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Integrated open geospatial web service enabled cyber-physical information infrastructure for precision agriculture monitoring

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ABSTRACT

Various wireless and wired sensors serve vital functions in situational awareness for precision agriculture (PA) monitoring. Achieving the seamless integration of these heterogeneous sensors into information systems to achieve interoperability is challenging. To solve this problem, an integrated open geospatial web service-enabled cyber-physical infrastructure was proposed in this study to acquire, integrate, process, and distribute monitoring information from the physical sensor space of the PA system over the World Wide Web space. This infrastructure was designed as a service-oriented architecture middleware between heterogeneous physical sensors and different PA information clients. In particular, sensor web enablement and web processing services were utilized. Ten types of distributed agricultural sensors were deployed in Baoxie field, Wuhan City, and two different experiments were conducted to verify the proposed cyber-physical infrastructure. Results demonstrated that this infrastructure was capable of handling data and analyses in sensor-based PA monitoring. The proposed approach was then compared with existing typical PA infrastructures. Results indicated that the proposed cyber-physical infrastructure provided interoperable access for heterogeneous sensors, data, and algorithms. The proposed infrastructure thus provides a new feasible method for information system design in PA.

1. Introduction

1.1. Background and problems

Precision agriculture (PA) has been promoted by multidisciplinary theories and technological advancements over the last decade. The core term in PA, called site-specific management, is related to natural resource variability, variability management, and management zones (Zhang et al., 2002). For a high yield, these field variables should be monitored, transmitted, stored, analyzed, mapped, and distributed. Therefore, electronic and electrical science (Fernandes et al., 2013), information science (Cox, 2002), and computer science (Batte, 2005) have been serving increasingly vital functions in agriculture. Heterogeneous sensors, especially wireless sensor networks and corresponding web systems, are widely used for precision seeding irrigation, fertilization, and harvesting.

A development trend in PA is standardization (Zhang et al., 2002; Wang et al., 2006) to achieve web sharing and interoperability (Murakami et al., 2007). Web sharing provides the prerequisites for wide access to agricultural data (Blank et al., 2013). For instance, soil moisture values in every management field can be obtained not only by the farmer himself but also by a third party in a standard-compliant manner. This feature helps to improve the value of agricultural data while reducing repetitive costs. Interoperability is recognized as a new paradigm for integrating heterogeneous systems into a synergistic unit. These two features are critical for the seamless integration of data, reusability of agricultural processes, and loose coupling in the PA web infrastructure (Murakami et al., 2007).

However, some barriers in achieving web sharing and interoperability exist because of different sensor manufacturers, system architectures, and software designs of PA systems.

The first barrier is heterogeneity in sensor interfaces. Sensor interfaces include early analog interfaces (i.e., pulse-width modulation), digital interfaces (i.e., RS232, RS485, and serial peripheral interfaces (SPI)), and fieldbus interfaces (i.e., controller area networks (CAN), highway addressable remote transducers local operating network, and process field bus). However, no uniform interface is suitable for all application contexts. Therefore, the interfaces used in the field can be diverse. As a result, the integration of agro-sensors with different interfaces in the field is cumbersome and requires extensive adaptation efforts (Ruiz-Garcia et al., 2009).

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The second barrier is agricultural data model. Several data models have recently been proposed by different organizations. These models include AgroXML developed primarily by the Association for Technology and Structures in Agriculture in Germany; the ArcGIS model for agriculture discussed by the Environmental Systems Research Institute, Inc.; AGROVOC created by the Food and Agriculture Organization (FAO) of the United Nations and the Commission of the European Communities; AgMES; International System for Agricultural Science and Technology; and AgXML. Although these models have their own advantages, a widely accepted agricultural data model remains unavailable. Understanding the syntax and semantics of different models and exchanging data smoothly on the World Wide Web (WWW) are hot research topics in PA.

The third barrier is related to the agriculture web system architecture and software design. An earlier agricultural web system may be designed as a closed architecture in a local network. This type of infrastructure is incapable of sharing information and cooperating with other systems (Kim and Evans, 2009). Given the need for seamless integration and reusability, software engineering provides PA with one solution called service-oriented architecture (SOA), which integrates distributed web services. Therefore, an increasing number of SOA-based PA systems have been proposed because of their openness and flexibility (Nikkila et al., 2010; Murakami et al., 2007). However, more studies and experiments should be conducted in PA to explore new potential advantages by utilizing multi-disciplinary web services, such as geospatial web services.

In addition to these three barriers, different data transmission protocols and security concerns are involved in the design of a shareable and interoperable web information system for PA. Therefore, researchers worldwide have conducted numerous studies to solve these heterogeneities in PA (Iftikhar and Pedersen, 2011; Schuster et al., 2011). However, a satisfactory solution for acquiring, integrating, processing, and distributing PA monitoring information interoperably over the WWW space from the physical sensor space remains unavailable.

The Open Geospatial Consortium, Inc. (OGC) and ISO/TC211 Geographic Information/Geomatics have proposed a series of geospatial and location-related standards for a number of fields in the last decade including PA. Different geo-information in PA can be handled using these OGC standards. This mechanism is another approach to achieve interoperability in PA sensor systems. Web Map Service (WMS), Web Feature Service (WFS), Web Coverage Service (WCS), and Geography Markup Language (GML) have already shown their advantages in distributing geo-information (Han et al., 2012).

The OGC published Web Processing Service (WPS) in 2007 to define standardized interfaces that facilitate the publishing, discovery, and binding of geospatial processes by clients (Schut, 2007). WPS is compatible with both Web Service Definition Language and Simple Object Access Protocol (SOAP), thus facilitating interoperability with generic, non-geospatial web services. Although Yang et al. (2012) discussed the potential of WPS in agricultural processing, research in this area is still in its infancy.

A promising open geospatial web service used in PA is Sensor Web Enablement (SWE). The NASA Sensor Web Applied Research Planning Group first proposed the term "Sensor Web" in the late 1990s. It is a macro-instrument concept comprising spatially distributed sensor platforms that share information among themselves and act in concert as a single instrument (Delin, 2002). The SWE initiative in the OGC standardized web service interfaces, data, and sensor models in sensor systems. After several revisions by the OGC, the SWE can support almost all aspects of heterogeneous sensor applications. Such applications include Sensor Model Language (SensorML) for sensor modeling and discovery; Sensor Observation Service (SOS) for retrieving sensor data and metadata; Observation and Measurement (O&M) for modeling different data; Sensor Planning Service for sensor tasking; and Web Notification Service for asynchronous notifications. Therefore, the SWE initiative has potential for providing an information middleware to integrate web-ready sensors (Nash et al., 2009). Kubicek et al. (2013) utilized O&M for agriculture, and visualized the O&M data adaptively. Given the interoperable and real-time characteristics of a sensor web, sensor web-integrated infrastructure provides some new features for PA, which is the focus of this study.

1.2. Purposes and outline

As different sensors are utilized to detect spatial-temporal variations in fields, this study attempts to design an open geospatial web service-integrated cyber-physical infrastructure for sensor-based PA monitoring. The proposed cyber-physical infrastructure can serve as an open standards integrated middleware between heterogeneous monitoring sensors and different PA applications. More importantly, this cyber-physical infrastructure can provide seamless interaction for real-time data sharing, loose coupling for reuse, and interoperability for cooperation. Therefore, this research includes three objectives (1) exploring merits of integrating open geospatial services, especially SWE in cyber-physical infrastructure for PA, (2) designing a novel architecture and orchestrated interaction patterns to coordinate these open geospatial web services, and (3) validating and evaluating the proposed cyber-physical infrastructure.

This article is organized as follows. Section 2 presents the design goals, architecture overview, and two interaction patterns for this cyber-physical infrastructure. Two field experiments that validate this infrastructure are then presented in Section 3. Section 4 presents a discussion of our approach, comparison with four existing approaches, and a summary of the merits and limitations. Finally, Section 5 presents the conclusions and future work.

2. Materials and methods

2.1. Design goals

Cyber-physical infrastructure is a coordinated environment, which includes several hardware components, software, and interactions. In PA, a cyber-physical infrastructure is similar to a bridge that connects heterogeneous agricultural sensors with different PA clients. The cyber-physical infrastructure is also similar to a black box, in which all differences between physical sensor interfaces, data transmissions, data formats, and control modes are hidden from the users. The higher-level applications only need to concentrate on a suite of standard interfaces. Therefore, acquiring, integrating, processing, and distributing monitoring information in PA are the aims of the proposed cyber-physical infrastructure. Before designing the architecture of this infrastructure, some design goals are given below.

(1) Integrating heterogeneous agricultural sensors

As discussed above, the sensors installed in a field can be coordinated through different interfaces, such as SPI and CAN. These sensors can also be accessed by different transmission protocols such as IEEE 802.11 or Bluetooth. Therefore, the proposed cyber-physical infrastructure should be capable of hiding these physical differences and managing them transparently over the WWW. In this manner, a higher-level application (i.e., a precision irrigation support desktop system, or an iOS-based fertilization monitoring system) can obtain sensor data without knowing their physical details. Applications can operate heterogeneous sensors in a simple