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Agricultural cyber physical system collaboration for greenhouse stress management

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ABSTRACT

This article presents a CPS (Cyber Physical System) oriented framework and workflow for agricultural greenhouse stresses management, called MDR (Monitoring, detecting and responding)-CPS. MDR-CPS has been designed to focus on monitoring, detecting and responding to various types of stress. CCT (Collaborative Control Theory) is applied in MDR-CPS to deploy CRP (Collaborative Requirements Planning), address CEs (Conflicts and Errors) and enable a collaborative architecture for better CPS interactions. Analytic studies and simulation experiments are conducted to compare our scheme with an alternative scheme for agricultural greenhouse stress management. The results show that MDR-CPS performance is better than the compared scheme, in terms of detection cooperated with human, CEs tolerance, and emergency response. Focus in this design and development is on the collaboration among sensors, robot, and human to improve the MDR-CPS' performance.

1. Introduction

Agricultural plants encounter many unexpected and abnormal stress situations, even in a greenhouse, such as abnormalities in temperature, humidity, water levels, disease emergence, and pests. If such abnormalities are not dealt with in a timely manner, through detection and localization, proper response and prevention, they may cause severe and irreparable damages (Ari et al., 2015). Sensors have been found effective in various types of application in agricultural monitoring (Gongal et al, 2015). Physical phenomena such as temperature, humidity, and rainfall over an agricultural region can be monitored by sensors. However, sensors produce massive amounts of data even in a very short period. If all those data must be analyzed with timely response by humans, it will impose unimaginable and tedious workloads. On the other hand, sensors cannot complete monitoring and responding tasks in typical agricultural environments without additional support, e.g., from humans and robots (Ko et al., 2015a, 2015b). Generally, robots are better suited than humans to take over repetitive tasks, report legitimate agricultural abnormal situations and conditions as soon as they emerge. Considering pests on plant leaves and stems rapidly sensed by infrared sensors that are faster than videos, agricultural experts can receive those abnormal reports, interpret them and dispatch a robot to arrive at that location, take pictures or record videos, and transmit them back to agricultural experts by WIFI or 4G.

The description above is a typical agricultural CPS (Cyber Physical System). With rapid development in information technology and cybernetics, intensive computing resources are used to connect computerized physical devices to provide control, communication, coordination, and collaboration. Networked manufacturing systems, intelligent transportation systems, smart infrastructures, and power grids are all appropriate examples of emerging CPSs (Zhong and Nof, 2015). Though CPSs have attracted significant research interest because of their promising applications across different domains; how to effectively model CPSs in real applications is still a challenge (Nayak et al., 2016). According to these studies, multiple factors have impact on agricultural CPS including humans, sensors, robots, agricultural plants and data, etc. How to make them work smoothly and operate in a way of cooperation, while avoiding conflicts, errors and disruptions, needs to be considered and designed carefully.

Recently, CCT (Collaborative Control Theory) has been widely applied to deal with the uncertainties in the market demand and capacity (Nof, 2007; Ko and Nof, 2012). Moghaddam and Nof (2014) combined two CCT-based protocols—Demand and Capacity Sharing Protocol (DCSP) and Best Matching Protocol (BMP) to maximize profit and resource utilization of supply enterprises. As to the management of conflicts and errors, a distributed conflict and error detection prediction network is designed and applied to a case study of collaborative control for a robotic nuclear decommissioning task (Zhong et al., 2013). An agent-base and distributed algorithm to identify and prevent errors (AEPA) was presented in production and service (Chen and Nof, 2012).

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Two constraint-based conflict and error prevention and detection (CEPD) algorithms, centralized and decentralized algorithms, were designed by Chen and Nof (2012). These previous concepts and methods could be suitably introduced to control and management in the agricultural procedure. The research reported in this article aims to facilitate the use of CCT in handling these uncertainties; and design a CCT-based CPS collaboration platform for prevention, detection and response system, targeting the stress situations and conditions in agricultural greenhouses. Response to detected stresses is considered too but is left for further research. The premise of this research is that to be effective. To summarize, this research aims at:

- Reducing uncertainty in agricultural CPS according to combined humans, sensors and robots who cooperate to monitor, detect, diagnose and respond to stresses in an agricultural greenhouse.
- Designing collaborative workflow based on the designed agricultural CPS.
- Applying collaborative control theory to the designed agricultural CPS.

This article is organized as follows. In Section 2, related work is described on Wireless Sensor Networks (WSNs), robots and CPS in agricultural areas. In Section 3, system framework and workflow are designed and elaborated, also, collaboration control theory is explained and applied for the designed agricultural CPS. The designed workflow and protocol are illustrated, evaluated, and validated through analysis and experiments in Section 4. Finally, concluding remarks and planned future research are found in Section 5.

2. Related work

Many agricultural crops and food is lost because of the damage by plant diseases, pests, and rats. Intensive research on monitoring and detection in agricultural environments has been deployed worldwide. New technologies such as CPS, Global Positioning Systems (GPS), WSN, and Agricultural Robots (AR) are widely used. In this research, we integrate WSN, a robot and humans to cooperate in an agricultural CPS for stresses monitoring and detection. First, we review applications of WSN, robot, CPS in agricultural field, respectively.

2.1. WSN in agriculture

WSN plays an important role in agriculture for monitoring different activities in the cultivation field. According to WSN application in agriculture, there are three typical WSNs.

First, WSN is deployed for monitoring and detection. For instance, an environmental monitoring system was implemented and was capable of measuring temperature, humidity, illumination, soil moisture, CO_2 concentration of greenhouse using a sensor array and the digital signal processing (DSP) board (Kumar et al., 2010a,b). Humidity sensors were deployed to observe whether humidity influences transpiration, condensation, and disease incidence in a tomato greenhouse (Hoshi et al., 2016). Second, WSN in precision agriculture has drawn greater attention in recent years. Blackmore (1994b) defined it as a comprehensive system designed to optimize agricultural production by carefully tailoring soil and crop management to correspond to the unique conditions found in each field, while maintaining environmental quality. A scheme based on the collaboration of integrated system was proposed for automated irrigation management with an advanced novel routing protocol for wireless sensor networks in precision agriculture (Nikolidaks et al., 2015). Third, WSN was deployed for monitoring animal agriculture. For instance, a potential utilization of wireless sensors for increasing livestock production was investigated (Wang et al., 2006). A smart farm was developed to apply wireless sensor network for animal agriculture (Wark et al., 2007).

2.2. Robots in agriculture

The idea of robotic agriculture is new with the breakthrough of sensors' constraints, recently there is an ever-increasing awareness of the necessity to develop and apply robotic systems in the novel fields of agriculture, forestry, greenhouses, horticulture, etc. (Belforte et al. 2006, Gay et al. 2008, Mcintosh 2012). Smart vehicles should be capable of working 24 h a day all year round, in most weather conditions and have the intelligence embedded within them to behave sensibly in a semi-natural environment, unattended, while carrying out a useful task (Pedersen et al., 2005). However, Contrary to industrial applications which are usually well-specified and known a priori, an agricultural robot must deal with an unstructured, uncertain and varying environment which cannot be predetermined. Fundamental robot applications in agriculture include the followings.

First, agricultural robots replace farmers to take on tedious and repetitive operations, such as precise fertilization and spraying, optimal irrigation, and selective harvesting (Reid et al., 2000, Keicher and Seufert, 2000). A comprehensive review about the state-of-the-art in robotic fruit harvesting and challenges ahead was published by Bac et al. (2014) and showed that over the past three decades research has been carried out for about 50 systems for harvesting, e.g., apples, oranges, tomatoes, cucumbers, strawberries, and melons. Second, agricultural robots aid farmers to improve and enhance agricultural activities, such as inspection and detection of crops and plants diseases, or pest disasters. For instance, a weed control robot was developed by Astrand and Baerveldt (2002). With breakthroughs in sensors' reliability, more robots are equipped with different kinds of sensors to navigate in the fields, to carry on precise inspection and detection. For example, a watch-dog robot with cameras was deployed to automatically collect information in agricultural fields (Nagasaka et al., 2004). A remote monitoring system of agricultural robots using web application was described to make clear conditions about robots' combination and adequately manage agricultural task data (Ishibashi et al., 2013). A prototype agricultural mobile robotic platform was designed and developed for robots to automatically navigate in pesticide spraying application (Ko et al., 2015a, 2015b).

2.3. CPS in agriculture

Applications of CPS arguably have the potential to dwarf the 21th century IT revolution, which includes high confidence medical devices and systems, traffic control and safety, critical infrastructure control, and so on. The key role of cyber in such complex systems and networks is its ability to endow computational, operational intelligence to handle and overcome real time challenges and uncertainties. Agricultural field is one of the complex domains that can benefit from applicable CPS. A swarm of cooperative sensors was utilized within a cyber-physical system framework to optimize the use of pesticides with precision spraying (Stark et al., 2013). Another precision agriculture architecture based on CPS technology was developed (Nie et al., 2014), including three layers: the physical layer, the network layer, and the decision layer. Every layer was analyzed in detail, helping the exploration of CPS in precision agriculture. An integrated open geospatial web service-enabled cyber-physical infrastructure was proposed (Chen et al., 2015) to acquire, integrate, process, and distribute monitoring information from the physical sensor space over the World Wide Web. With the development of information technology, new monitoring and detection technologies have been utilized in agricultural greenhouses. The wide applications of WSN and robots, introducing a human operator into the system can help improve performance and simplify the robotic system (Bechar et al., 2009).

WSNs and robots are the currently popular monitoring and detecting techniques in agricultural applications, however, both are highly specific and tailored prototype and cannot be used on a broad scale. The full potential of sensor based disease detection has still not