An Integrated Cloud-Based Platform for Labor Monitoring and Data Analysis in Precision Agriculture*

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Abstract

Harvest labor has became a prevailing cost in cherry and other Specialty Crops industry. We developed an integrated solution that provided real-time labor monitoring, payroll accrual, and labor-data-based analysis. At the core of our solution is a cloud-based information system that collects labor data from purposely designed labor monitoring devices, and visualizes real-time labor productivity data through a mobile-friendly user interface. Our solution used a proprietary process [1] to accurately associate labor data with its related worker and position under a many-to-many employment relation. We also describe our communication API and protocol, which are specifically designed to improve the reliability of data communication within an orchard. Besides its immediate benefits in improving the efficiency and accuracy of labor monitoring, our solution also enables data analysis and visualization based on harvest labor data. As an example, we discuss our approach of yield mapping based on harvest labor data. We implemented the platform and deployed the system on a cloud-based computing platform for better scalability. An early version of the system has been tested during the 2012 harvest season in cherry orchards in the U.S. Pacific Northwest Region.

1 Introduction

Specialty crops are defined by USDA as “as fruits and vegetables, tree nuts, dried fruits, horticulture, and nursery crops (including floriculture)” [2]. The production of specialty crops is important to U.S. agricultural industry. Take cherry production as an example, the United States exports more than $206 million worth of Cherry in 2006-2007. Due to the importance of specialty crops in the United States, the United States congress passed the Specialty Crop Competitiveness Act of 2004 (Act). The Act seeks to promote increased consumption of specialty crops and increase the competitiveness of specialty crop producers in a global market. This research was funded by a USDA grant under a directive set up for the Specialty Crop Competitive Act. The research aims to improve labor efficient for the sweet cherry industry. Nevertheless, our system may also be used for monitoring labor activities in other agricultural operations.

Harvesting cherry is a labor intensive operation. Due to its high price and fragile nature, cherry is often harvested by manual labor. The harvest labor has been frequently cited by growers as the prevailing cost in sweet cherry operations. Researchers are studying machine-assisted harvesting for cherry [3]. Nevertheless, even with the machine-assisted harvesting, monitoring and accruing harvest labors is largely a tedious and manual process. In a typical cherry orchard in the United States’ Pacific Northwest Region, cherry is picked by a group of pickers, most of whom are migrant and seasonal workers. Each picker is equipped by a bucket and a punch card, and he is paid by the number of buckets that he picks. A checker makes sure that each bucket is full before punching the card. At the end of the day, the picker presents his punch card to a payroll specialist, and gets paid based on the number of buckets picked, as recorded on the punch card. Not only this manual process of recording and accruing harvest labor is labor intensive, it is also often error-prone. Based on our interview with a group of Pacific Northwest cherry growers in March 2013, it is estimated that a grower typically overpays for about 5% of harvested cherry due to inaccurate labor accrual and pickers’ abusive practices.

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In addition to these shortcomings, the manual process also throws away valuable information that may otherwise be analyzed for improving the efficiency of an agricultural operation. For instance, the information on the quantity of cherry harvested and the locations where the cherry is harvested may be used to produce a yield map for an orchard. Yield mapping is a very useful tool for a grower to analyze the distribution of productivity of an orchard, to identify low-yield blocks, and to correlate the yield with other factors such as fertilizer and water usage.

To overcome these shortcomings of manual labor monitoring process, what is needed is an integrated solution that automates labor monitoring, captures harvest labor data, analyzes the data, and visualize the result to help a grower make informed decision. Nevertheless, developing an integrated labor monitoring system presents several research challenges: (i) first, pickers are typically seasonal and migrant workers. One picker may work for multiple employers, and/or he may work for the same employer in different positions (e.g. as a picker or as an office helper). Pay rates generally vary depending on the position at which a task is performed. A research challenge is how to accurately associate labor data with its related employee and position. (ii) second, a labor monitoring system needs to interface with a variety of labor monitoring hardware in field, which often comes in different configuration suitable for different harvest operations; (iii) finally, we need to develop techniques for efficiently analyzing harvest labor data.

To address research challenge (i), we developed a patented method that can efficiently associate labor data with the appropriate personnel and position. The data association may be used to decide pay rate and to compute individual payroll. The method is described in Section 2.

To meet research challenge (ii), our system includes a web portal through which field-operated labor monitoring devices may transmit labor data to our cloud-based system. We design and implement a session-based communication protocol for efficiently transferring labor data between the system and labor monitoring devices. The protocol enables our system to interact with labor monitoring devices of different configuration, as long as they can follow our communication protocol. The details of the communication component of our system and the session-based protocol is discussed in Section 4.

To address research challenge (iii), we develop a data analysis and visualization module that can produce a yield map based on harvest labor data. Yield mapping contains the important information on geographic variants of yield in an orchard. When paired with other information, such as water and fertilizer usage, yield mapping help a grower identify problems in orchard production, and make informed decision to improve the production. Our approach of yield mapping is discussed in Section 5.

2 Labor Data Association and Payroll Accrual: system design and workflow model

In the United States, specialty crops are often harvested by migrant workers. Labor relations for these migrant workers are generally temporary and seasonal. A migrant worker may work for multiple employers during the same time period, and in some case, he may even work for the same employer at different positions at the same time, each of which may incur different pay rates. We refer to such a labor relation as a many-to-many employment relation. For example, a temporary worker, Luis, may work for a grower John in a morning as a cherry picker, and in the afternoon as an office helper for John. And yet in the next day, he may work for another grower Bob to pick up peaches. A challenge for an online labor monitoring system under many-to-many employment relations is to correctly identify the person and his position at which a labor activity occurs, and to accurately accrue the labor activity.

It turns out that a similar need for accurately accruing labor activities exist for many industries, such as hospitality industry, where many-to-many employment relations are an industrial norm. To address this common need, we developed a proprietary process that can accurately identify the worker and his position responsible for a given labor activity, under a many-to-many employment relation. The process and system design may be customized for different applications in a variety of industries. The propriety process and system design has been filed for U.S. Utility patent [1]. The workflow of our LMS system and its core engine is an implementation of this proprietary process.

Figure 1 shows the overall design of our Labor Monitoring System. It has two major components: Labor Monitoring Devices (LMD) and an online Labor Monitoring Software (LMS). Each user is assigned with a Local Identification Record (LIR) by his employer. A LIR is often provided in form of a Personal Identification Device, which can transmit the LIR to the LMD. An example of a Personal Identification Device is a Radio-Frequency Identification (RFID) device, which is used in our labor monitoring system designed for specialty-crop harvesting.

A LMD measures labor activities *quantitatively*. The exact form of the measurement depends on applications. For instance, a LMD designed for cherry harvesting measures the weight of fruits being picked, whereas a LMD designed for office use records the time stamps of punch-in and punch-out. A LMD also has the ability of receiving a LIR from a worker, either through direct input or via a Personal Identification Device (PID). During its operation, a LMD sends to the online LMS the measurement of a labor activity, along with the LIR received from a worker and the LMD's own Device Identification Record (DIR). A DIR uniquely identifies a LMD within a labor monitoring sys-

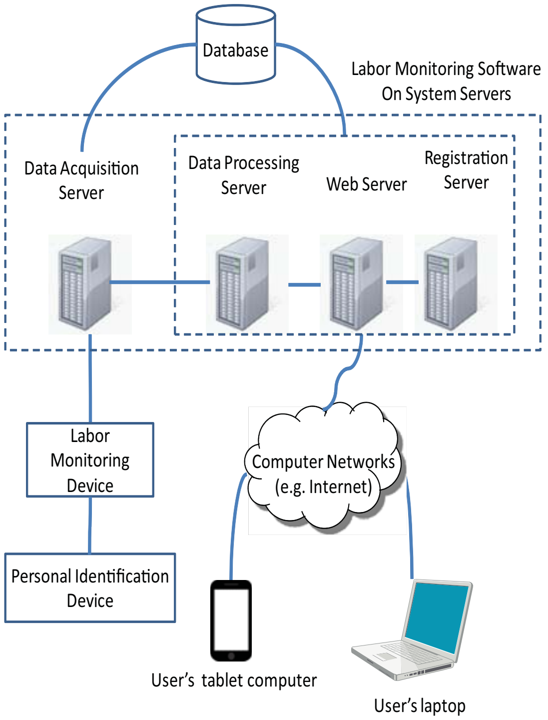

Figure 1. Design of Labor Monitoring System

Figure 2. A variant of Labor Monitoring Device on an electric utility vehicle (EUV)

tem. Depending on the design and the application, a DIR may be in different forms. For example, a DIR can be the MAC address of the communication module within a LMD, or the geological location of the LMD.

The online labor monitoring software provides a web interface to its users, and a communication interface to LMDs. Once receiving from a LMD a data record of a labor activity, the LMS uses an algorithm that identifies the worker and the position responsible for the labor activity. The LMS maintains in a database the following information required by the algorithm. In an application of LMS, each LMD belongs to at most one employer. The LMS registers the owner of a LMD. It also associates with the owner all the possible DIRs of the LMD. For each employment relation $\langle employer, worker, position\rangle$, the LMD also associates the relation with a combination of $\langle D, L\rangle$, where D is a set of Device Identification Records and L is a set of Local Identification Records.

The employment identification algorithm used by the LMS is an implementation of the methods patented in [1]. We illustrate the algorithm using an example in a cherry harvesting operation: when a picker Luis starts his work for a grower John, John registers with the LMS the employment relation $r = \langle John, Luis, picker\rangle$, meaning that Luis works for John as a cherry picker. John also uses the LMS to associate with r Luis' payroll information, e.g. Luis' pay rate. John assigns to Luis a LIR l_{Luis}, in form of a PID. Meanwhile, John also specifies a set B of the LMDs monitoring Luis' labor activities. Let us denote $dir(b)$ for the DIR of a LMD d. The system then associates with r with a pair of DIRs and LIRs $\langle D_{Luis}, \{l_{Luis}\}\rangle$, where $D_{Luis} = \bigcup_{b\in B}\{dir(b)\}$. When Luis works in the field, he uses his PID to send l to a LMD b that is assigned to monitor his labor activities, i.e. $dir(b) \in D_{Luis}$. The LMD also measures the output of Luis' work, in this case the weight of the fruit that Luis picks. The LMS sends to the LMS (Figure 1) a data record $\langle labor\_data, dir(b), l_{Luis}\rangle$, where d is the LMD's device identification record. Once receiving the data record from the LMD, the LMS identifies the related employment relation $r = \langle John, Luis, picker\rangle$ by checking the following condition: let $\langle D, L\rangle$ be the pair of DIRs and LIRs associated with r, then $dir(b) \in D$ and $l_{Luis} \in L$. The LMS then associates the $labor\_data$ with Luis and his position as a picker. The LMS uses the payroll information associated with r to compute the compensation for Luis. Interested users may refer to [1] for more details on the general LMS workflow and its variants.

3 Labor Monitoring Devices for Specialty Crop Harvesting

We developed a cloud-based labor monitoring and payroll accrual software (LMS) for specialty crop harvesting. The software implements the labor monitoring process in Section 2. Our LMS communicates with purposely designed LMD to collect labor data. These purposely designed LMDs are instances of the conceptual LMD described in Section 2, and they are customized for specialty crop harvesting. In specialty crop harvesting, a labor activity is measured by a quantitative measurement of its output, i.e., the fruits that a worker picks. The current prevailing practice in cherry orchards in the United States is that a worker is paid by the number of buckets of fruits that he picked. To improve the precision of harvest labor measurement, LMDs integrate digital scales. Another customization was the use of RFID as a Personal Identification Device. A grower issues a RFID-embedded wrist-band to a worker for use in his orchard. The identification number of RFID works as the worker's local identification record, which uniquely identifies the worker within the grower's field operations. Each LMD has an integrated RFID reader. The RFID-embedded wrist-band allows the worker to quickly enter his LIR by waving his wrist-band before the RFID reader embedded in a LMD.

In general, a LMD designed for cherry harvesting consists of: (i) a digital weighing system; (ii) a radio frequency identification (RFID) reader; (iii) a GPS; and (iv) a computational unit (CU) with a wireless transceiver. RFID tags, containing unique ID numbers embedded within rubber wrist bands, are worn by pickers. During its operation, a LMD sends to the LMS (a) the weight data as the result of measuring fruits being picked; (b) LMD's identification number; and (c) the worker's RFID. We developed a communication protocol for a LMD to send data efficiently to the LMS in an orchard environment. We will introduce the protocol shortly in Section 4.

The design and implementation of a LMD varies depending on the characteristics of a field operation. A design feature of our LMS is that it may work with different LMDs, as long as they follow the same communication protocol outlined in Section 4. In our field tests, we tested the LMS with several designs of LMDs.

One design of LMD being tested was initially developed in 2010 [4] and modified in 2011 [5] (Figure 2). The LMD uses a modified bin trailer as its mechanical platform. The platform integrates a digital scale. The weight of fruits being picked is measured as the difference in weight of a bin, before and after a picker drops a bucket of fruits into the bin. We also tested a portable LMD (Figure 3). The portable LMD integrates a digital scale that measures the weight of a worker with his fruit-collecting bucket. The weight of the fruits being picked is measured as the difference in weight of the worker with the bucket, before and after the worker empties the bucket into a collection container. The collected data is transmitted wirelessly to the LMS in real-time.

4 Communication Layer and Protocol

In a field operation, a LMD measures a labor activity, and transmits to the LMS its measurement of the labor activity, a worker's local identification number (LIR), the LMD's device identification records (DIR), and other information that help identify the underlying labor relation and analyze labor data. The system used for cherry harvesting has to withstand the rigid working environment in a cherry orchard. Due to the interference from tree canopy, terrain, and other factors, it is often costly and technically challenging to provide a reliable wireless coverage in an orchard. Another constraint is the limited power source available for a LMD. For portability, we use rechargeable battery to power the LMD. Wireless communication often contributes to an important share of power assumption in mobile devices.

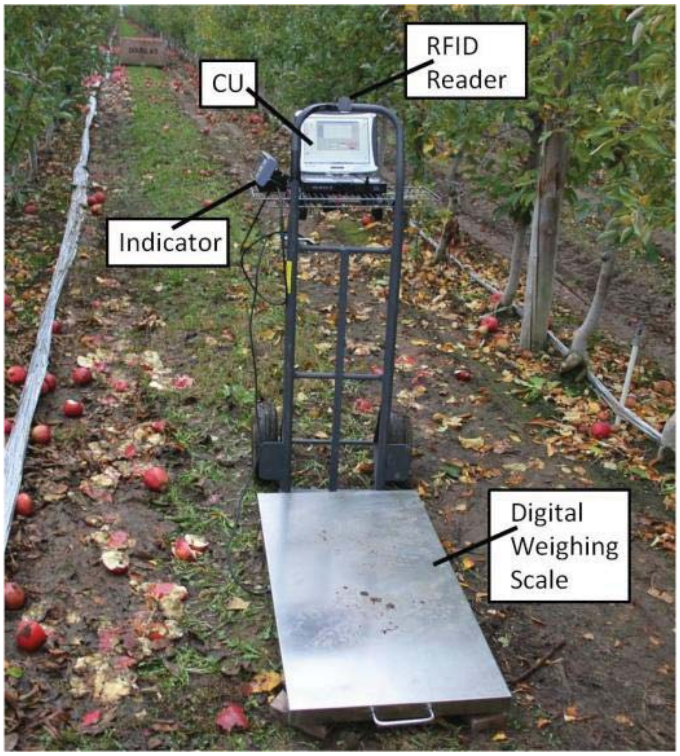

Figure 3. A variant of Labor Monitoring Device on a dolly.

We use a two-fold strategy to address these constraints in wireless communication: in addition to experimenting different wireless configurations, we also design our communication software with better resilience in an unreliable network. At the core of our design is a purposely designed communication protocol for data transmission between LMDs and the LMS. The protocol is developed to reduce the volume of the data transmission, and hence it reduces the bandwidth requirement for a wireless network. It also features a session-based design, which enables a LMD to communicate with LMS in a *burst* mode, instead of constantly connecting to the LMS.

Figure 4 shows the communication protocol in a UML

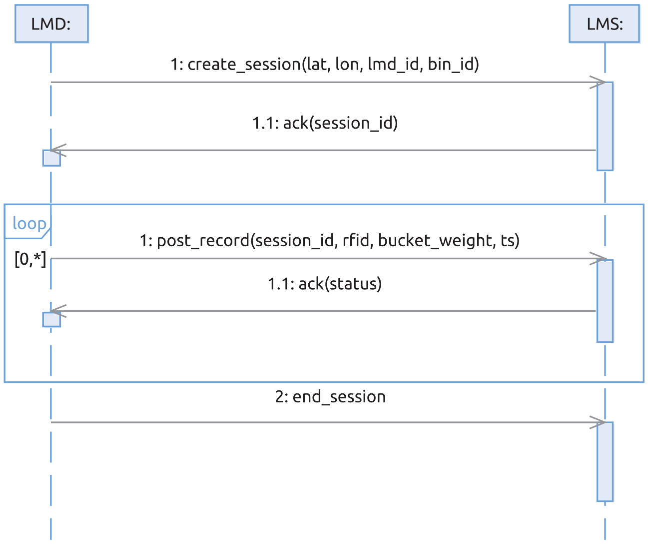

Figure 4. Communication protocol in a UML sequence diagram

sequence diagram. The communication from a LMD to the LMS is organized as sessions. The data transmitted by a LMD to the LMS may be categorized into two types: the data independent of a labor activity, such as the LMD's Device Identification Record (DIR), its geological location etc. These data remain same, as long as the status (e.g. location) of the LMS is unchanged; and the data that are dependent of the labor activity, such as the measurement of the labor activity, the time stamp etc. The idea of session-based protocol is that, by transmitting the data independent of a labor activity per session only, we are able to reduce the bandwidth required for transmitting labor data.

Each session starts with a request $create\_session$ with the LMD's geological location (longitiude and latitude), Device Identification Record (lmd_id), and other auxiliary information such as the identification number of a bin (bin_id). The LMS acknowledges the request with a session ID ($session\_id$).

Once a session is established, the LMD sends labor data records to the LMS in a loop. A record consists of a measurement of a labor activity ($bucket\_weight$), time stamp (ts), the worker's Personal Identification Record in form of RFID ($rfid$), and the session ID received from the LMS at the start of the session. The session ID is used to associate the labor data record with the session-dependent data sent out by the LMD during the initialization of a session. The LMD may end a session by sending $end\_session$.

As we will discuss shortly in Section 6, our LMS is implemented using Ruby on Rails. The communication between the LMD computational unit and the LMS uses specific HTTP methods. Due to Rails, the HTTP methods used in the communication conform to the Representational State Transfer (REST) API [6]. REST's client-server architecture separates the network interface from the data storage, which improves the client's portability across multiple platforms as well as the server's scalability by reducing server components. REST utilizes HTTP request methods such as GET, POST, PUT, and DELETE; each method performs an operations on the resource (URL). Ruby-on-Rails API offers operations such as "index", "show", and "update" that encapsulate these REST's HTTP methods, and translate them to specific controller actions on Ruby-on-Rails' Model-View-Control architecture. Parameters of messages are encapsulated in JavaScript Object Notation (JSON), a JavaScript-based open standard designed for exchanging data in a human-readable format.

In our implementation, the $create\_session$ request is sent by a LMD using a HTTP POST request. The POST request contains an UUID representing the Device Identification Record of the LMD. The LMS authenticates the device using the UUID. If the UUID is registered with the system, that is, its operator can be identified, the LMS returns to the LMD with the session ID.

With a valid session ID, the LMD may start to post collected record data to the server, following the protocol in Figure 4. The server processes the received data by first verifying the existence of the session ID. It then uses the LMD's location to identifies the identification number of a field (FID) where the LMD operates from. Finally it uses the timestamp, RFID, and FID to verify the uniqueness of the received data record, and associates the record with the session data, before saving it to the database. A status code is then returned back to the LMD based on wether the record is successfully saved in the database.

5 Labor Data Analysis for Yield Mapping

Fruit harvesting directly deals with the end product, in this case, fruits, of agricultural operations in an orchard. The data on harvest labor contains wealth information about the characteristics of an agricultural operation. If collected and analyzed correctly, it will yield important insight into the operation and provide an opportunity for a grower to refine and improve his operation. The first step of analyzing any data is, of course, to collect the data. Our labor monitoring system provides a platform to collect labor data, which otherwise may be lost in a harvesting process monitored by manual labors. Next by enabling labor data analysis and visualization, the LMS may provide value-added services that help a grower make informed decisions.

Using yield mapping as an illustrative example, we showcase LMS's data analysis capability. Yield mapping is the process of pairing geographical data with the weight

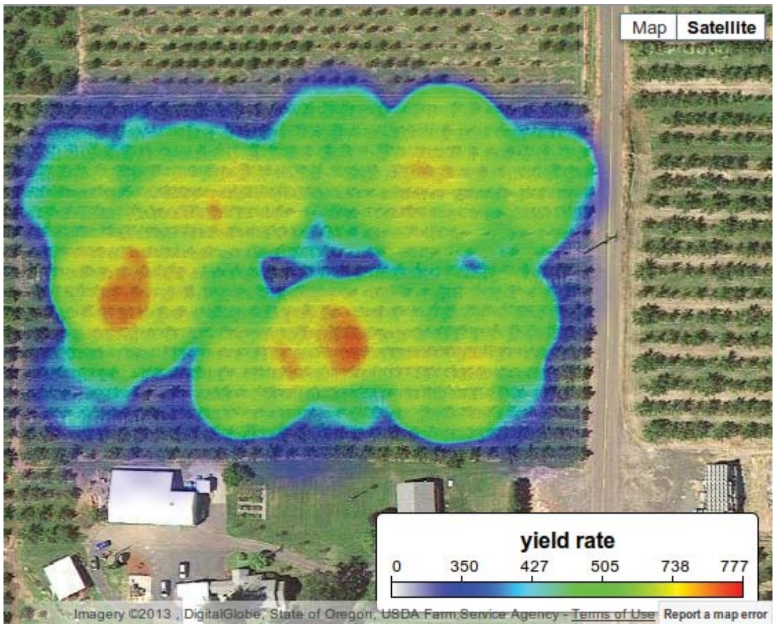

Figure 5. Geo-referenced yield map produced from simulated harvest labor data

of the fruit produced from the harvest, and displaying the result in a visual format accessible to a farmer. One common format is a geographical map with colors to represent how much was harvested from one specific area. A yield map in this format helps a farmer visualize the productivity of their farm. As one of many important tools in increasing productivity farmers can utilize yield mapping to aid them in showing areas of high and low production in a discrete section of land or a farm overall. Yield maps can be used, combined with other information (e.g. soil, weather data, input rates-fertilizer, crop protection chemicals, irrigation, etc.), to investigate factors affecting the yield, to define spatially variable yield goals, and to prescribe variable rate applications of agricultural inputs. Farmers can utilize this information to vary the inputs spatially to meet the varying needs of the crop at different locations.

Because of the practical importance of a yield map to an agricultural operation, various methods for producing yield maps have been widely studied (cf. [7]). Additionally, automated yield mapping systems specifically designed for specialty crops have been developed to some extent ([8, 9]). Many existing approaches involve a range of sensors, which is often translated to additional cost and technology equipment to growers [10]. Compared with these existing methods for producing yield map, our LMS-based approach analyzes the labor data that are already collected for the purpose of labor monitoring, so there is no additional cost for collecting data. Additionally yield mapping is integrated into our cloud-based Labor Monitoring software, providing a streamlined user experience for both real-time labor monitoring and field assessment on a single platform.

Our approach of labor-data-based yield mapping starts with the harvest labor data that are augmented with geographic location information. Equipped with an optional GPS unit, a Labor Monitoring Device (LMD) can now record its location and attach it to the labor data sent to the LMS. A technical detail is that our session-based communication protocol in Section 4 has been specifically optimized to improve the efficiency of transmitting geo-referenced labor data: When the LMD is stationed in one location, the LMD creates only one session with the geographic location as part of its session parameters. The labor records sent during the same session are all associated with the same geographic locations. This reduces extra bandwidth required by sending additional geographic information.

We developed a data analysis and visualization algorithm that uses geo-referenced labor data for yield mapping. First, the algorithm computes the quantity of fruits collected at a LMD location. Next, the quantity of fruits will be plotted using a probabilistic distribution function. The probabilistic distribution function describes the probability that fruits may be picked from a particular location surrounding the LMD. Finally, the plotted yield map is overlaid on Google map. Figure 5 shows an example of yield map produced by the LMS using a set of simulated labor data.

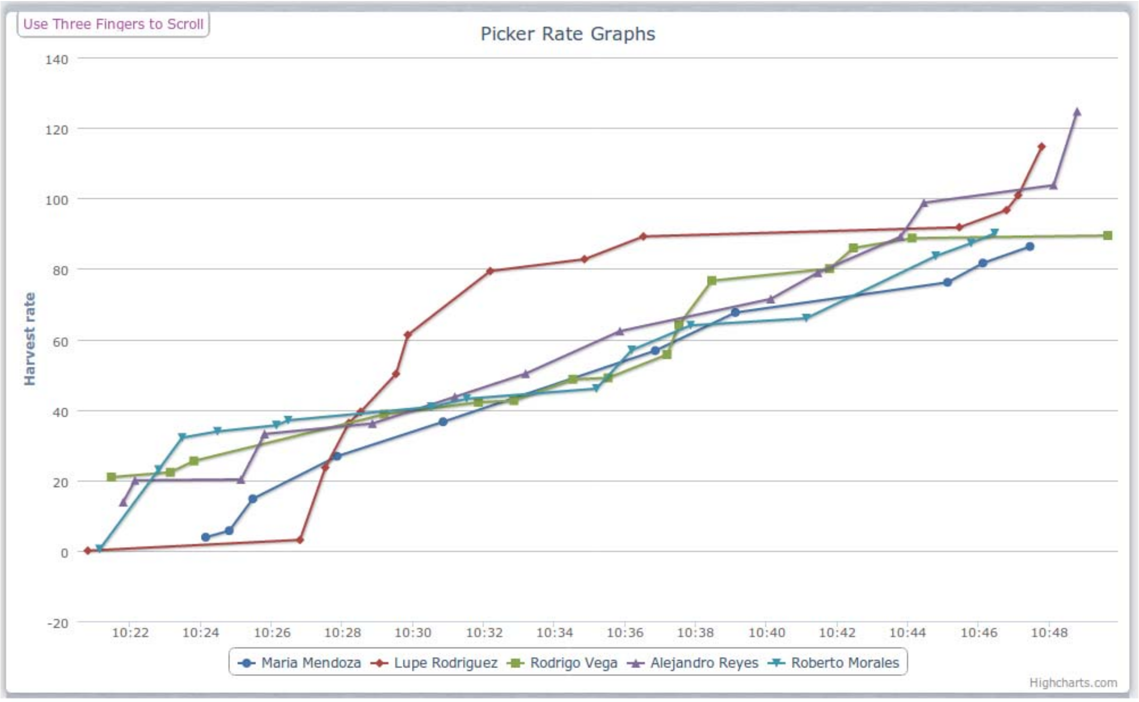

Figure 6. Real-time monitoring interface

6 Implementation and Cloud-Based Deployment

Our Labor Monitoring and Payroll Accrual Software (LMS) is developed with the Ruby-on-Rails application framework. Ruby is a dynamic and reflective object-oriented programming language. Ruby is popular among web developers. An important factor contributing to its popularity is Ruby-on-Rails, which provides an open-source web application framework for Ruby. Ruby-on-Rails provides a structured web development environment using Model-View-Controller (Observer) [11] as its primary architecture pattern. In our application, we use *models* to declare underlying database schema. These *models* add an object-oriented layer on top of a relational database. We developed LMS' web interface as different *views*, and we define the access to the database using *controllers*. We also use several existing Ruby libraries, referred to as *gems* in Ruby, to implement some visualization components and the interface with Google earth [12].

Our LMS is designed for supporting multiple harvesting operations across the global simultaneously, including cherry orchards in the United States and Chile. To achieve the desired scalability, we deploy our LMS on a cloud-based computing environment. One advantage of a cloud-based computing platform is its flexibility. It can provide different levels of services and infrastructure supports to fit the needs of an individual application. Typical types of cloud-based computing services include Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), and Software-as-a-Service (SaaS), each of which provides additional layer of services on the top of the previous one. Our LMS is a SaaS application. The details of actual infrastructure and platform are transparent to users of the LMS. The LMS is deployed on a PaaS cloud-computing platform, which provides the Ruby-on-Rails running environment on top of the Amazon Web Services (AWS), a cloud-based IaaS service.

The LMS enables the distributed access to labor data and visualized results using a variety of Internet-connected devices, including mobile devices. As mobile devices are gaining popularity in precision agricultural engineering and business, we specifically design the web interface of the LMS to be *mobile-friendly*. Specially considerations have been given to the LMS web interface so that it has an streamlined and intuitive interface on a mobile tablet device such as iPad. The website also supports multiple-touch gestures. As an example, Figure 6 shows a (partial) screen shot of real-time monitoring interface. The interface displays the real-time productivity data for selected employees. By simply clicking on the employee's name on the legend or on a line, an authorized user may select/deselect employees whose productivity data are visualized.

7 Conclusion

We designed a real-time labor monitoring and data analysis platform for precision agriculture, with its accompanying labor monitoring devices. The platform enables real-time monitoring of labor activities through a variety of Internet-connected devices, including Apple iPad and other tablet devices. At the core of our platform is a patented algorithm that can accurately associate labor records with its related employee and his position. Our platform provides an integrated and cloud-based solution for data collection, real-time monitoring, and value-added data analysis. Using yield mapping as an example, we demonstrated the benefits of cloud-based labor data analysis for precision agriculture. In addition to improving the accuracy and efficiency of labor monitoring and payroll accrual, our integrated solution is also able to recap the information hidden in labor data, in this case yield map, that may otherwise be lost during a manual process, and use the information to assist the decision-making process in an agriculture operation.

As an implementation of the real-time labor monitoring platform, we described in details a cloud-based labor monitoring system used for cherry harvesting operations. We discussed labor monitoring devices designed for cherry harvesting. We also designed a session-based communication protocol that improved the communication from the LMDs to the cloud-based labor monitoring software. Our software is being deployed on a cloud-based computing platform. An early version of the LMS software has been tested in the field, and we receive positive feedbacks and strong interests from cherry growers in the U.S. Pacific Northwest region.

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