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Review

Agricultural robots for field operations: Concepts and components

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This review investigates the research effort, developments and innovation in agricultural robots for field operations, and the associated concepts, principles, limitations and gaps. Robots are highly complex, consisting of different sub-systems that need to be integrated and correctly synchronised to perform tasks perfectly as a whole and successfully transfer the required information. Extensive research has been conducted on the application of robots and automation to a variety of field operations, and technical feasibility has been widely demonstrated. Agricultural robots for field operations must be able to operate in unstructured agricultural environments with the same quality of work achieved by current methods and means. To assimilate robotic systems, technologies must be developed to overcome continuously changing conditions and variability in produce and environments. Intelligent systems are needed for successful task performance in such environments. The robotic system must be cost-effective, while being inherently safe and reliable—human safety, and preservation of the environment, the crop and the machinery are mandatory. Despite much progress in recent years, in most cases the technology is not yet commercially available. Information-acquisition systems, including sensors, fusion algorithms and data analysis, need to be adjusted to the dynamic conditions of unstructured agricultural environments. Intensive research is needed on integrating human operators into the system control loop for increased system performance and reliability. System sizes should be reduced while improving the integration of all parts and components. For robots to perform in agricultural environments and execute agricultural tasks, research must focus on: fusing complementary sensors for adequate localisation and sensing abilities, developing simple manipulators for each agricultural task, developing path planning, navigation and guidance algorithms suited to environments besides open fields and known a-priori, and integrating human operators in this complex and highly dynamic situation.

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Nomenclature

ARS	Autonomous robot systems
CCD	Charge Coupled Device
CMOS	Complementary Metal Oxide Semiconductor
DGPS	Differential Global Positioning System
FOG	Fibre Optic Gyro
GPS	Global Positioning System
HO	Human Operator
HRS	Human Robot System
IR	Infrared
NIR	Near Infrared
LIDAR	Laser Scanner
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
RMSE	Root Mean Square Error
RTK	Real Time Kinematic
SF1	Starfire free access
SF2	StarFire paid subscription access
VLSI	Very Large Scale Integration

1. Introduction

Extensive research has been conducted on the application of robots and automation to a variety of field operations, and technical feasibility has been widely demonstrated. Recent research and developments in robotics for agricultural field applications and the associated concepts, principles, limitations and gaps are reviewed.

1.1. *Background*

Agricultural productivity has increased significantly over the years as a result of intensification, mechanisation and automation (Nof, 2009; Zhang, 2013). It is an important target for the application of various kinds of technology designed to increase both crop yield and quality while reducing agriculture costs. For example, precision seeding and planting increase average plant size and uniformity of plant maturity, precise fertigation consisting of adding water and plant nutrients required by the crop only at the optimal time and position decrease the ratio of agricultural inputs to crop production (Tremblay, Fallon, & Ziadi, 2011) and environmental impact (Tremblay, Bouroubi, et al., 2012): optimising in-season nitrogen application based on remote sensing and fuzzy inference system resulted in the same yield as that obtained with the recommended uniform application, which required 31% more nitrogen (Tremblay et al., 2010). In addition, recent studies indicate that the practise of robots or autonomous tractors in various agricultural tasks reduce the fuel consumption and air pollution (Gonzalez-de-Soto, Emmi, Benavides, Garcia, & Gonzalez-de-Santos, 2016; Gonzalez-de-Soto, Emmi, Garcia, & Gonzalez-de-Santos, 2015).

In the 20th century, technological progress in developed countries reduced the manpower that was traditionally available for farming activities by a factor of 80 (Ceres, Pons, Jimenez, Martin, & Calderon, 1998). Automation has considerably increased the productivity of agricultural machinery by increasing efficiency, reliability and precision, and reducing the need for human intervention (Schueller, 2006). However, agriculture is still suffering from an important lack of minimally trained workers, especially in the horticulture sector.

The problems generated by the absence of workers are amplified by the trends of increasing farm size, decreasing numbers of farmers and increasing environmental impact of food production, requiring even more efficient agricultural practices (Nagasaka, Umeda, Kanetai, Taniwaki, & Sasaki, 2004) and the productivity of conventional farming, in which the crop cultivation and management manually conducted by farmers, can be significantly improved by using intelligent machines (Xia, Wang, Chung, & Lee, 2015). Although robotics and automation require a more costly specialised workforce and equipment, they contribute to increased agricultural productivity because the required workforce, including skilled machine operators, generally declines enough to compensate for the higher initial cost. In addition to the reduced number of farms, the average age of the agricultural workforce is continuously increasing, indicating that this profession is not attractive enough for the younger generation (Iida et al., 2013; Noguchi, Will, Reid, & Zhang, 2004; Zhang, Noguchi, Ishii, Yang, & Zhang, 2013). However, despite the huge challenge of robotics and automation applications for farming operations, the reduction in tasks performed under harsh conditions and the increase in the farmer's quality of life should increase their attractiveness to the farming profession.

Unfortunately, unlike industrial applications which deal with relatively simple, repetitive, well-defined and predetermined tasks in stable and replicable environments, agricultural applications for automation and robotics require advanced technologies to deal with complex and highly variable environments and produce (Hiremath, Van der Heijden, Van Evert, Stein, & Ter Braak, 2014; Nof, 2009). Furthermore, agricultural production deals with live produce (fruit, vegetables, grains and flowers) which is highly sensitive to environmental and physical conditions (Eizicovits & Berman, 2014), such as temperature, humidity, gas, pressure, abrasion and acceleration. Live produce requires gentle, accurate and often complicated handling operations to maintain sufficient quality to travel the distance and time separating their production site from consumers. This characteristic makes the replacement of human ability by machines or automation extremely difficult. Therefore, most fruit, vegetable and flower growing and similar production tasks, e.g., trellising, harvesting, sorting and packaging, are still performed manually (Zion et al., 2014). This makes manual labour a major cost component in field operations (Eben-Chaime, Bechar, & Baron, 2011), reaching up to 40% of the total cost (Bechar & Eben-Chaime, 2014).

Most agricultural operations occur in unstructured environments characterised by rapid changes in time and space, such as military, underwater and space environments (Bechar & Edan, 2003). The terrain, vegetation landscape, visibility, illumination, and other atmospheric conditions are ill-defined, vary continuously, have inherent uncertainty, and generate unpredictable and dynamic situations (Bechar, 2010).