry robot

This structure can be adapted to work both on fixed benches and directly on the soil. The gate structure laying directly on the ground allows to construct heavier robots and could be used also outside greenhouses.

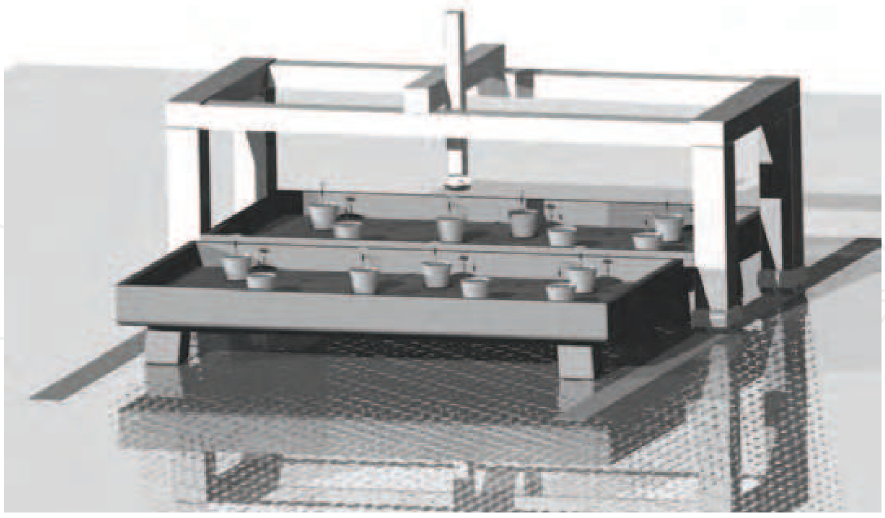

Fig. 3. Moving gantry robot.

4.4 Moving asymmetric gantry robot

Also this structure can be adapted to work both on fixed benches and directly on the soil. Since it requires an elevated rail, such solution could take advantage of existing columns in greenhouses. At the same time it is less suited for use in open fields.

4.5 Aerial robot

This structure is similar to the previous two ones. Its main difference is the fact that both rails are high and possibly attached to the columns or to the structures of the greenhouse. The main advantage of such structure is that it does not occupy any portion of the ground. Indeed when the rails on which the robot moves along are attached to the columns or structures of the greenhouse it should be verified that these last are strong enough to support also the robot. The problem is less important if the robot is designed together with the greenhouse, but if the robot is added in an existing greenhouse this point must be carefully considered.

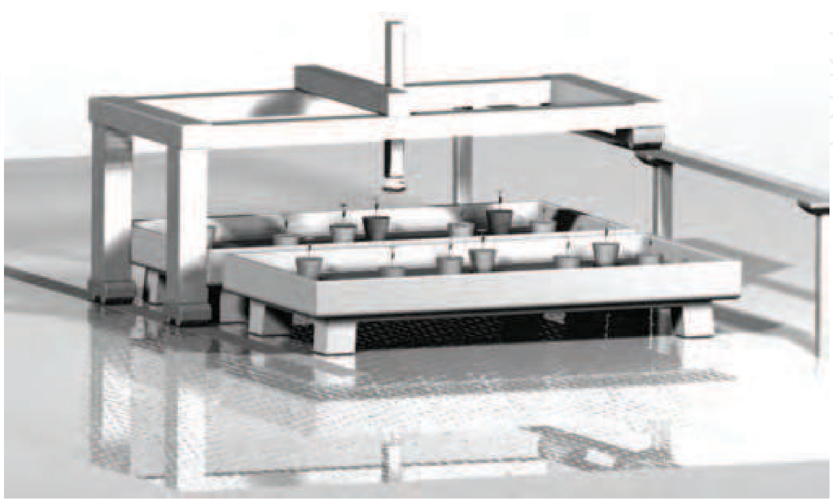

Fig. 4. Moving asymmetric gantry robot.

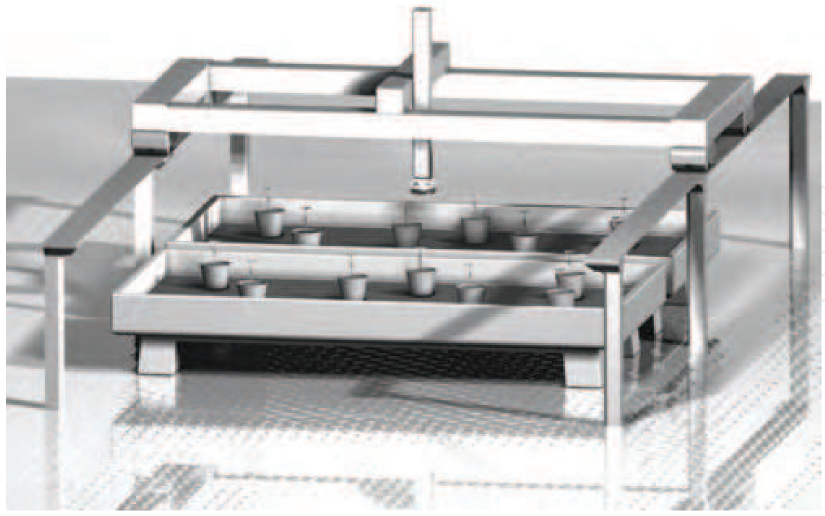

Fig. 5. Aerial moving robot.

4.6 Moving throat depth robot

This robot has the same advantages/disadvantages of the similar fixed structure, indeed with the difference that in this case the robot is mobile.

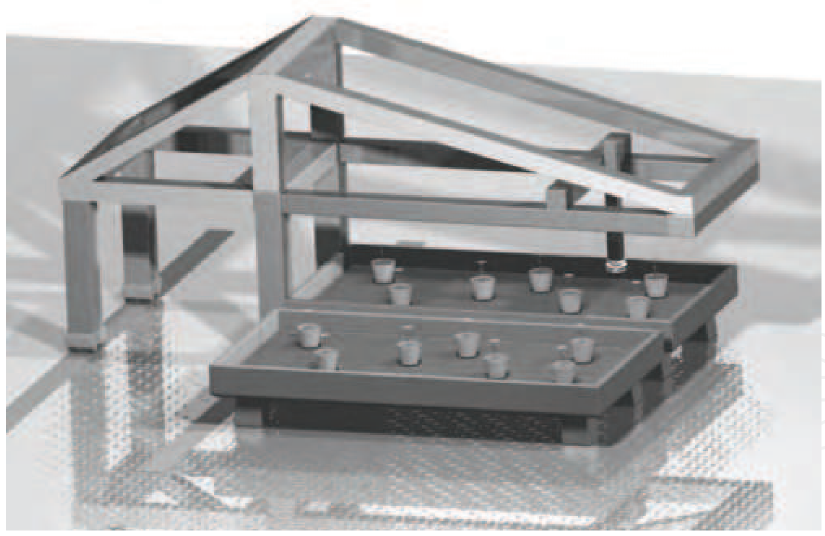

Fig. 6. Moving throat depth robot.

4.7 Vertical mounted moving robot

This structure seems very different from the previous ones, but the difference is more apparent than real. In this case the robot is placed vertically instead than horizontally. The movement in the greenhouse (or perhaps in the field) is facilitated by two rails one on the floor and the other high over the previous one. In this way the robot can better operate on plants with a consistent vertical extension that are organized in rows (like fruit plants and similar).

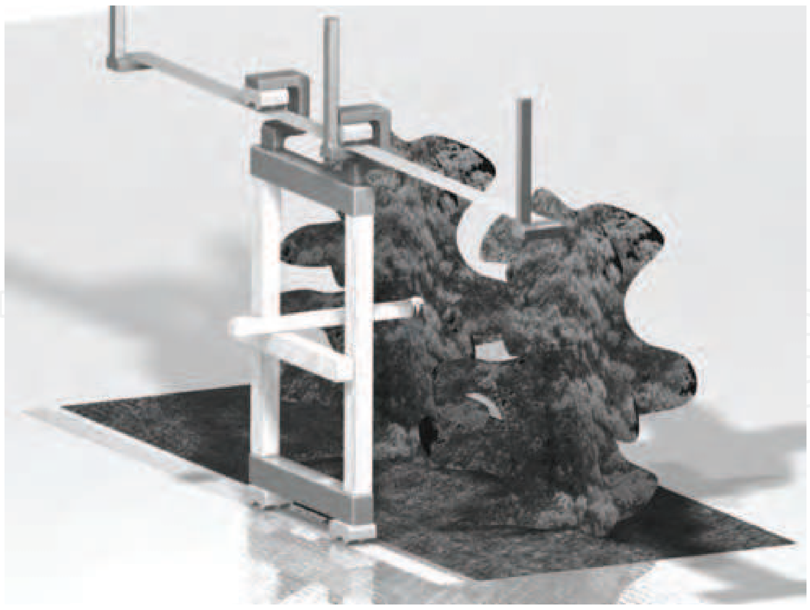

Fig. 7. Vertical mounted moving robot.

4.7 Hanging robot

This last structure could be convenient in those greenhouses that are equipped with one monorail running high over the soil to which different equipment can be attached. Indeed these solution could pose severe constraints on the weight of the robot.
The main advantage consists in keeping the soil clear from supports and in using of existing solutions integrated in some greenhouses.

5. Design of an experimental robot for applications in agriculture

Based on the above considerations and on previous experiences the research group, to which the authors belong, decided to construct a cartesian robot prototype to be used for research and study of automated solutions in agriculture.

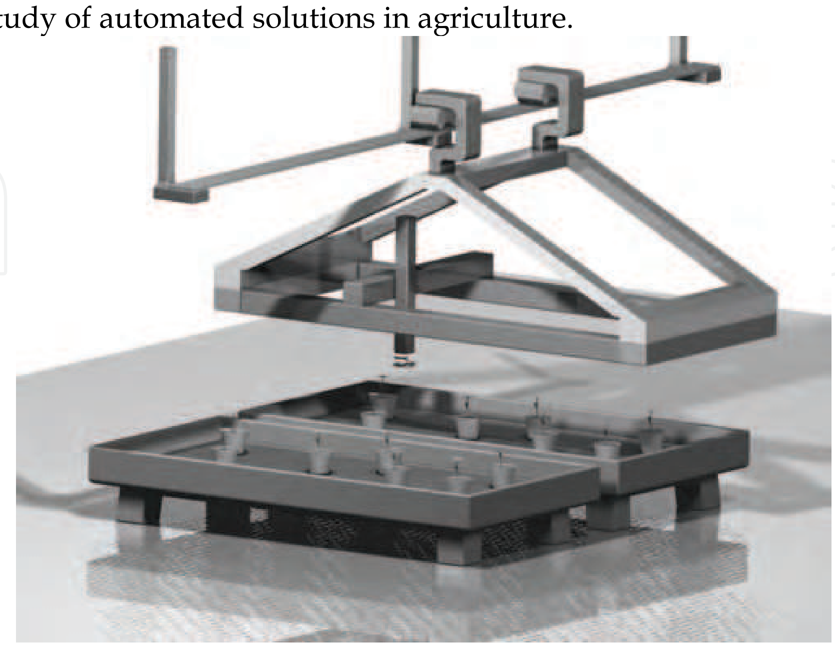

Fig. 8. Hanging robot.

Beside providing a research tool, the construction of the robot was expected to represent a first tentative in the direction of relatively low cost robots specifically minded for agricultural applications.
For this reason the robot was developed assembling together to the largest possible extent standard components available on the market.
While for commercial robot the operability throughout the greenhouse is an essential feature that can be ensured with any of the solutions discussed in Section 3, for a research tool this feature is not important. In fact the focus in research is on developing tools, programs and procedures to enable the robot to perform different basic operations within its operational volume. Once this is achieved the integration of the robot with moving benches or its coupling with a dislocation system will enable to operate on the whole crop throughout the greenhouse. For these reasons the prototype we constructed works in fixed position.
The robot structure is represented in fig. 9. The dimensions of the robot are 3,60 m (x-axis), 2,50 m (y-axis) and 0,80 m (z-axis), according to the guidelines discussed above. The electrical motors ensuring the movement to the robot axes are standard 48V DC motors with encoder and speed transducers. Four independent PWM axis drivers, plugged to velocity sensors, supply and control the motors.
The robot control logic has been implemented on a National Instruments 1000b PXI controller unit equipped with a PXI-8170 Pentium III CPU board, a PXI-7344 Motion Controller and a PXI-6255 I/O board.
The PWM amplifiers are driven by the digital axes controller on the PXI-7344 board. The position measurements of the four axes are fed-back to the digital PID controllers on the 7344 that generates velocity paths. Input/output signals are managed by a PXI-6255 board. Maximal velocities along the axes are of 1 m/s and enable the robot to move fast in order to ensure a satisfactory productivity.
The robot has been equipped with a forth axis that allows complete rotation around the z axis. This axis is powered by a standard 48V DC motor with encoder and speed transducer. The gearing ration has been designed in order to allow mechanical operation to the soil, such as weed control.
The robot has been equipped with a vision subsystem constituted by one colour and one NIR CCD camera (both are KC-40H1P Rapitron Day and Night CCD cameras) fixed to the y-axis. This solution allows to maintain a constant distance from the floor of the bench, i.e. to operate with fixed focus. The camera view angles allow to investigate only a portion of the bench at a time, but this is not a limitation since the cameras are used to plan trajectories in the neighbourhood of the single plants and not to control wide displacements, that are controlled using encoder feedback.

6. Elementary agricultural operations and tasks performed by the robot

As discussed before it is important to enable the robot to do as many operations as possible. In previous studies (Belforte et al. 2006) performed with a pantographic robot structure some elementary operations were already studied. They were: a) the precise spraying of cyclamines and b) the precise fertilization. The interest of these operations lies in the fact that they cannot be manually performed on extended cultures because human operators lose their concentration in this kind of repetitive activity and are far to slow to ensure acceptable costs.

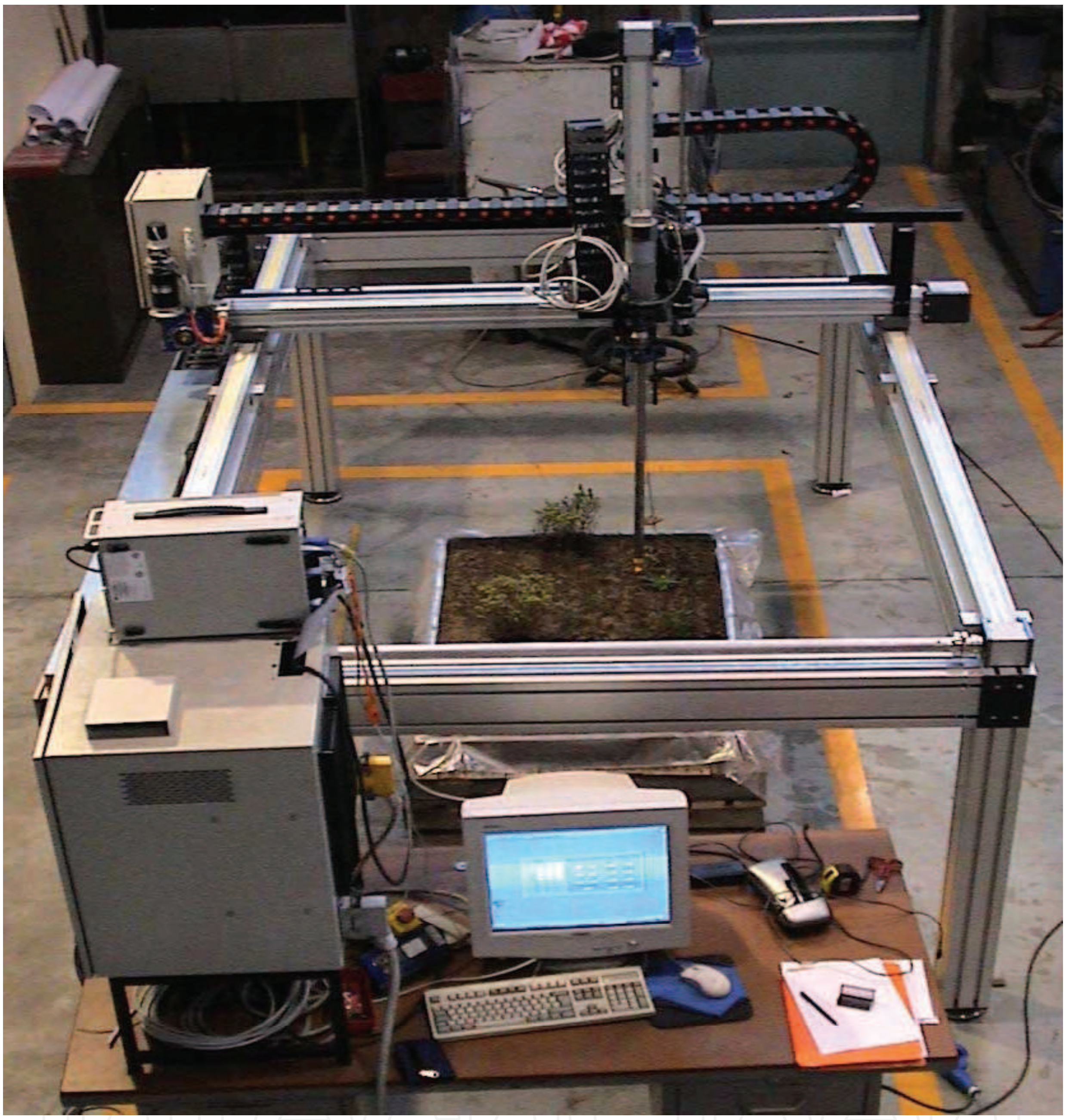

Fig. 9. Cartesian fixed gantry robot prototype.

With this new robot a third operation has been added: c) mechanical weed control. This is obtained with a “fork-like tool” secured to the end effector of the robot, that rotates along the *z* axis, moved by the forth axis motor. The tool can then weed the soil around the plants mechanically removing not desired vegetation. The interest of this operation lies in the fact that it could substitute, at least in part, chemical treatments and could therefore contribute to pollution reduction and to a safer working environment.

7. Future activities

In Section 3 it has been evidenced that robots should be able to perform as many elementary operations as possible in order to facilitate their industrial use in intensive farming. This because a robot that can automatically manage the whole growing cycle of several crops is commercially appealing. To contribute to the definition of this kind of robot the future lines of study and research that we will develop mainly consist in the derivation of tools and techniques enabling other significant elementary operations. In doing this particular attention will be devoted to the integration of the elementary operations with the artificial vision system integrated in the robot. Actually the vision system seems to be a very important part of an efficient robot for two reasons. The one is that several elementary operation need guidance and control. In the greenhouse where the environment is not completely structured and changes can be caused by chance or by the action of human operators, a visual control for the localization of plants and obstacles seems an almost obliged choice. The second reason is that the artificial vision system integrated in a robot can itself perform evaluations, comparisons, and monitoring of growth and of other characteristics that cannot be performed by human operators and could become highly useful for optimal management of crops.

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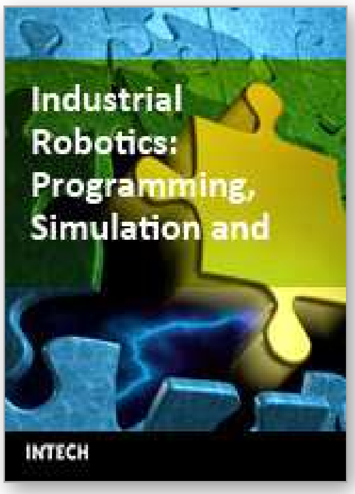

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This book covers a wide range of topics relating to advanced industrial robotics, sensors and automation technologies. Although being highly technical and complex in nature, the papers presented in this book represent some of the latest cutting edge technologies and advancements in industrial robotics technology. This book covers topics such as networking, properties of manipulators, forward and inverse robot arm kinematics, motion path-planning, machine vision and many other practical topics too numerous to list here. The authors and editor of this book wish to inspire people, especially young ones, to get involved with robotic and mechatronic engineering technology and to develop new and exciting practical applications, perhaps using the ideas and concepts presented herein.