OpenFactory: Enabling Situated Task Support in Industrial Environments

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Abstract. Combining an awareness of a worker's physical environment with a model of their task enables a system capable of playing an active role in supporting workers in the environment. We discuss OpenFactory, a prototype system for industrial settings that demonstrates how data from low level components published as services can be provided in a situated manner to workers pursuing a variety of tasks. In the context of a maintenance scenario we explore how an industrial environment's ability to sense its state and the resulting information can be used to augment collaboration both among workers as well as between workers and their environment. The benefits of this approach include improved accuracy on worker tasks, continuous regulatory compliance and increased flexibility of service delivery to the facility. In essence, for the worker OpenFactory represents a task-oriented interface to the facility.

1 Introduction

Industrial environments differ from the home or office environment in fundamental ways. Pervasive computing systems have been discussed for home environments with the intent of making them more livable for people [1]. In the office, pervasive computing research tends to focus on making knowledge workers more aware and productive [2]. Within industrial environments, on the other hand, the emphasis is often reversed. The role of people in industrial environments is often to make machines more productive. In many cases the machines are very expensive and any downtime can be costly. Such machines are therefore often heavily instrumented with sensors and wired to control rooms, enabling their state to be monitored and recorded. Industrial environments are optimized to repetitively perform a narrow range of processes very efficiently, thus a good deal of automation has been in place for many years. Industrial environments have been among the most successful pervasive computing environments to date, yet with few exceptions (e.g. [3]) they have received little attention from researchers in pervasive computing.

We believe industrial environments provide unique challenges and opportunities for research. Within industrial environments it is the physical environment itself –the building, machines, sensors, effectors, in essence, everything but the people – that produces and consumes much of the information central to the operation of the facility. Therefore, there is a greater need for people to communicate with the physical environment here than elsewhere. More intuitively, a nuclear power plant worker has a lot more to talk about with his work environment than an accountant does with hers. Cost considerations have restricted the intensive use of such technologies to the most expensive and mission critical of machines. While the cost of processors has dropped dramatically over time, the costs of large numbers of sensors and the necessary cabling of these sensors and processors to a control room have not, making them expensive to deploy. These costs are now changing as well. While highly precise sensors for mission critical components will continue to be expensive, low cost, less precise sensors are available which are suitable for a broader array of equipment. Additionally, the advent of low cost short-range wireless technologies such as Bluetooth ([4]), and IEEE 802.11 ([5]) provides more cost effective methods of connecting sensors and processors embedded throughout a physical environment. Ultra-Wideband locationing technology will allow the environment to track and respond to workers as they service and work with the equipment. As a result of these decreasing costs, we believe that less-expensive, more commonplace equipment, as well as the maintenance engineers themselves, will be able to derive the same benefits previously afforded only to more expensive components.

As wireless sensing capabilities proliferate, the applications they enable will change. Rather than focusing on the state of a few critical components, the wider distribution of sensors results in an increasingly transparent environment. The details of a component's past states, its changes through time, its service history, and its current operation become much clearer. In our OpenFactory project we are exploring different ways that such capabilities can be used to improve the way various services are performed within industrial environments. The rest of this paper will discuss the capabilities that pervasive computing provides in industrial settings, an architecture and prototype that demonstrate these capabilities and their ramifications.

2. Pervasive Computing Capabilities in Industrial Environments

The OpenFactory system is a prototype that simulates an industrial environment consisting of a series of pumps and valves outfitted with sensors and capable of communicating their state and changes through Bluetooth. Additionally Ultra-Wideband position detecting sensors, and Pan-Tilt-Zoom cameras within the environment allow the environment to track and assist workers performing tasks. We demonstrate the benefits of the system through a scenario involving the maintenance of a small secondary pump supporting the feedwater system[1] in a nuclear power plant. The OpenFactory system demonstrates three key capabilities: Activity Sensing, Human-Environment Collaboration, and Human-Human Collaboration.

[1] The feedwater system supplies the water used to make steam for power production.

2.1 Activity Sensing

Increasingly connected industrial equipment is enabling plants to be aware of conditions beyond the state of individual components to entire systems and processes. In OpenFactory we show how the addition of short-range wireless components allow activities that would have previously gone unnoticed to be sensed, recognized, and logged.

Traditional sensors provide low-level data such as position, acceleration, flow, or voltage. Higher level notions of system activity or state must often be deduced from composition of this low-level data. In addition to providing communication capabilities, short-range wireless technologies, such as Bluetooth or 802.11, can be used as a localized activity sensor. Bluetooth-equipped devices can broadcast their activities and state on a periodic basis. Neighboring Bluetooth devices receive this broadcast, processing and storing the information if called for. Due to the inherent limitations of range, this broadcast is only available to objects and individuals in the immediate vicinity where it may make sense contextually. Receiving these broadcasts allows a system to perform automatic annotation of relevant activities and "activity auditing" at a later date. For instance, when an x-ray machine is performing an x-ray it can broadcast the details of the procedure, possibly including details on power levels and other parameters[2]. Only individuals and objects in the immediate vicinity will receive that broadcast and treat the information accordingly. Later, it becomes possible to determine who was present during a particular test from the system's annotations. Similarly, individuals and objects who record the activities of environments as they travel through them can refer to logs of activities for which they were present.

Bluetooth enables localization of devices to the range of a room or work environment. More precise positioning is possible using Ultra-Wideband devices. Specifically, newly Ultra-Wideband beacons that enable positioning to an accuracy of a few inches with readers tens of feet away – or more. In our work we examine the potential of such beacons with this degree of precision to provide greater visibility into the activities and processes of an industrial environment.

2.2 Human-Environment Collaboration

Humans and machines work together in industrial environments to accomplish a variety of tasks. OpenFactory demonstrates how humans and machines can share task information in their environment. Unlike many office environments, the primary goal of an industrial environment is not to facilitate the task of a person, but for people to facilitate the tasks of the machines. The environment's role is to assist the person in the completion of those tasks, guiding the user when necessary [6].

Many tasks (e.g. maintenance or operations) in industrial environments are represented by clearly defined procedures in order to ensure quality and uniformity of work. These tasks are ideally suited for a system where the environment proactively

[2] Although x-rays are commonly associated with medical applications, they are frequently used in industrial environments as a method of nondestructive testing of components (e.g. to examine welds or castings).

participates in the execution of the task. Systems have been built which provide procedural guidance using task and user models for a maintenance task (such as [7]). OpenFactory combines these approaches with sensory feedback from the environment. Sensors in the environment become additional "eyes" for the user as the system anticipates information and equipment needs based on the details of a particular procedure. In the process, the user becomes an "actuator" that has the unique and powerful capability to physically interact with components. Since the system manages the procedure, it can use its sensors to monitor its proper execution. If sensors indicate that a step has not been properly completed, the system can warn the user, alert others to the situation, or even refuse to continue to the next step in the procedure. In addition, Ultra-Wideband beacons allow the system to detect whether a worker is about to make a mistake or is progressing appropriately through the task at hand. For example, by noting the position of beacons embedded in a worker's glove, we can detect whether the worker is approaching the correct or incorrect valve in the context of a maintenance task. The system controls progress, guiding and correcting the user where necessary. Additionally a Pan-Tilt-Zoom camera follows the location of the Ultra-Wideband beacon, to capture and log the maintenance. The end result is better adherence to procedure – an important part of high quality maintenance and safety.

2.3 Human-Human Collaboration

As information throughout the plant is created, captured, and delivered in an increasingly flexible fashion, workers can collaborate in novel ways. OpenFactory demonstrates how workers can collaborate across time by capturing information generated by both workers and the environment and recalling it at appropriate times.

Information capture can often be time-consuming and tangential to the completion of a task. Filling out paperwork takes time and is often done after the task is complete, introducing potential sources of error. It is important, therefore, to incorporate system-driven capture into the task itself, while recognizing users will likely be involved to a degree. As historical information becomes more accessible, users need to consider the needs of future individuals when deciding what to capture. The system provides users a way to highlight exceptions and special cases, as well as document decision points to give future users insight into the process. As a consumer of this information, workers virtually collaborate with their counterparts from the past. They are able to view snapshots of past states or reconstruct timelines of changes to a system. Users can save and retrieve artifacts which are related to the task, such as notes, drawings, decision-making processes, or video.

2.4 The OpenFactory Architecture

We designed a system to enable the capabilities previously discussed using a variety of wireless, mobile, and embedded technologies. The OpenFactory system builds upon a previous web services architecture originally developed for consumer-based web services [8]. An existing Radio Frequency Identification (RFID) system for tracking safety-related equipment [9] was also incorporated. A prototype has been implemented in the context of a typical fluid-flow system found in many industrial environments such as the feedwater system in a nuclear power facility.

Physical components in the system are equipped with embedded computers and appropriate sensors for instrumentation and incorporation into the OpenFactory system. Components are organized hierarchically and equipped with either RFID, Bluetooth, 802.11, or combinations thereof based on functionality and need. RFID is used for components requiring identification only. Bluetooth is used for local communication with other components and mobile devices, as well as to provide activity sensing capabilities. 802.11 is used for relay between local environments and where longer range or higher bandwidth is required. Finally, Ultra-Wideband is used to determine a worker's location to provide warnings, alerts, and produce video logs.

The system uses a web services architecture for communication and composition of services. Individual components publish services representing their sensor data, equipment status, historical information, drawings or schematics, and functionality. Assemblies of components form higher level services through composition of component services, such as the feedwater system publishing performance statistics for the system. Other examples of potential services include regulatory alerts, performance analysis, maintenance procedures, or activity auditing.

Humans interact with the system through consoles or mobile devices designed to invoke system services. A monitoring / operating console can be used to monitor events, receive alerts, and control system behavior. A component manufacturer at a remote site can view performance data and operational characteristics of their products in real environments to develop product insights and improve design, maintenance, and construction techniques. A regulator can subscribe to alerts from various systems to monitor regulatory compliance instead of performing periodic spot-checks of paperwork and documentation. Finally, maintenance technicians in the field can use mobile devices such as PDAs (personal digital assistants) or tablet computers to wirelessly interact with the system at the point of need. The intent is for the information to be presented in a situated manner [10], allowing workers to pursue their task and become aware of relevant information at the appropriate times and locations as governed by the requirements of the task.

3. The OpenFactory Prototype

The OpenFactory prototype, shown in Figure 1, includes one pump and two valves using Pocket PC devices as embedded computers.[3] The pump communicates with a technician's mobile device via Bluetooth and with an operator's console via 802.11. The valves are instrumented with position sensors to detect open vs. closed operation.

[3] Pocket PC devices where chosen based on cost, ease of development, and the fact that they are readily available.

The worker's glove is outfitted with a Ultra-Wideband beacon. The prototype illustrates the benefits of the system through a simulated maintenance service.

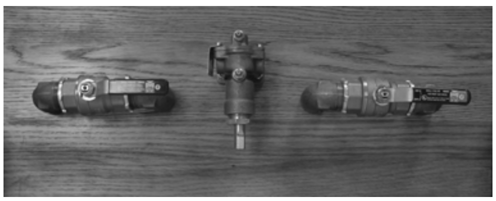

Fig. 1 Prototype pump and valves

Fig. 2 Technician's Bluetooth mobile device waiting for closure confirmation from the isolation valves.

When the pump's condition monitoring unit detects a potential problem, it sends an alert to the subscribers of its monitoring service – in this case, the operations engineer. Problem diagnosis and resolution often involve understanding activities that seem unrelated at first glance. Changes in neighboring systems, other maintenance work in the area, or the presence of certain equipment or materials may all contribute to the root cause of a problem. At the time the problem is detected, the pump captures the context of the problem (e.g. recent operating characteristics) as well as relevant activities from sensor readings in the environment. For instance, suppose a team of workers is disassembling a neighboring piece of equipment. Even though the equipment may be functionally out-of-order, its embedded computer is still broadcasting the status of work activities related to its repair via Bluetooth. The maintenance activities on this piece of equipment could inadvertently affect the operation of the pump or another related component. This may or may not be the cause of our pump's problem, but those activities are sensed, captured, and presented with the problem description in case they are needed. When the repair process begins on this pump, it can in turn broadcast that it is being shut down and an auxiliary system may broadcast that it is preparing to be brought online. By sensing these activities, we make details about an artifact more transparent, providing easy access to information that would otherwise be lost or difficult to reconstruct later.

The use of short-range wireless technologies, such as Bluetooth and Ultra-Wideband, provides the opportunity to enable a new type of behavior. Wireless capabilities were not provided for the purpose of enabling activity detection, but instead to reduce wiring costs. As costs go down, there is a business cases for instrumenting components that were previously not cost-effective. For one client, the cost of wiring alone for four proposed new sensors in a power plant was USD$250,000. Once the infrastructure is in place for communications purposes, devices can broadcast and receive information for activity sensing as well.

The operating engineer uses the relevant available information to determine the best course of action to address this problem and dispatches a maintenance technician to repair the pump. When the maintenance technician arrives, he cooperates with the environment to optimize the performance of the repair task. The environment can use its sensors to assist in the diagnosis of the problem and then guide the technician through the steps of the required maintenance procedure. During many phases of the repair process, the environment is better equipped to verify proper completion of the repair steps. For instance, when the technician needs to close two isolation valves before opening the pump, the environment can make use of its network of sensors – including the Bluetooth equipped valves – as well as the Ultra-Wideband equipped gloves - to guide the technician to the proper valves and to verify that the correct valves have been closed before allowing him to continue, as shown in Figure 2. When the valves have been properly closed, the technician is allowed to continue and the system alerts the operating engineer with the updated status as shown in Figure 3. The video log of the procedure is shown in Figure 4. Through cooperation of human and environment, the technician is able to leverage the expanded sensory capabilities of the environment to perform the repair.

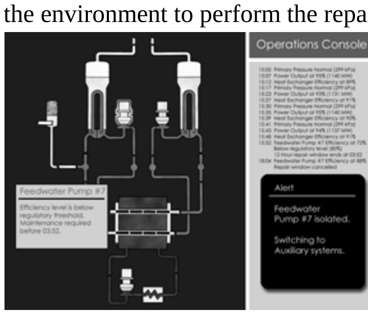

Fig. 3 Operator's Console showing alert and current status

Fig. 4 Operator's console showing video log data collected by camera track ing the Ultra-Wideband beacon.

In the course of the repair, the technician refers back to historical data collected about the pump. The system provides an overview of the maintenance history of this particular pump. Additionally, the system can generate aggregate-level summaries of maintenance for similar components to help track down larger-scale problems such as a commonly occurring problem on a particular type of pump. Using his portable device, the technician virtually collaborates with previous technicians by viewing a sketch made by the last technician showing areas that might require attention and a video made of the inspection of the pump's internals using a borescope. Collaborating with previous users in this manner is the next best thing to actually linking the two individuals in real-time. Even in cases where real-time collaboration may be necessary, the system can improve that interaction since it provides a memory of the previous technician's experience. As the current repair is performed, the system captures similar information with reference to the current situation, augmenting it with its own sensor information and context from activity sensing. In this way, the technician is also collaborating with future users by recording insights and repair details.

This approach is in some ways similar to other systems, such as [3], [11], and [13] in which humans leave virtual annotations in physical locations that can be retrieved by others at a later time. A key distinction here is that much of the information is being generated by the environment itself. In this case the worker is not simply leaving an annotation, but is in effect highlighting and annotating a small subset of the massive data generated by the environment. In this way the worker can communicate far more to subsequent consumers of this information than if the worker were responsible for providing all information.

4. Discussion

OpenFactory combines a model of the workers task with relevant aspects of the state of the physical environment to essentially "walk" a worker through a procedure. By doing so we believe a worker is less likely to overlook relevant environmental conditions and preparatory steps. Easy access to information captured during previous task executions is an additional means of increasing the consistency of procedures. OpenFactory therefore essentially serves as a task-focused interface to the facility. By continuous compliance we mean that as a plant becomes "transparent", it becomes possible to monitor continuously whether a plant is in compliance with a variety of safety and industry regulations. Moreover, as opposed to inspection regimes that are designed to periodically check for compliance, continuous sensing enables early warning of when the plant strays from compliance or even approaches conditions that threaten compliance. Finally, the ability to monitor the presence and actions of workers, as opposed to simply the fixed facilities of a plant, helps to verify that procedures are performed in an appropriate manner by the right workers with the right equipment.

As it becomes possible for service providers to obtain information directly from individual components and systems rather than through the centralized plant facility records, it lowers the system complexity and therefore also lowers the threshold for having an interaction and providing a service. This means that there is greater flexibility in the service providers chosen, and more fine grained services.

Fundamental industry drivers have and will continue to lead to the inclusion of embedded processors, sensors, and connectivity into industrial environments. Future opportunities lie in recognizing that once these technologies are in place we can begin to explore new ways to augment and use these technologies that go far beyond their originally envisioned use. The global positioning system, for example, was put in place originally for military applications yet it has found application in a variety of areas that go far beyond the original vision.

What our work, as well as [3] begins to explore is how these technologies change the way work is performed and services are provided. We believe that industrial environments are of particular interest because the environment itself is particularly active in the execution of many tasks. It does not merely support people; if anything, people tend to support the environment. It does not merely make it easy or convenient for people to communicate task information with each other; the environment itself is both a producer and consumer of information. Going forward we are continuing to explore the unique collaboration challenges afforded by these circumstances. As industrial environments become better able to both sense and remember information relevant to the narrow tasks they are designed to enable, they become a partner for collaboration rather than merely a setting for collaboration between people.

As we go beyond sensing individual, instrumented components to sensing the broader activities of people and the tools they use within a physical setting we encounter novel challenges. For example, how do we interpret and use disparate information from a variety of sensors to recognize less structured and somewhat ad-hoc activities such as the activities of workers? What applications can tolerate the ambiguity and lower reliability of such approaches? How do we handle the massive amounts of data produced by larger bodies of sensors? These are but a few of the questions that we believe are fertile ground for exploration. We believe, therefore, that the increased proliferation of information technology does not mean that these environments are "finished" from a pervasive computing perspective. On the contrary, the fact that industrial environments are so heavily outfitted with information technology, combined with the highly task specific nature of such facilities makes them ideal settings to explore and pursue a variety of pervasive computing challenges.

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