Robotics and Automation for Crop Management: Trends and Perspective

Comba L., Gay P., Piccarolo P., Ricauda Aimonino D.
D.E.I.A.F.A. - Università degli Studi di Torino, via Leonardo da Vinci 44, 10095 Grugliasco (TO) – Italy E-mail paolo.gay@unito.it

Abstract
Current automated machines in agriculture and, particularly, in protected crops mainly consist in ad-hoc equipments able to perform one specific operation (sowing, transplanting etc.) obtaining high performances in terms of speed and work accuracy.
Available equipments for greenhouse productions are not enough to fulfil the specific demand of specialized machines and there is a strong need of high level of automation machines that could move and operate autonomously in the production site. The introduction of robotics in glasshouses or tunnels could represent a viable solution once robotized multitasking platforms, which can autonomously perform repetitive tasks, will be available. Autonomous robots could be adopted for localized high precision chemical applications, as well as to perform other operations such as products handling, mechanical weed control, precision fertilization and cutting.
Aim of this paper is to discuss, also on the base of the recent results appeared in literature, future trends and application of robotics in protected crops.

Keywords: automation, robotics, greenhouses

Introduction
Robotics and automation (R&A) are widely diffused in many production sectors. At present, agriculture has been only partially involved in this process. The reasons of the delay in the technological transfer of R&A towards agriculture and, in particular, protected crops have been thoroughly analyzed in Kassler (2001) and Belforte et al. (2006).
Despite that, many researches have been conducted to develop reliable technologies, based on ICT, R&A, artificial vision and intelligence, and prototypes for agricultural applications. Twenty years have been passed since the publication of the first results and until now many hundreds of papers have been published. Different approaches and prototypes typologies have been presented and some of them have been successively revised and improved.
Scope of this paper is to analyze a selected subset of 45 papers, that authors considers among the most relevant, with the aim to outline a general framework and to summarize whose that turn out to be the most promising solutions.
This study has been focused on robots and high-level of automation machines that can autonomously perform operations on crops. The general features of prototypes and robotics systems proposed in the selected literature have been grouped according to four main headings: the operative environment (greenhouse or open field), the typology of the solution (autonomous robots, guided navigation robotic platforms, fixed point cells and tractor implements), the performed operation on the crop, the navigation and control strategies. The results of this analytical study is summarized in Table 1 and discussed in the next sections.

Operative environment

Researches can be firstly classified considering if the applications are in open field or in protected crops, mainly in greenhouses. Although many operations are performed in both environments, some important factors influence the design strategies and the reliability of the equipments, in particular for what concerns the displacement of the robot or, in the advanced applications, the autonomous navigation.

Many contributions are devoted to the use of robots in open field (see Table 1), with particular emphasis to automatic guided machines. Open field is strongly unstructured, without fixed reference points, subject to variable climate and, often, presents severe conditions (humidity, powder…) for robots. In this context, many studies concern robotic weeding in organic farming, where the employment of herbicides is not allowed (see e.g. Sørensen et al. 2005). Greenhouses have a higher predisposition to the introduction of robotic systems than the open field, for a number of technical and economical reasons (Belforte et al., 2006; Belforte et al., 2007; Sandini et al. 1990). Crops are intensively cultivated following regular schemes, in the presence of infrastructures, on regular surfaces and taking advantage of facilities (power supply, irrigation plants, pressured air…). In addition, greenhouses are typically equipped by climate, lighting and irrigation control systems that make environment condition more controlled than in open field. Finally, the intensive production of high value crops justifies the investments needed for the introduction of new technologies.

Typology of the robot machine

A first classification within this heading can be made between stand-alone robotic platforms (fixed or mobile) and tractor implement. In the latter case, studies concern the development of "intelligent" implements as, for example, the automatic driving of steerage hoes for mechanical inter-row weed control (Tillet et al., 2002; Tillet and Hague, 1999), or different intra-row weeding implements (Nørremark et al., 2008; Tillet et al. 2008; Blasco et al., 2002). Other kind of automated implements can be found in Bulanon and Katoaka (2010), and in Leemans and Destain (2007) where robotic harvesting of apples and precision seed drill guidance are presented, respectively.

Among robotic platforms, many studies were focused on mobile autonomous vehicles able to follow crop rows, performing specific operations on crop (see Table 1). Most of them have been conceived to operate in open field for weeding or distribution of chemicals on crops. Only few examples have been specifically developed for greenhouse applications (Balloni et al., 2008; Sandini et al., 1990). With regard to the motion system, wheels have been preferred to tracks, which have been employed only in Chatzimichali et al. (2009), Belloni et al. (2008) and Hayashi et al (2002). Although a better traction and a less soil compaction, tracks suffer steering operations in narrow spaces (Bakker et al., 2010). Four driving and steering wheels give a high manoeuvrability to the vehicles both along crops rows and in headlands respect to other solutions, thus this travelling gear is adopted in more recent autonomous robots (Bakker et al., 2010; Sørensen et al., 2010 and 2007; Slaughter et al., 2008; Bak and Jakobsen, 2004).

Robotic cells that operate at fixed point or that move thank to a fixed navigation system are typically employed in greenhouses. In the first case the product is provided to robotic station by conveyor belts or mobile benches (Rath and Kawollek, 2009; Belforte et al., 2006; Cho et al, 2002; Reed et al., 2001; Ryu et al, 2002), whereas in the second case the robotic cell moves on fixed path along crops rows. Rails are the most frequent solution to displace robotic stations through the greenhouse. They can be installed on floor (Hayashi et al. 2009; Tanigakiet et al, 2008), exploiting greenhouse structures as proposed by Belforte et al. (2007) or existing facilities (e.g. exploiting heating plant pipes as in Van Henten et al., 2003 and 2007).

Fixed point and fixed navigation systems avoid the autonomous navigation, which is technically quite complex, devoting hardware and software resources to crop operations (Belforte et al., 2007). A number of high throughout fixed-point machine are already available on the market for seeding, potting and transplanting in plant nurseries (see e.g. Urbinati, 2010).

Operations on crops

Among the operations that could be performed by agricultural robots, weed control has been the most studied so far, as can be observed in Table 1. Robotic weeding is considered a valid solution to reduce the employment of herbicides in the next future, improving the sustainability of the agriculture (Slaughter et. al, 2008; Griepentrog et al., 2004).

A first solution to reduce the usage of herbicides is the precision spraying. This technique consists in the application of herbicides only in regions of the field in which a weed emergence occurs. Product distribution is typically performed using spraying bars equipped with valves driven by an artificial vision system, which identifies weed emergencies (Slaughter et. al, 2008; Soegaard and Lund, 2007).

More studies have been focused on physical weed control. Inter-row weeding can be improved introducing automation for driving conventional steerage hoes with an artificial vision system (Tillet et al., 2002; Tillet and Hague, 1999). Regarding to physical intra-row weed control numerous autonomous robots were developed. Besides the autonomous navigation along crops rows, the control unit of these robots have to identify and separate crops and weeds in order to remove each weed seedling with by a specific tool. Some examples of implementation of this kind of mechanical actuators for intra-row weeding are in Bakker et al. (2010), Sørensen et al. (2007), Åstrand and Baerveldt (2002), Lamm et al. (2002). For the inactivation of the weed, Lee et al. (1999) proposed the employment of an air pressure jet, whereas Blasco et al. (2002) applied an electrical discharge. Jeon and Tian (2009) developed a direct chemical application end effector that cuts the stem of weeds and wipes chemical on its cut surface, promoting the penetration via the vascular tissue.

Distribution of chemicals for diseases control is a further important item in agriculture, in particular in protected crops, where the climatic conditions and the intensive practice impose several treatment cycles. In this case the main challenge is to avoid the presence human operators inside greenhouses during treatments using autonomous vehicles (Balloni et al., 2008; Mandow et al. 1996; Sandini et al., 1990) or fixed robotic cell in the case of pot crops (Belforte et al., 2006 and 2007). Robotic systems can also perform a precise application of chemicals reducing product leakages with significant economical and environmental advantages. In this case, an automatic crop recognition system is required (Belforte et al., 2006 and 2007; Tillet et al. 1998, Sandini et al., 1990).

Several studies have also been dedicated to the harvest or fruit, vegetables and flowers with the aim to reduce the labour requirement, especially when this operation is exclusively manually performed. Excluding a mobile robot for asparagus harvesting in open field proposed by Chatzimichali et al. (2009), two tractor implements developed by Bulanon and Kataoka (2010) and Peterson et al. (1999) for apples and the oranges harvesting proposed by Muscato et al. (2005), harvesting robots developed so far have conceived to operate in greenhouse with highly structured growing schemes (Kondo et al. 1996) adopting fixed point (Rath and Kawollek, 2009; Cho et al., 2002; Reed et al., 2002) or fixed navigation platforms (Hayashi et al. 2009 and 2002; Tanigakiet et al, 2008; Van Henten et al., 2003). Harvest is the most difficult crop operation since involves the direct interaction of the robot with extremely delicate targets. For this reason particular tools have been developed in order to manipulate the objects avoiding damaging them. Usually, these end-effectors consist of two parts: a

gripping mechanism, often in combination with a suction device, and a peduncle-cutting system that in most cases are a sort of shears, whereas Van Henten et al. (2003) propose a thermal cutting device for cucumber harvesting.
A feature that we consider fundamental is the ability to host different tools carrying out a number of tasks. It has to be noted that most agricultural robots are able to perform only a single specific operation. Only in Belforte et al. (2006 and 2007) and Van Henten et al. (2003 and 2007) multipurpose robots are presented. In the first case two different fixed-point robotic cells were equipped with a set of tools (precision spraying, precise grain fertilization, pot handling, mechanical weed control) operating on pot crops, whereas cucumber harvesting and de-leafing were performed in the second one.

Navigation and control strategies

Core technologies for agricultural robots implemented as autonomous vehicles are the localization and guidance systems. Among the number of guidance-sensing technologies investigated in last decades two type of sensors have achieved a commercial maturity: Global Position System (GPS) and machine vision (see e.g. Slaughter et al. 2008). These technologies were employed alone or together to increase the accuracy (see Table 1). The operating environment typically conditions the choice between the two systems. The employment of GPS based navigation systems is not recommended in protected crops, in particular in glasshouses, where the presence of metallic structures strongly attenuates the satellite signals. As an example, Soegaard and Lund (2007) developed an autonomous robot able to operate both in field and indoor, but GPS is activated only outdoor. On the contrary, the performances and the robustness of machine vision based systems strongly depend on light conditions (Slaughter et al., 2008), therefore particular row tracking algorithms have to be developed in particular for open field. To cope with this problem, some robots have been designed to work during the night, under artificial light conditions. Information provided by GPS and/or artificial vision were integrated with other sensors such as encoders installed on traction and steering system, electronic compass and accelerometers. Ultrasonic sensors were also considered to assist the autonomous guidance as proposed in Cho and Lee (2000), Harper and McKerrow (2001), and Mandow et al. (1996).
With regard to control of tools, machine vision is widely employed since the spatial position of the operations targets (crops, weeds or parts of them) is generally unknown. When the contact with the target is foreseen, such as precision spraying, the same vision system adopted for autonomous navigation could be exploited (Tillet et al. 1998). Otherwise, for example in the case of GPS based mobile robots or robotic cells, tools are controlled by a proper artificial vision system. Many researches were focused on the development of algorithms able to separate the objects in different classes (crop, background, weed…). Even in this case, light conditions variability affects the artificial vision system performances, thus some authors adopted illumination systems, in combination with shields, in order to acquire images in standard light conditions. Åstrand and Baerveldt (2002) and Lee et al. (1999) apply this technique for robotic weeding in open field.
Harvest needs more complex artificial vision systems, usually based on stereovision, because objects (fruits, vegetables or flowers) have to be identified and located in a three-dimensional space.

Table 1. Features of agricultural robotic systems grouped within four main categories

	Greenhouse	Open Field	Autonomous robot	Fixed navigation	Fixed point cell	Tractor implement	Multiporpose	Spraying on crop	Precision spraying W C	Mechanical/Phisical WC	Harvest	Other operations	Vision navigation	Vision Tools Control	GPS	Other sensor	Giudelines	Perspectives	Review
Åstrand and Baerveldt (2002)		x	x							x			x	x		x			
Bak and Jakobsen (2004)		x	x										x		x	x			
Bakker et al. (2010)		x	x							x					x	x			
Bakker et al. (2010)		x	x							x			x	x	x	x	x		x
Balloni et al. (2008)	x		x					x					x						
Belforte et al. (2006)	x				x		x	x				x		x			x		
Belforte et al. (2007)	x			x	x		x	x		x		x		x			x		
Blasco et al. (2002)		x				x				x				x					
Bulanon and Kataoka (2010)		x				x					x			x					
Chatzimichali et al. (2009)		x	x								x		x						
Cho and Lee (2000)		x	x					x							x	x			
Cho et al. (2002)	x				x						x			x					
Griepentrog et al. (2004).									x	x								x	
Hagras et al. (2002).			x																
Hague et al. (2000).		x	x										x			x			
Harper and McKerrow (2001)	x		x													x			
Hayashi et al. (2002)	x			x							x			x					
Hayashi et al. (2009).	x			x							x			x					
Jeon and Tian (2009).	x	x	x						x	x				x					
Kassler (2001).																		x	
Kondo and Monta (1999).				x							x			x					
Kondo et al. (1996)											x							x	
Lamm et al. (2002)		x	x							x			x	x	x				
Lee et al. (1999)		x	x							x			x	x	x				
Leemans and Destain (2007)		x				x						x		x					
Mandow et al. (1996)	x		x					x					x			x			
Muscato et al. (2005)											x								
Nagasaka et al. (2004)		x	x									x			x	x			
Nørremark et al. (2008)		x				x				x					x				
Pedersen et al. (2006)																		x	
Peterson et al. (1999)											x								
Rath and Kawollek (2009)	x				x						x			x					
Reed et al. (2001)	x				x						x			x					
Ryu et al. (2001)	x				x							x		x					
Sandini et al. (1990)	x		x					x					x						
Slaughter et al. (2008)			x						x	x			x	x	x	x			x
Soegaard and Lund (2007)	x	x	x						x					x	x	x			
Sørensen et al. (2007)		x	x							x			x		x				
Sørensen et al. (2010)	x																x		
Tanigakiet al. (2008)	x			x							x			x					
Tillet and Hague (1999)		x				x				x				x					
Tillet et al. (2002)		x				x				x				x					
Tillett et al. (2008)		x				x				x				x					
Tillett et al. (1998).		x	x					x					x	x		x			
Van Henten et al. (2003)	x			x			x				x			x					
Van Henten et al. (2007)	x			x			x					x							

Conclusions and perspectives

The introduction and diffusion of robotics systems will represent an important opportunity for agriculture in next future. The employment of robotic systems will improve sustainability and work safety in many agricultural sectors as well as a consistent production costs reduction. Distribution of chemicals by means autonomous robots would avoid the presence of human operator during treatments in particular in greenhouses where this operation is still manually performed. At the same time, a significant reduction of pollutants can be obtained with precise application of pesticides. Environmental friendly practises as physical weed control would became economically feasible with consistent costs depletion in particular in organic farming (Sørensen et al, 2005; Griepentrog et al., 2004). Pedersen et al. (2006) demonstrate the economical feasibility of applying autonomous robotic vehicles, compared to conventional systems, in micro-spray robotic weeding, crop scouting and grass cutting in golf courses. However some technical and economical challenges will have to be faced in next years to achieve a real diffusion of robotics in agricultural practices and its consequent benefits. The high costs and reliability of guidance systems as well as the small throughput are still an obstacle that increase the cost of robotic systems (Pedersen et al., 2006). Detection and identification of crops and/or weeds under a wide range conditions common to agricultural scenarios remains another important challenge (Slaughter et al., 2008).

In the authors opinion there are some interesting perspectives in R&A for agriculture. First of all, the development of light robots, that could perform simple operations, using the simplest possible technologies, without the presence of human operators. This kind of machines could be primarily devoted to spraying operations, but could also be used in other repetitive simple tasks. To reduce costs and complexity, these robots could be designed to use fixed references (laser pointers, straight magnetic or optical line etc.) for the navigation, favouring greenhouse applications. Furthermore, research efforts should be addressed to develop more flexible robots in terms of row distance and parcel size as well as of ability to host different tools. In this way the same robotic platform (fixed or mobile) could perform many operations on different crops, optimizing the costs.

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