Cloud-Based Harvest Management System for Specialty Crops

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Abstract*—Harvesting labor is a major cost factor in the production of specialty crops. Today accruing harvest labors is still done by hands, which is error-prone and costly. By integrating cloud-based web application with purposely designed labor monitoring devices (LMDs), we developed a harvest management system for monitoring and accruing harvest labors. The system comprises of two major components: an in-orchard data collection network collecting harvest data and transmitting them to a cloud-based labor management software (LMS); and, LMS processing harvest data and delivering results to users via a tablet-friendly web interface. Using a patented technology, the system accurately accrues harvest labor activities for multiple orchards, even under complex many-to-many employment relations. The system provides multi-fold benefits to stakeholders of specialty crop harvesting: a picker can be compensated accurately by the actual weight of the fruits he picked; and an orchard manager may monitor labor activities in real time and improve his orchard operation based on the analytical reports generated by the system. The dynamic resource allocation provided by a cloud computing platform ensures that the system can handle the fluctuating demand for processing real-time harvest data during and off harvest seasons. The design of the system is optimized for cloud computing, improving the access to orchard data while preserving their privacy for growers. A prototype of the system has been validated in field tests in United States' Pacific Northwest Region.

Keywords*—*cloud computing; agricultural information systems; harvest labor management; wireless mesh networks.

I. INTRODUCTION

Specialty crops are defined by USDA as "as fruits and vegetables, tree nuts, dried fruits, horticulture, and nursery crops (including floriculture)"[1]. The production of specialty crops is important to U.S. agricultural industry. For example, in 2006-7 grow season, the United States exported more than $206 million worth of Cherry. Globally, driven by the rising of middle classes in places like China and the increasing consciousness for healthy foods, the demand for fruits and nuts is anticipated to continue arising in next decade. A challenge for special-crop industry is how to capitalize on these opportunities, increasing the efficiency of production and reducing its cost.

Even with modern orchard technology, special crop production is a labor intensive operation. Harvesting labor is often cited as a prevailing cost in orchard operations. Unlike commodity crops such as wheat and corn, which may be harvested by automated machinery, many special crops such as cherry and blueberry are still picked by hands, due to their delicate nature. Moreover, today monitoring and accruing harvest labors is still mostly done by hands. For example, the United States' pacific northwest region is its largest sweet cherry producing area. In a typical orchard in this region, cherries are mostly picked by temporary and immigrant workers. A picking team comprises of several pickers and a checker (team leader). After each picker fills a bucket with cherries, the checker checks the fullness of the bucket and punches a card for each bucket being filled. At the end of a day a picker is compensated by the number of buckets s/he picked.

This manual labor accruing process is costly and error-prone. Growers have to pay for checkers' time. The measurement of "fullness" of a bucket is subjective. Based on our field survey, it is estimated that a grower in the pacific northwest region typically overpays for about 5% of harvested cherry, due to inaccurate labor accrual and abusive labor practices.

The manual labor accruing process also throws away valuable data that may bears important information about an orchard operation. The ultimate measure of an orchard operation is the output of it product. Harvest data provides a direct measurement of an orchard's output and its harvest labor operation. Much of these data, such as where and when fruits are picked, are lost in the manual accruing process.

The goal of this work is to automate the labor accrual process and to enable data-driven harvest operations. To reach this goal, we need to address the following research questions: (i) *how to collect and transmit real-time harvest data in an orchard*? Harvest data needs to be collected without introducing overhead to an existing harvesting workflow; and the nature conditions of an orchard, such as the dense foliage, present a particular challenge for wireless transmission; (ii) *how to process voluminous real-time harvest data and provide concurrent access to stakeholders across global*? The volume of harvest data fluctuates greatly during a growing season,

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and our system aims to provide access to growers in both south and north hemispheres; (iii) *how to deliver results in an intuitive and meaningful way to growers, to help them make data-driven decisions*? The harvest data is only useful if they can be interpreted in a way that growers can understand, so they can apply the outcome to their decision processes.

To address these research questions, and to provide growers a tool for better managing their harvest operation, we designed and developed a cloud-based harvest management system. The system captures harvest data in the field, automates the accrual of harvest labor, and analyzes the data and delivers results to growers for better decision making. The system comprises of two major components: (1) an in-orchard data collection network comprising labor monitoring devices (LMD) and wireless relaying nodes; and, (2) cloud-based labor management software (LMS) processing harvest data collected from an orchard.

The in-orchard data collection network consists of LMDs, routing nodes, and an Internet gateway. The communication components of these devices form a wireless mesh network in an orchard. A LMDis a data collection terminal purposely designed for interacting with pickers in orchard. Its design is optimized to work with existing harvest workflow. The LMD collects data during a harvesting operation, and transmits the data to the Internet through the wireless mesh network. We greatly improve the reliability of data transmission in orchard by using a combination of the wireless mesh network and an application-layer communication protocol we designed specifically for transmitting harvest data.

The cloud-based labor management software consists of a collection of web apps and databases running on a cloud-based platform. The cloud-based deployment drastically improves the scalability of our system: it can scale up and down resources on-the-fly based on needs for data processing; growers and other stakeholders may monitor fruit harvesting and access analytical reports anywhere using a web browser. We also developed a yield mapping function that uses harvest data to map yield distribution in an orchard. Yield mapping provides growers an intuitive tool to evaluate their production in a finer granularity.

This research is truly an inter-disciplinary work: our team consists of software engineers (SE), electrical engineers (EE), and mechanical engineers (ME). The SE team develops cloud-based labor management software (LMS), the EE team develops devices for the in-field data collection network, and the ME team fabricates mobile mechanical frames for LMDs. We deployed the LMS on Amazon's cloud computing platform AWS, and validated LMDs in field tests in the Unite States' Pacific Northwest Region. These field tests showed the potentials of cloud computing by enabling data-driven precision agriculture. Our work also demonstrated that it would take coordinated inter-disciplinary efforts to unlocking these potentials.

The rest of the paper is organized as follows: Section II provides an overview of the system; Section III introduces the cloud-based labor management software (LMS); Section IV discusses the in-field data collection network, including Labor Monitoring Devices (LMD); Section V describes the design of LMD's mechanical platform; Section VII discusses the implementation and cloud-based deployment of LMS; finally, Section VIII concludes this paper.

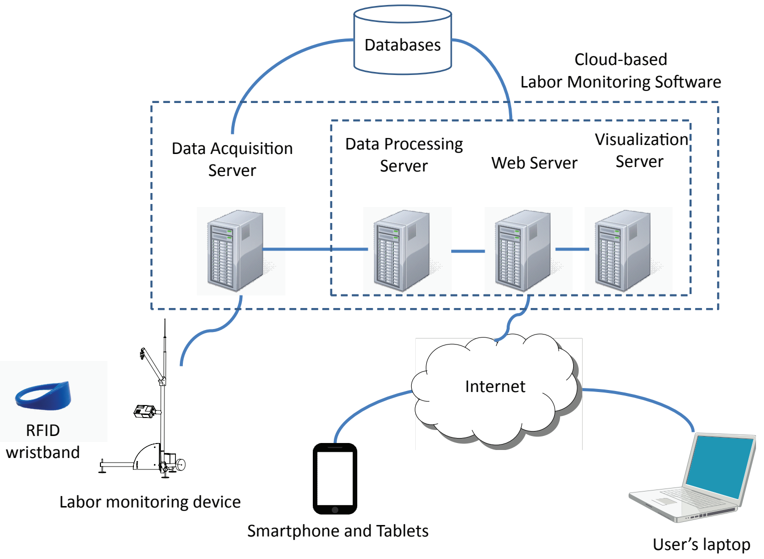


Fig. 1. Overview of the cloud-based harvest management system

II. System overview

The cloud-based harvest management system automates the entire process of accruing and auditing harvest labors. It collects harvest data, analyzes them, and delivers results to stakeholders via a web portal. It includes a complete tool chain of software and hardware that enables the flow of harvest data from orchards to stakeholders. The harvest management system comprises of two major components: (1) the labor management software (LMS) (Section III) processing, managing, and analyzing harvest data; (2) the in-orchard data collection network (DCN) (Section IV) collecting harvest data and transmitting them to the LMS. LMD's mechanical frames (Section V) providing a platform for integrating the LMD's electronic components and enabling its mobility in an orchard. Figure 1 shows an overview of our cloud harvest management system.

The system is designed to work with existing workflow. Each picker is assigned with a picking bucket as usual, as well as a Radio Frequency Identification (RFID) wristband. To record fruits being picked, a picker simply puts his bucket on a scale attached to a LMD. He then waves his RFID wristband before the LMD, which reads the RFID. The LMD also reads its location from its GPS receiver. The LMD sends the geo-tagged harvest data to the cloud-based LMS. The LMS then identifies the employment relation associated with the harvest data using a patented technology [2], and accrues the labor using the pay rate defined by the employment relation. The LMS provides real-time labor monitoring for managers, prepares payroll reports for pickers, and also analyzes harvest data and visualizes results. One particular feature of the LMD is its ability of plotting yield distribution, known as yield mapping, using harvest data. The LMS includes a website with an intuitive and touch-friendly web interface. The website provides role-based access for each stakeholders to access data and reports most relevant to his role.

III. CLOUD-BASED LABOR MANAGEMENT SOFTWARE

The cloud-based labor management software (LMS) is responsible for processing and managing harvest data received from the in-orchard data collection network. The LMS has a data acquisition portal that communicates with LMDs using an application-layer protocol designed for use in orchards (Section IV-B). The harvest data being received may be incomplete or corrupted, due to the inference from foliage in an orchard and other factors. The LMS starts with pre-processing the data, to remove redundant or corrupted records. The LMS associates harvest data with its picker, and accrues labor activities for the picker (Section III-A). The LMS includes a cloud-based web portal which provides role-based access to data and reports. The LMS analyzes harvest data and visualizes results for growers. We developed a yield mapping module that visualizes the yield distribution within an orchard based on harvest data (Section III-B).

A notable feature of the LMS is its real-time labor monitoring capability. Harvest data is collected by LMDs and delivered to the LMS in real time. The LMS' web portal provides several options for a manager to monitor the harvest operation. He may choose to see the efficiency or overall productivity of an individual or a team. Figure 2 shows the web interface for monitoring individual productivity. Each line presents the accumulated weight of fruits being picked by an individual. As a picker weights his harvest at a LMD and waves his RFID wristband, the record is sent to LMS and a new node is instantaneously added to his line on Figure 2. The web interface of LMS is purposely designed to be touch and mobile friendly: for example, the manager may click a node on a line to see its related harvest record.

A. Accruing labor data

The initial motivation of the HMS is to automate the accrual of harvest labor activities. It turned out that accurately accruing harvest data is anything but easy. One major challenge roots from complex and transitional labor relations in specialty crop harvesting. In the United States, a majority of harvest labor force is immigrant workers. Their labor relations are often temporary and seasonal. A picker may work in multiple orchards at the same time, and in some cases, even in the same orchard at different pay rates, depending on what job he is doing. For example, a picker may pick up cherry in mornings and blue berry in afternoons, and the pay rate, measured by pounds of fruits being picked, is very different between two. To complicate the matter even further, our cloud-based system needs to work with multiple orchards at the same time, and the labor forces of different orchards may be overlapped with each other.

To address this challenge, we developed a patented technology [2] to accurately associate a picking record with its underlying employment relation. In its simplest form, the technology uses a combination of the identification of a LMD and picker's RFID to identify the picker responsible for a picking record. In our harvest management system, each LMD is assigned with a unique identification lmd_id, and an orchard/employer assigns at most one RFID pid to a picker (and register this employment relation with LMS). Prior to operating in an orchard, a LMD is associated with the orchard in the cloud-based LMS. During its operation, the LMD reads the picker's RFID pid as part of its standard workflow, and sends a picking record with its lmd_id and the picker's pid. LMS uses lmd_id to identify the orchard operating the LMD, and then uses pid to identify the picker and his employment relation with the orchard, including his pay rate defined by the employment relation. The LMS then accrues the picker's labor activities using the weight of fruits he picked and the pay rate. The patented technology is also capable of handling much more complicate situations, for example, in the case that the pay rate is decided by where fruits are picked in the orchard. Interested users may refer to [2] for details.

B. Mapping yield with harvest data

Harvest data bear rich information on harvest operations as well as the overall production of orchards. It provides a direct measurement on the output of an orchard, that is, the fruits being produced. LMDs further enhance harvest data with temporal (i.e. picking time) and spatial (i.e. the geological coordinates of a LMD) information. The temporal and spatial harvest data record when and where fruits are harvested. The data may be used for assessing the temporal and spatial distribution of yield in an orchard.

The harvest management system includes a feature for mapping yield in an orchard. The yield mapping function overlays a *heat map* of yield distribution with a geographic map. Yield mapping is an important tool in modern farming practice: it provides an intuitive way for farmers to visualize the yield distribution in a field. The HMS collected temporal and spatial harvest data at LMD locations. To mapping yield, one must trace fruits from a LMD back to trees. We solved this problem by formally modeling spatial pattern of picking activities. An important observation is that pickers usually organize their picking activities around a point of collection, that is, the location of a LMD. Trees closer to a LMD are picked first. The picking pattern is also influenced by the canopy architecture (layout and shape) of trees. In [3] we formally modeled picking patterns using Yield Distribution functions (YDF). A YDF is a probabilistic distribution function defining the probability that the fruits collected at a LMD location may come from a tree location. We pay special attention to the usability of the yield mapping function. Its interface is optimized to provide an intuitive workflow for growers. A grower does not have to know YDFs, or the theory behind them. All he needs to do is to select the canopy architecture and fill in parameters related to his operation, in a semantics familiar to a grower. The yield mapping module automatically infers the appropriate YDF from these parameters, and computes yield distribution using harvest data and the YDF.

Our harvest data-based yield mapping represents a significant improvement over existing yield mapping methods. Prior to our approach, there is no direct and cost-effective way to measure yield distribution in an orchard. Researchers have been using a variety of techniques to estimate yield distribution in an orchard. These techniques include satellite and airborne imagery [4], [5], machine vision[6], and thermal imaging [7]. These techniques provides only indirect measurement of yields, and most of them also requires costly equipments. Our yield mapping approach reuses harvest data that are already collected for other purposes (labor monitoring and accrual),

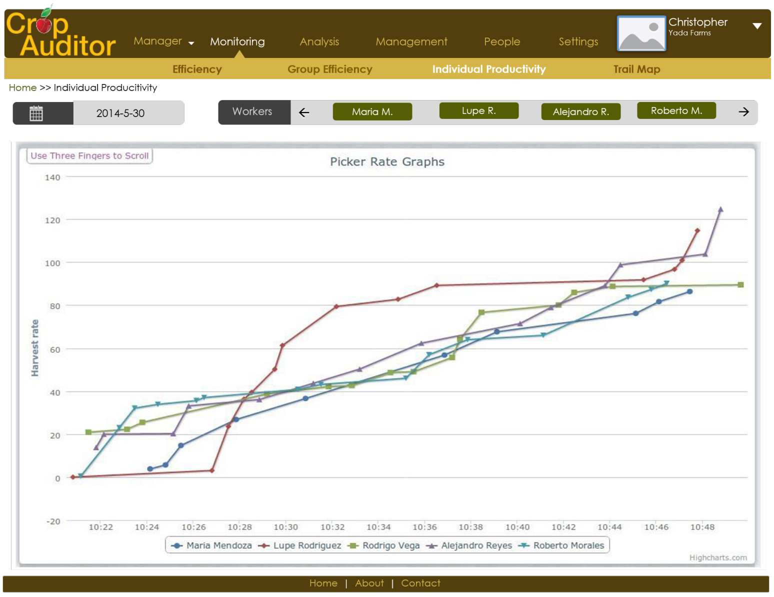


Fig. 2. Real-time monitoring of picker's productivity

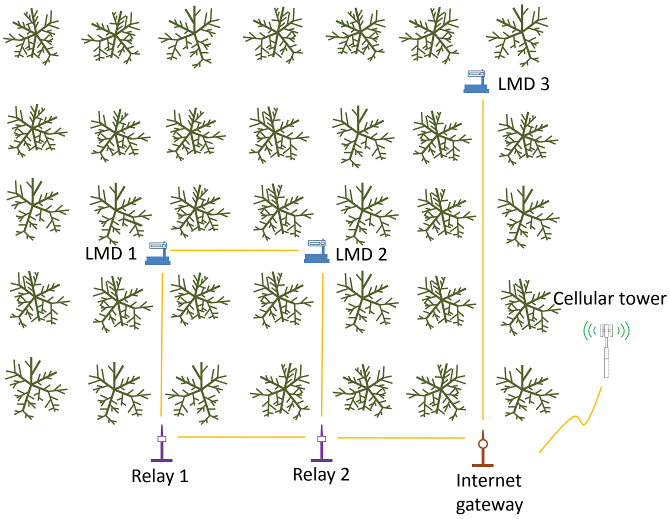


Fig. 3. A configuration of an in-orchard data collection network

and the harvest data is a direct measurement of yields. This enables our cloud-based HMS to map yield with a better precision and at a much lower cost.

IV. IN-ORCHARD DATA COLLECTION AND TRANSMISSION

The data collection subsystem collects harvest data in an orchard and transmits them to the cloud-based harvest management software. The data collection subsystem consists of data terminals, relaying nodes, and Internet gateways. The data terminals, referred to as labor monitoring devices (LMDs), interact with pickers and record the weight of fruits they picked. The data is transmitted through a wireless mesh network formed by LMDs and relay nodes, to an Internet gateway, which then delivers the data to an existing Internet provider's network. Figure 3 shows a configuration of the in-orchard data collection network.

Orchards present a particular challenge for wireless transmission. Take Cherry orchards as an example, a medium sized cherry orchard in the US pacific northwest region has over 500 acres of land. The biomass and water content of foliage also weaken wireless signal. To improve the reliability of wireless transmission, we used a wireless mesh network powered by Xbee modules running Digimesh protocol [8]. The Digimesh protocol is a symmetric protocol developed by Digi Inc. for mesh networks : every node can play as a routing node and there is no dedicated coordinating node. This improves the survivability of the network by avoiding dedicated coordinating nodes as a single source for failure. There are three type of devices in our in-orchard data collection network: LMDs, relaying nodes, and Internet gateway. Each of them is a node of the wireless mesh network, and capable of relaying messages as needed. For example, in Figure 3 the data from LMD 1 may be routed via LMD 2 or Relay node 1. Even if one of these nodes is down, the data from LMD 1 may still reach the Internet gateway.

A. *Labor Monitoring Devices*

LMDs are data terminals that collect harvest data as picking records. A picking record consists of the weight of fruits being picked, picker's identification, and temporal/spatial information. In our implementation a picker is identified by his RFID wristband. A LMD designed for cherry harvesting consists of (i) a digital scale comprising of load cell and scale harness; (ii) a radio frequency identification (RFID) reader; (iii) a GPS receiver; (iv) a wireless module powered by Xbee; (v) input/output devices; (vi) power/battery management system; and (v) a micro-controller board. Figure 4 shows an overview of the schematic diagram of a LMD. Components (ii)-(v) are assembled in an enclosure, referred to as Computational Unit (CU). The electronic components are assembled and mounted

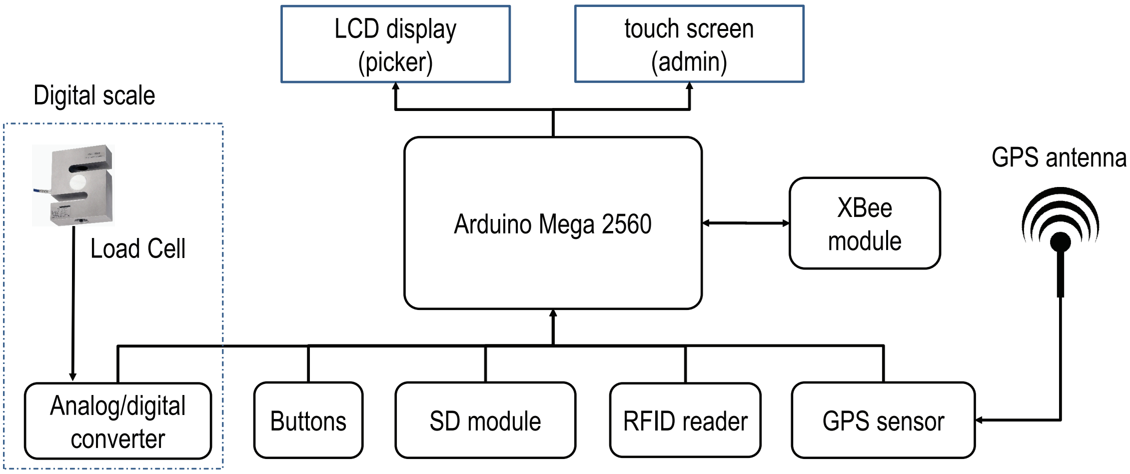


Fig. 4. An overview of the schematic design of Labor Monitoring Device

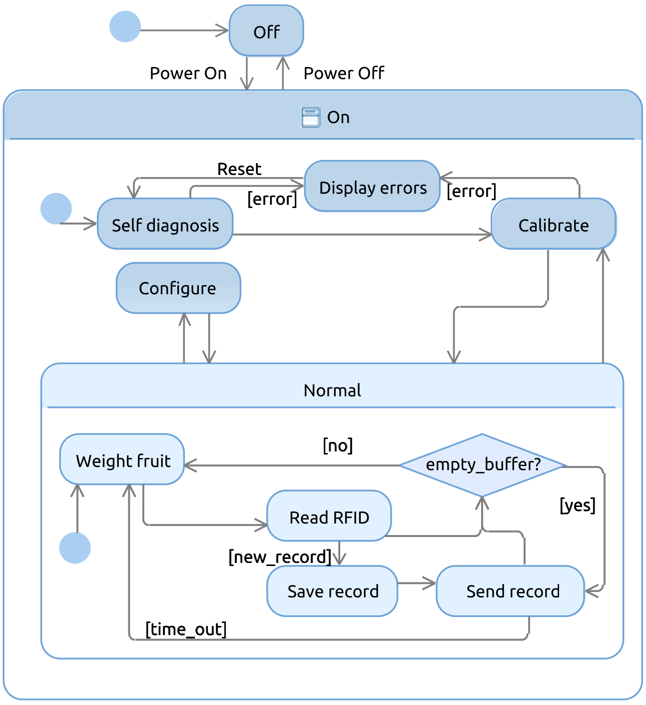


Fig. 5. An overview of the workflow of the Labor Monitoring Device

on a purposely-designed mechanical frame, whose details will be discussed in Section IV. We chose Arduino Mega 2560 [?] as our micro-controller board, because it is one of the most widely-used open-source micro-controller architectures, meaning that we may leverage readily available components known as Arduino "shields" for rapid prototyping. A LMD may also have an optional webcam, which provides video surveillance capability; and an optional thermal printer, which prints out a receipt as a picker's record.

CU is the "brain" of a LMD. Its internal logic is optimized for working with an existing harvest workflow. Figure 5 shows the CU's workflow. CU starts with self diagnosis and scale calibration. It then goes to its main loop, which reads the weight on the scale as well as a picker's RFID. If the record is new, i.e., a new reading of weight with a valid RFID, the CU stores the record to its internal buffer. It then goes to the communication state ("Send record") and sends records to the Data Acquisition Server. The CU may also switch to the configuration state ("Configure"), in which an authorized user may change the settings of LMD. The details of the communication and configuration states are omitted due to space limit.

B. *Application-layer Protocol*

Foliage and sheer size of a production orchard makes it challenging to establish a reliable wireless network within a reasonable cost. To build a resilient network, we used Digimesh as the network-layer protocol, to build a symmetric wireless mesh network. To further improve the reliability and efficiency of data transmission, we developed a application-layer communication protocol optimized for transmitting harvest data in orchards.

Our application-layer protocol features a session-based design. A LMD moves from one location to another in an orchard, collecting harvest data at those locations. This means that picking records are naturally grouped by their geographic coordinates. Our application-layer protocol leverages this feature for reducing the data being transmitted. Before a LMD starts to transmit harvest data to a location, it requests a session from the cloud-based LMS. The request includes session parameters such as the LMD's location $\langle longitude, latitude \rangle$ and its identification number lmd_id. This information remains same in a session, and is sent to the LMS only once at the initialization of a session. Once received the session request, the LMS stores the session parameters and return to the LMD an session id $session\_id$. For harvest data transmitted during a session, the LMD only needs to include $session\_id$, and the LMS associates the data with the stored session parameters. Interested readers may refer to [9] for the details.

The session-based design reduces the amount of the data being transmitted. This reduces not only bandwidth usage, but also the energy used for wireless transmission. The operating time of a LMD is limited by its battery power, and much of

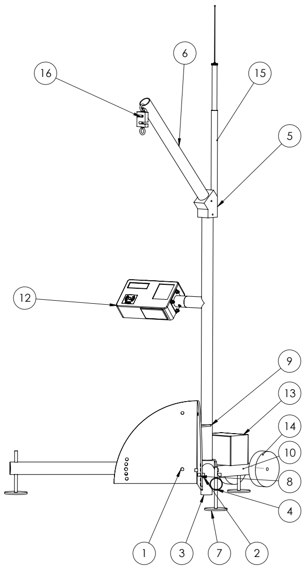


Fig. 6. Mechanical frame for LMD

its energy is spent on wireless communication. Reducing the amount of energy spent on the wireless transmission means that a LMD can operate longer on a single charge.

V. MECHANICAL FRAME AND SENSOR PLATFORM

A LMD is designed to work reliably in orchards even under harsh environment. Its purposedly designed mechanical frame not only provides mobility enabling the LMD to move and work in various terrain, and it also provides a platform that mounts and supports the LMD's sensors and electronics. The LMD frame is also part of user/device interface. During harvesting, pickers will constantly interact with the LMD. The LMD frame and its components are carefully designed to work with existing harvest workflow and streamline user/device interaction.

Figure 6 shows the structure of the LMD frame. The frame hosts the CU enclosure (12), the loading cell for the digital scale (16), and a telescope antenna (15) for the GPS receiver. The frame is optimized for enabling the LMD to function in a variety of orchard environments. The telescope antenna enables the LMD to receive the GPS signal even under a dense tree canopy. The lower portion of the frame is interchangeable, and it can be quickly adjusted for various terrains of an orchard. The interchangeable base shown in Figure 6 has adjustable leg panels (1) and wheels (14), which allows the frame to be moved easily and stationed securely on an uneven terrain.

VI. DESIGN FOR CLOUD-BASED DEPLOYMENT

Special crops such as cherry are produced and traded globally, to take advantage of reverse seasonal pattern of north and south hemispheres. An objective of the LMS is to support orchards across the global simultaneously. To achieve the desired scalability, we optimize the design of the LMS for cloud deployment. One advantage of a cloud computing platform is that it can dynamically allocate resources on demand. This is particularly important to harvest operations, as the needs of processing harvest data fluctuates greatly during and off a harvest season. The LMS is developed as a Software-as-a-Service (SaaS) application. To access the LMS, a grower only needs a web browser and a subscription to our service. The details of software installation and maintenance are transparent to users. Low maintenance and easy access are very important to orchard managers and pickers, many of whom lack either technical background and/or interest in maintaining software.

The design of the LMS is optimized for cloud deployment, with special considerations on data privacy and security. Growers, particularly those in the United States, often see their operations data as an extension of their properties. During our study, many of growers we interviewed identify data privacy and security as their No.1 concern on adopting a cloud-based software. To improve data privacy and security, we shard the harvest data based on their underlying orchards, and provide role-based access. Figure 7 shows the design of LMS optimized for cloud-based deployment. The LMS categorizes the data as "shared" and "private". An example of shared data is Geological Information data (GIS). Growers have a shared access to GIS data. In comparison, private data such as harvest data can only be accessed by its related grower and LMDs. For example, A farmer A may access LMS through a unified domain name. A load balancer will route his request to an instance of LMS' web application. If the request is for accessing his harvest data, the access control module will determine whether the farmer has the right permission to access the harvest data. The database storing harvest data is organized and sharded based on their underlying owner. When coupled with role-based access control, the sharded private database prevents unqualified access to sensitive private data.

VII. IMPLEMENTATION

The cloud-based labor management software (LMS) has been implemented using the Ruby-on-Rails application framework. Ruby is a dynamic and reflective object-oriented programming language. Its popularity among web developers is largely due to Ruby-on-Rails[10], a framework enabling rapid development of web applications in Ruby. Ruby is well supported by mainstream HTTP servers such as Apache 2. Our LMS runs on Phusion passenger[11], an application server directly integrated into Apache 2. The LMS has been deployed on Amazon Elastic Computing Cloud (Amazon EC2), a PaaS platform provided by Amazon's Cloud Computing Service AWS. The LMS uses PostgreSQL as its underlying database engining, and its databases are sharded per design in Figure 7, for improved performance and controlled access to farm data.

The LMS is designed and implemented as an information "clearing house" for collecting and accessing harvest data. Using the notion of "web apps", the LMS provides a role-based access that provides stakeholders the tailored access the information and functions most relevant to their roles. The *Admin* web app provides administrators the functions including site, user, and role managements; The *Management* web app enables orchard managers to monitor harvesting operations and to access analytical reports for their orchard. Figure 8 shows an example of yield mapping prepared by the *Management* web app using harvest labor data; Finally, the *Worker* web app allows an individual picker to access his/her personal labor records and payroll reports. The web graphic user interface (GUI) is engineered to support role-based access.

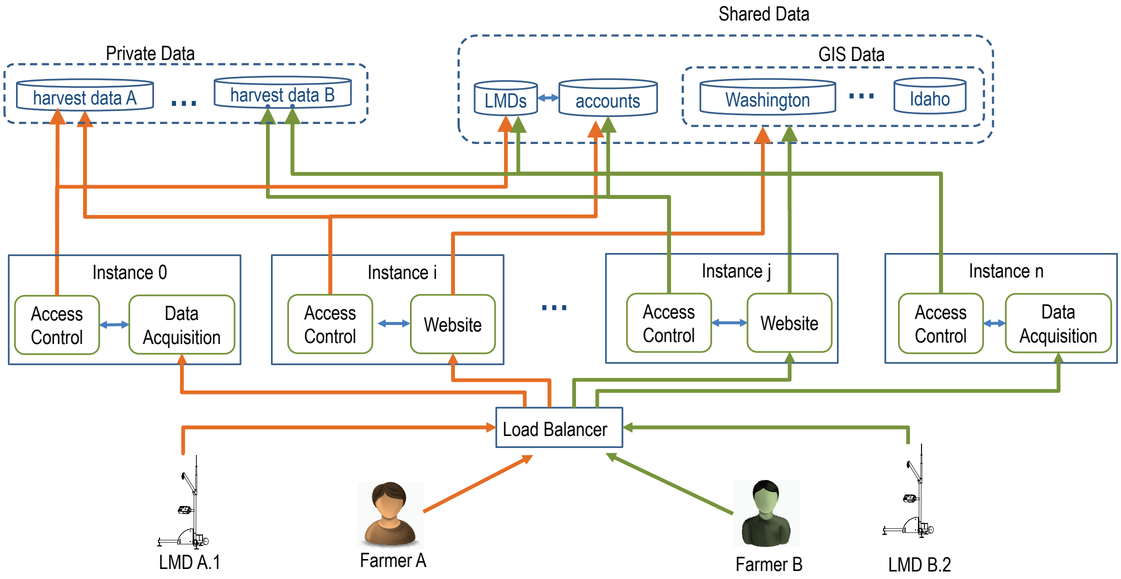
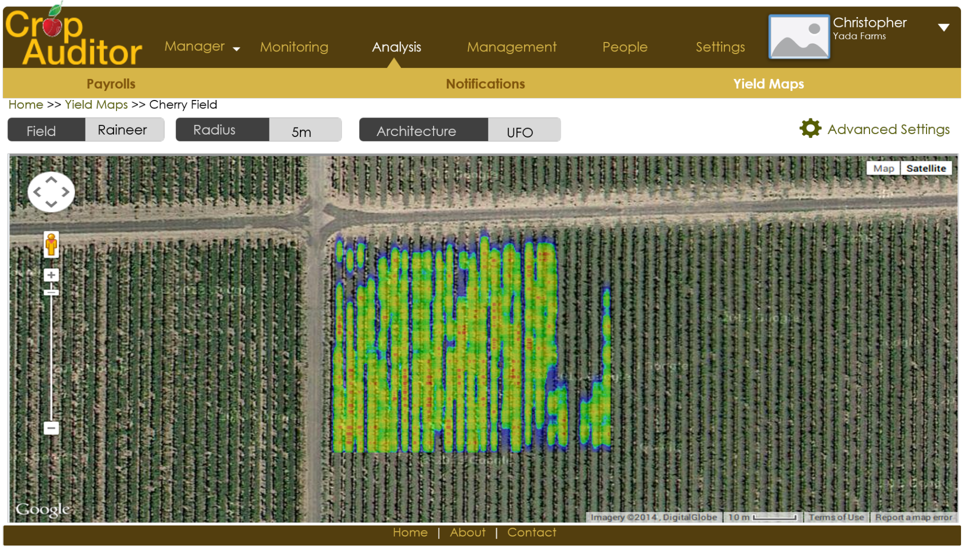


Fig. 7. Cloud-based design and deployment



Field Raineer
Radius 5m
Architecture UFO

Fig. 8. A sample yield map produced by the LMS

The web GUI is purposely design to be touch-friendly for tablet computers, allowing users to have on-the-go access to the LMS.

A prototype of LMD has been developed and field-tested at orchards in the US pacific northwest region [9]. The system was well received by growers and pickers during our field tests[12]. The system enables growers to move from “pay-by-bucket” to “pay-by-pound”, which were liked by growers and pickers. For growers, the technology reduced errors and cost in labor accruing; for pickers, the “pay-by-pound” encourages honest labor practices and boosts team moral, which help improve the efficiency of harvest labor and reduce the cost. The growers in field tests also showed a strong interest in yield mapping function of the tool, which provides them a low-cost and non-invasive way to assess their orchard production.

VIII. CONCLUSION

We developed a cloud-based information system for managing specialty-crop harvesting. The system drastically improved current manual labor accrual practice by leaping from “pay-by-bucket” to “pay-by-pound”. It automated the accrual of harvest labor with better precision, and enables growers to monitor their harvest operations in real time from a web browser. The system collects, analyzes, and visualizes harvest data. It delivers results to growers through an intuitive web interface. Besides managing harvest data, the system also provides advanced data analysis tools for growers to evaluate their operations. One of such tools is yield mapping using harvest data, which provides a cost-efficient and accurate method for visualizing yield distribution. The system demonstrated how cloud computing may benefit special-crop industry by enabling data-driven operations.

The system has two major components: an in-orchard data collection network (DCN) acquiring harvest data and transmitting them to a cloud-based labor management software (LMS); and the LMS processing and analyzing harvest data, and delivering results to growers through a web portal. The system is optimized to work with existing harvesting workflow. To improve the reliability of data transmission in an orchard and to reduce the energy use, we used a combination of a wireless mesh network and a purposely-designed application-layer protocol.

This research is a work of an interdisciplinary team comprising of software engineers, electrical engineers and mechanical engineers. Our experience showed that it takes a holistic vision and an inter-disciplinary approach to realize the potentials of cloud computing in precision agriculture. Equally important as data management and analysis is data collection and decision support to end users.

We deployed the LMS on Amazon's cloud services (AWS) and validated a prototype of the system in field tests. For future work, we will continue to test and refine the entire system, and to improve its reliability in orchards. Our yield mapping function demonstrated that our system was capable of tracing fruits back to trees. We are working on an extension to our system that enables the fruit traceability from trees to warehouses. When coupled with an existing fruit supply chain, this extended system will enable the full traceability from trees to stores, improving fruit safety and marketability.

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REFERENCES

[1] U. S. Congress, "The Specialty Crop Competitiveness Act of 2004," http://www.govtrack.us/congress/bills/108/hr3242, 2004.

[2] L. Tan, "Systems and methods for collecting and accruing labor activity data under many-to-many employment relation and with distributed access," US utility patent 13751410, February 2015.

[3] L. Tan and R. Wortman, "Cloud-based monitoring and analysis of yield efficiency in precision farming," in *Proceedings of 2014 Intl. Conf. on Info. Reuse and Integration*. IEEE, 2014.

[4] P. K. Goel, S. O. Prasher, J.-A. Landry, R. M. Patel, A. A. Viau, and J. R. Miller, "Estimation of crop biophysical parameters through airborne and field hyperspectral remote sensing," *Transactions of the ASAE*, vol. 46, no. 4, pp. 1235–1246.

[5] A. Dobermann and J. L. Ping, "Geostatistical Integration of Yield Monitor Data and Remote Sensing Improves Yield Maps," *Agronomy Journal*, vol. 96, no. 1, pp. 285–297, Jan. 2004.

[6] O. Safren, V. Alchanatis, V. Ostrovsky, and O. Levi, "Detection of green apples in hyperspectral images of apple-tree foliage using machine vision," *Transactions of the ASABE*, vol. 50, no. 6, pp. 2303–2313.

[7] D. Bulanon, T. Burks, and V. Alchanatis, "Study on temporal variation in citrus canopy using thermal imaging for citrus fruit detection," *Biosystems Engineering*, vol. 101, no. 2, pp. 161–171, Oct. 2008.

[8] Digi Inc, "The digimesh network," 2015. [Online]. Available: http://www.digi.com/technology/digimesh/

[9] L. Tan, R. Haley, R. Wortman, Y. Ampatzidis, and M. Whiting, "An integrated cloud-based platform for labor monitoring and data analysis in precision agriculture," in *Proceedings of 2013 Intl. Conf. on Info. Reuse and Integration*. IEEE, 2013.

[10] Rails core team, "Ruby on rails," 2014. [Online]. Available: http://www.rubyonrails.org/

[11] Phusion, "Phusion passenger," 2014. [Online]. Available: http://www.phusionpassenger.com/

[12] Growing Produce, "Paying fruit pickers per pound," 2013. [Online]. Available: http://www.growingproduce.com/fruits/paying-fruit-pickers-per-pound/