Using Wearable and Contextual Computing to Optimize Field Engineering Work Practices

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Abstract. Industrial work, as performed in field engineering and manufacturing, is inherently different from traditional office work. Industrial work is highly mobile and physical, and involves continuous interaction between people and machines in settings such as factory floors, power plants, oil rigs, locomotive maintenance yards, etc. This domain has recently benefitted from a set of disruptive technologies such as the Internet of Things (IoT) [2], mobile and wearable computing, and contextual software applications. In particular, GE's Industrial Internet initiative [1] aims at researching new ways to connect people and machines, enabling communications between people and traditional software systems, between people at work, and between people and intelligent machines. When allied with wearable and mobile computing, the Industrial Internet enables new forms of contextual user experiences focusing on the delivery of the right information to the right user at the right time and place. Moreover, these new technologies have enabled experiences that better adapts to industrial workers' needs. For example, using virtual reality glasses and natural language interaction, workers can readily access information about their tasks at hand, the machines nearby, and people located at a distance. This is achieved with minimal distraction, in a proactive way, leveraging the knowledge about each person's tasks and surroundings. In this paper, we describe a general approach and architecture designed to support contextual and mobile applications in the industrial domain and the application of this architecture in the development of the MyWorld application, a contextual mobile applications that works as a single point of entry for a field engineer's needs.

Keywords: Mobility · Collaboration · Wearable computing · Field engineering · Smart manufacturing · Virtual reality · Workflow automation

1 Introduction

In industrial application domains such as service engineering and manufacturing, people, machines, and information must come together to achieve common goals. People utilize various tools and interact with multiple machines and devices to perform complex tasks. Those tasks usually must follow well-defined procedures and guidelines and are subject to continuous quality checks. Workers' expertise may vary according to the tasks they have to perform, and collaboration may emerge motivated by different

needs such as information, reporting, quality assurance, etc. Machines are becoming not only tools utilized in the production but also important sources of information that, when mined and analyzed, can be used to improve operational and maintenance efficiency. For example, machines can supply production quality information, energy consumption, and key performance parameters that can be used to diagnose problems, trigger maintenance procedures or adjust the production throughput. Moreover, industrial environments have different data, information and work dependencies among people. For example, workers in a factory have parts and supply dependencies on one another, and must perform their work under pre-defined quality guidelines that are usually assessed by other workers. Field engineers need to follow inspection and maintenance procedures during factory operation outages to recover the proper operation of machines while minimizing downtime and production delays. Railroad inspectors need to assess the safety of train cars, and must find the best ways to reposition those cars in order to load the next train.

In spite of these well-known requirements, today's service and manufacturing information systems are less than optimal. They are implemented for traditional desktop computing environments, and therefore, lack the mobility and contextual characteristics of industrial workspaces. Consequently, in many of today's industrial environments, traditional modes of interaction such as paper and radio communication are still commonplace. Workers rely on printed schematics, field notes, and radio links with experts. Very often, workers have to commute back and forth from field offices located far away from the workshop in order to search for documents, write reports, e-mail experts or interact with managers. In this context, the goal of our research is to address those and other industrial work inefficiencies, and provide the user with contextual information in a way that does not obstruct her work. We achieve this by combining contextual and communication services with mobile and wearable computing platforms, together with environmental sensing.

This paper is organized as follows. In the next section, we discuss the physical and information architecture utilized in our approach. We showcase the use of this architecture in the development of MyWorld as described in Sect. 3. We then conclude by discussing lessons learned from the use of the approach and some user feedback in Sect. 4, and discuss related work in Sect. 5.

2 General Approach and Architecture

To address the afore-mentioned characteristics of industrial work, automation systems should embrace the mobile and collaborative nature of industrial work by means of integrated hardware and software systems. From a hardware perspective, the system must be portable: wearable and/or mobile, and must cope with weak network connectivity and disconnected operation, which are common in industrial environments. Furthermore, it should be portable and compatible with the type of hands-on tasks performed by industrial users. From a software perspective, the system must support deep context harvesting from multiple corporate sources, continuous environment sensing, including surrounding environmental and wearable devices and machines, as well as indoor and outdoor positioning systems integration. Additionally, information

should be properly formatted and delivered to users using naturalistic interfaces including head mounted displays, audio visual clues and tactile notifications (e.g. vibration).

Figure 1 illustrates the type of integration between the smart machines and tools, wearable devices, and corporate information systems we aim at supporting. Information from smart machines and devices are combined with corporate information systems data such as task models, schematics, documents, historical databases, and with indoor and outdoor location positioning systems. That information is used to anticipate and deliver information to users, and to guide users through complex procedures. By utilizing devices such as head mounted displays, wearable and mobile computers, users have unobtrusive access to information with minimal impact to the task at hand.

From a software architecture perspective (shown in Fig. 2), the system combines information mined from cloud-based information services with real-time environmental sensing. This information is processed locally and delivered to end-users via natural language and augmented reality interfaces. The main software components of our reference architecture include:

Corporate Cloud-Based Services: These services provide standardized access (mainly in the form of RESTful Web services [3]) to existing and legacy information systems including Customer Relationship Management (CRM) databases, Factory Management System (FMS), and Enterprise Resource Planning (ERP) systems. These systems are mined for relevant information including project-specific documents, user assigned tasks, preferences, and schedules. This information is abstracted and managed by the context fabric, which externalizes that information to client-side contextual services in each wearable and mobile client instance.

Collaboration Services: These are another important class of cloud-based services. They enable user location and communication with key personnel in the field, e.g., managers and experts in equipment and procedure. Video and document sharing is also supported allowing for communication between workers and experts.

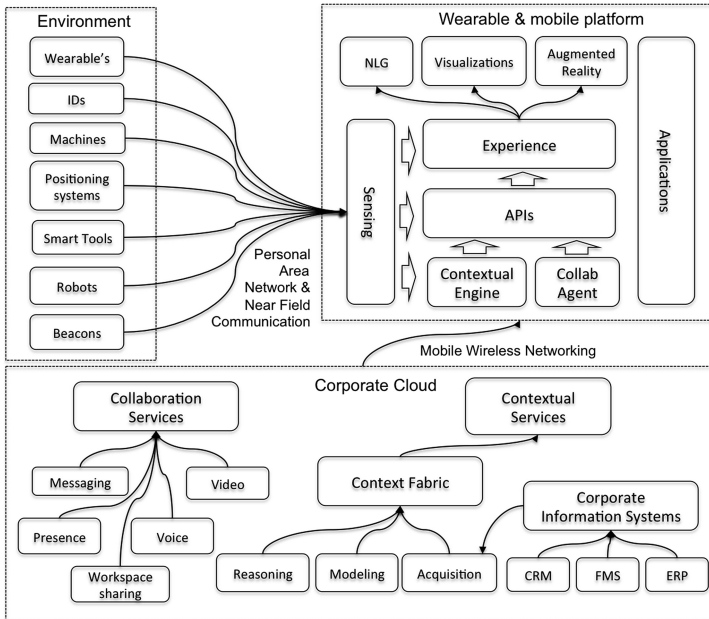**Fig. 1.** Integrated contextual mobile services overview

Fig. 2. General architecture for industrial internet contextual wearable computing

Wearable and Mobile Software Platform: Comprises a set of software services that combine data from cloud services with real-time information from the environment. They work closely with hardware devices such as head mounted displays and smart phones to support different types of experiences including gestures, natural language and touch, but provide a single point of access to user information. The multi-modal, multiple-device characteristic of the wearable platform allows users to select between different modes of interaction and information channels. For example, one can choose to display document data in the heads-up display or in the wearable device, to receive notifications as audio or as visual clues, and to interact with the system via touch or voice. Offline operation is another important characteristic of the software architecture. Both client-side agents for the context engine and collaboration services are supported. They provide caching, delayed updates, and prefetching of data in support of disconnected operation.

Contextual Services: At the core of our wearable and mobile software platform there are contextual services responsible for gathering information from different sources, abstracting them into domain models, and supporting contextual queries relevant to each application. The context engine consists of cloud-based and mobile-based services. This separation allows disconnected operation and integration with user-specific surroundings information.

Environmental Sensing: Provides a set of protocols and interfaces to machines in the field, beacons, RFID tags, smart tools, as well as communication with other wearable devices.

Indoor and Outdoor Positioning and Navigation: Industrial systems are often located indoors, which rules out the use of traditional GPS-based applications due to weak satellite signals. Besides beacons, indoor positioning systems can also incorporate sensory data, e.g., camera, geo-magnetic and acoustic site survey, to support presence and proximity detection. Indoor navigation can also be integrated with outdoor, GPS-based navigation to provide a smooth experience as users roam in/out both domains.

Hands-Free Interaction: Support for hands-free interaction is achieved by a combination of augmented reality head-mounted displays and natural language interfaces (NLG). Our natural language interface engine dynamically builds grammar and knowledge around domain ontologies in industrial setting, which are important in speech recognition tasks. By understanding the domain-specific language of the user, natural language interaction can be improved. Moreover, by learning the context-specific jargon of each user, and merging that information in server models, this component enables an architecture where ontologies can evolve on a global scale. The augmented reality head mounted devices allow users to interact with information in an unobtrusive way, enabling experiences such as the projection of instructions over existing artifacts, and the capture of data through head mounted cameras.

3   MyWorld Application

In order to showcase the different components of our reference architecture, and the mobile and collaborative experiences it affords, we developed a contextual prototype application called MyWorld. This mobile application is a single point of access to information needs of field engineers. In doing so, it works as a tool for optimizing field workers performance in their daily activities. MyWorld combines indoors navigation, task guidance, access to maintenance documents, and communication channels to experts. From a hardware perspective, MyWords integrates capabilities from Google Glass (wearable computing), iPads (mobile device), iBeacons (BLE – Bluetooth Low Energy – presence beacons installed in the environment), and Augmented Reality applications for field maintenance operations.

In a typical site inspection scenario, a field manager walks through the factory or maintenance yard floor wearing a Google Glass. The MyWorld app running on this device utilizes image recognition software to identify nearby assets. It identifies individual milling machines, CNCs and other assets. Assets are complex machinery and heavy-duty equipment used in manufacturing, energy generation, transportation, among others. Once an asset is recognized, a query to cloud services is issued, looking for current status and historical operational and maintenance information of that asset. A health status of the machine in focus is then computed, and conveyed to the field manager through a hue (green, red, yellow), which is superposed around the asset image in the Google Glass. This allows the field manager to easily identify the health condition of the asset. If the machine requires any kind of maintenance, a red or yellow hue is shown around the asset with a brief description of the problem. The field manager is then given the option to dispatch a qualified field engineer (or FE) to fix or service the machine. In this process, the system locates the best field engineer based on

past work orders, experience with the asset at hand, and his calendar availability from corporate cloud services.

Once an FE is assigned to the job and arrives at the site, he can use MyWorld application, executing on his iPad (shown in Fig. 3) to quickly locate tools and navigate to the faulty asset. The site is properly instrumented with iBeacons [4] used to tag machines and work cells. Through in-door location algorithms, those beacons provide the exact location of the user in the factory floor, together with a map with relevant assets.

Once the FE arrives at a work site, he utilizes this map to locate the asset, and to get directions to that machine from his current location. The application updates the user location in real time. With assets and field engineers positioned on the factory floor, indoor navigation can guide a field engineer with turn-by-turn instructions. This is useful in situations where field engineers are unfamiliar with a site they are assigned to work at. There have been instances where an FE had to spend 2 h finding the right tools for a 10-minute maintenance job simply because the factory floor had an unfamiliar layout and thus much time was spent on locating the tools.

One example screenshot of indoor navigation is shown in Fig. 4 where the FE is guided on the map to reach the Tool Depot via the Milling Station. In order to facilitate the asset location, a photo is shown at the top left corner of the app. The in-door map continuously updates the user location with respect to existing assets, and provides a suggested route for the maintenance task. In the example of Fig. 4, the user first gathers tools in depot, then returns to milling station for repair.

Once the FE retrieves the required tool and locates the asset needing his attention, an overview of the asset including past activities, sensor readings, and repair history are automatically displayed, as seen in Fig. 5. In Fig. 5, as one example, we see the historical data and detailed maintenance procedure for a milling Station. On the right-hand side of Fig. 5, the relevant events in this asset's history are listed as reference. Only events
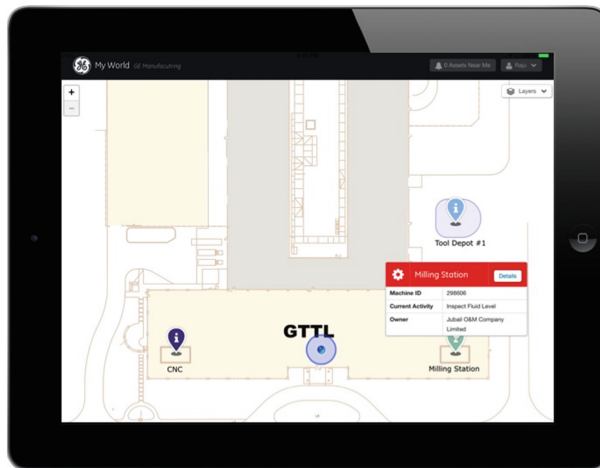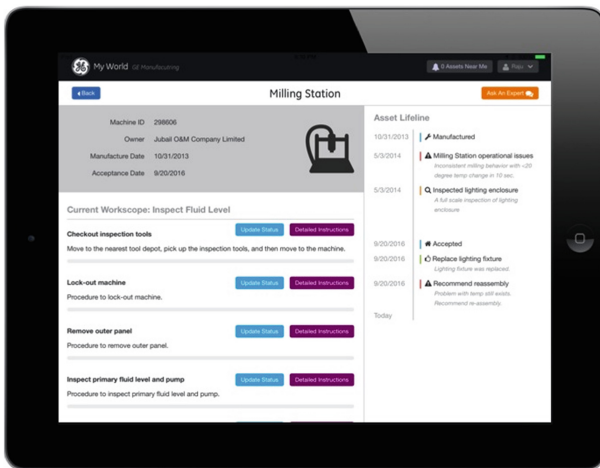

Fig. 3. Screenshot of MyWorld application: with iBeacon technology, assets and the field engineer (blue circle) are positioned on the factory digital map (Color figure online).
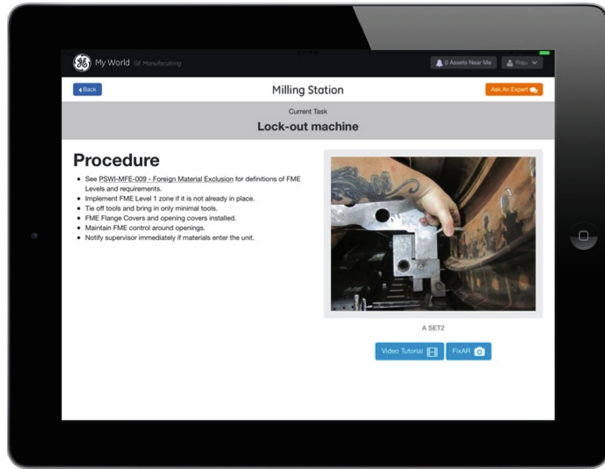
Fig. 4. Screenshot of MyWorld application: Indoor turn-by-turn navigation enabled by iBeacons installed on site.

relevant to current tasks are shown in this asset lifeline for simplicity. On the left-hand side of Fig. 5, suggested tasks to maintain or fix this asset are listed for field engineer to perform. This combined presentation of status and procedures allows the field engineer to quickly understand what to do without go through pages of asset manual.

Figure 6 shows a detailed maintenance procedure available when the FE clicks on one of the tasks shown in Fig. 5. Note that the detailed instructions in the procedure are prepared by the contextual engine based on analysis of the machine data, identified
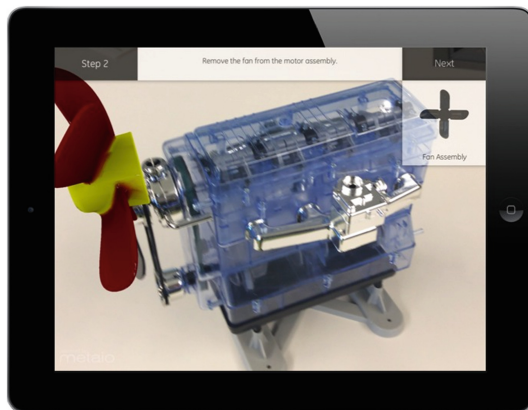

Fig. 5. Screenshot of MyWorld application: On the right-hand side, we see the relevant events in this asset's history. On the left-hand side, we see suggested maintenance tasks.

Fig. 6. Screenshot of MyWorld application: Each task in Fig. 5 is explained in details with video to play and augmented reality to help field engineer perform the task.

issue, and the known best practice to resolve the issue. If necessary, the FE can also play one or multiple video clips to demonstrate how to perform the task correctly. Again, this simple way of presenting a procedure allows FE to quickly understand what to do without going through pages of manual.

Additional help can be obtained by using Augmented Reality (or AR). By combining real-time video and 3D asset models, MyWorld provides superimposed step-by-step instructions indicating how to service complex assets. This interactive instruction user interface can greatly help the FE to understand the task at hand and the steps required for its execution. For example, in Fig. 7 we see a real-time view of an asset

Fig. 7. Screenshot of MyWorld application: Augmented Reality is superimposed on real-time images to give the users step-by-step instructions how to remove the fan assembly.
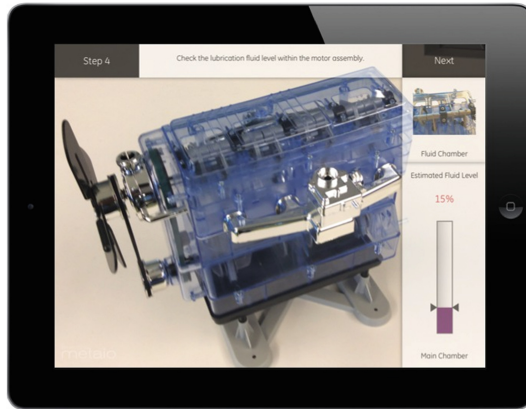
Fig. 8. Screenshot of MyWorld application: Workflow is integrated with the augmented reality (AR) instructions.

(in this case an engine used for demo purposes) that needs to be serviced. The FE utilizes the iPad and its camera as AR lenses where animated 3D models are used to convey step-by-step instructions. As the FE moves the viewing angle, the superimposed AR will also adjust its rendering so that the AR component is always in the right position with respective to the asset.

MyWorld's user experience is highly contextual, and integrated with the user workflow. As shown in Fig. 8, once the machine is dissembled and problem has been identified (a low fluid level in this example), a menu with action options is provided. Using this menu, the FE can order the fluid and schedule downtime within the app itself. Using the information about the site, and the maintenance procedure itself, MyWorld will also automatically update the maintenance procedure status and notify the site manager when the FE has successfully repaired the asset.

This typical maintenance scenario shows how MyWorld reacts to the user context to provide the right information at the right time. It does so by gathering information form different data sources: project management tools, training material, and expertise databases, mashing up this information with environment data using BLE beacons and camera, and leverages the potential of wearable technology such as Google Glass and mobile devices such as iPhones and iPads. The result is an improved experience where FE can access contextual information to improve operation efficiency.

4   Lessons Learned

The MyWorld application was developed as a test bed for better understanding the use of wearable, mobile, and augmented reality technology in field engineering and manufacturing domains. To this extent, we have showcased MyWorld capability to different types of users within GE including field engineers, management and technology leaders, and have conducted workshops with potential users. This has enabled us to obtain valuable feedback.

These are some of the issues that have been raised as concerns include: the need for adequate ergonomics and usability of both hardware and software platform; the need to cope with unreliable connectivity; Adequate location and positioning in in-door locations; and adequate battery life for a typical work day shift.

Perhaps the most common feedback received with respect to wearable technology has been the need for ergonomics and user-driven ability to control the activation/deactivation of the technology. For instance, in the words of one FE, "once it goes down, it stays down". Imagine a field worker is using a wearable device, and while performing a task in the field, he has to put it down on the ground or workbench for some reason (e.g., safety and regulation, obtrusion of his view sight or movement, etc.). When this happens, the chances are high that it will stay down and the worker will not put the wearable device back on later. The main lesson here is that any wearable device has to be comfortable and ergonomic enough that a worker does not need to put it down at any point during his daily routine. As a result, we have been porting MyWorld application to industrial-grade head-mounted computing devices that are closely integrated with FEs safety equipment, and that can be repositioned away when not needed while not removing it completely from the body. We are testing head mounted displays that can slide in and out of the user's view sight, and that can be mounted on existing hard hats and safety glasses.

Connectivity is also an important concern that was expressed during our interviews. While the use of mobile technology can significantly improve a worker's productivity, it can also become an impediment if resources become unavailable due to lack of connectivity. Imagine a worker relying on his mobile device for accessing documents and updating status and workflows, and for some reason, the connectivity to the cloud fails. This could mean that he is not able to complete his task, forcing him to wait for the connectivity to be restored or to fall back on low-tech methods such as pen and paper. Adoption of mobile technology will be hindered and workers may reject the technology altogether. As a consequence, we have been developing offline operation algorithms and technology to support disconnected operation.

The lack of reliability and the range of existing indoor location technology poses another set of challenges to using wearable technology. For example, the integration with existing devices such as Bluetooth beacons is not always seamless. Sometimes, it takes a few seconds to lock on to a beacon signal, which means that the worker has to wait until then, thereby delaying his work. We are currently working on technologies that improve the reliability and responsiveness of indoor location.

The battery life of wearable devices is another potential source of usability issues. Most of the devices currently available in the market are not capable of lasting an entire workday, especially if the work involves capturing any video. We have been researching several options as well as algorithms to improve the power efficiency of the applications.

5   Related Work

The experiences afforded by our integrated approach have benefited form research in both industry and academia. Our work combines some of these ideas in the construction of a context-aware software architecture that incorporate contextual information,

multi-modal interfaces, virtual reality and mobility. This section discusses some related work in these fields.

Anticipation of workers' needs in industrial environments has been described in [5]. In particular, context information has been used in industrial applications as a way to optimize network bandwidth, power consumption and resource utilization of mobile devices. Context has also been applied to optimize processes in field work automation [6]. Our work exploits the use of context information for optimizing voice interactions and indoor location and task automation, anticipating end-users needs and optimizing user experiences.

A comprehensive survey of technologies for context-awareness in for the internet of things is available in [7]. Current technology is largely focused on the gathering and abstraction of information form sensors and equipment in the field. Our architecture leverage on the functionality provided by our own context engine that integrates not only data from the environment but also from corporate information sources.

Previous work on mobile applications for field service showed the benefits of mobility in these environments [8], and of the use of virtual reality as guiding mechanism in complex tasks [9, 10]. These approaches, however, have little focus on IoT integration and wearable computing. More recently, the work described in [11] presents many challenges faced in the development of industrial field service mobile applications, showing the need for further research in the areas of: indoor positioning systems, beacons, voice and mobile devices; while the work described in [12] showcases the application of IoT and mobility in industrial settings. Our work adds to this body of knowledge, by showcasing the benefits of context-aware mobile & wearable computing for service engineering.

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