An Overview of the Research in Mobile/Wearable Computer-Aided Engineering Systems in the Advanced Infrastructure Systems Laboratory at Carnegie Mellon University

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Abstract:

Research on means for accessing and collecting information in the field for infrastructure-oriented contexts is being conducted in the Advanced Infrastructure Systems (AIS) Lab, one of nine labs in the Institute for Complex Engineered Systems (ICES) at Carnegie Mellon University. The objective of ICES is to provide an environment that fosters multidisciplinary research at the interfaces between people, their physical space, and their information space. This paper specifically focuses on the AIS research being conducted in the mobile and wearable systems area. Three specific research projects, at various stages of completion, are briefly presented: (1) the Java Inspection Framework (JIF) for rapidly creating and field-testing speech-controlled inspection applications; (2) Situation-aware Interface Design: finding the right interaction for mobile and wearable computer systems; and (3) Information representations and data structures that support efficient data access and data collection on construction sites. This research is aimed at developing a more systematic, knowledge-driven approach to the development of these systems.

1 Introduction

The infrastructure in the US is receiving failing grades from the American Society of Civil Engineers (ASCE). There are opportunities to improve the current mode of monitoring and maintaining infrastructure. By infrastructure, we refer to the various complex support systems upon which our society depends: transportation systems (roads and bridges), power distribution systems, telecommunication systems, water treatment and distribution systems, etc. These systems are typically large, long-lived and exposed to the environment. They deteriorate with use and exposure, interact with other systems, and when disrupted cause major delays, loss of economic activity, and most importantly, loss of necessary support functions.

During construction, inspection, maintenance, and repair of infrastructure projects, field-based engineers and technicians need to refer to maps, engineering drawings, databases, and other technical documents to check the location of structures and structural elements, and to collect data related to these structures. For example, there are nearly 590,000 bridges in the American National Bridge Inventory that must be inspected at least every two years. The current means by which bridges are inspected and assessed uses a condition rating method, whereby the inspectors go to the bridge and assign a condition rating to the various elements of the bridge. The rating of the entire bridge is based on the conditions of all of the elements, no matter the relative importance of the elements. This approach, while easier to collect data, does not recognize that the nature and location of damage on an element, and the type of element will greatly change the reliability of the overall structure. Frangopol et al. describe a reliability-based approach for managing highway bridge maintenance [5]. They claim that this approach could save at least 50% of the costs of conventional maintenance strategies. These reliability-based approaches are going to demand a much greater amount of condition information to be collected from bridge elements. The location and amount of damage along all elements will have to be determined so that the relationship of the damage to the reliability of the elements and to the bridge can be assessed.

Research relevant to this need for collecting more information on a more frequent basis is being conducted in the Advanced Infrastructure Systems (AIS) Lab, one of nine labs in the Institute for Complex Engineered Systems (ICES) at Carnegie Mellon University. The objective of ICES is to provide an environment that fosters multidisciplinary research at the interfaces between people, their physical space, and their information space. The objectives of AIS research are to identify, understand and explore opportunities in infrastructure activities (design, construction, operation, and maintenance) that can significantly benefit from the use of emerging computing technologies, such as embedded intelligent sensors, mobile and wearable computers, and data mining technology. Much of the AIS research activity is at the interface between physical infrastructure systems and information management systems.

Various projects within this lab address the interface where data and information must be extracted from the physical infrastructure and provided to an infrastructure management system. As such, the research in this lab is organized into several themes: (1) *sensor systems*, such as the development of new Microelectromechanical Systems (MEMS)-based sensors and the conduct of field evaluations of off-the-shelf sensor systems; (2) *mobile IT support systems* for humans at the above-described interface, such as the development of prototype mobile and wearable computer applications, and the development of frameworks and knowledge-bases for creating these mobile and wearable computer systems; (3) *new approaches for infrastructure system decision support*, such as the development of construction management systems able to take advantage of the new streams of data and information made available by (1) and (2), and the use of data mining for deriving valuable relationships from these data streams.

This paper specifically focuses on the AIS research being conducted in the mobile systems area. First, a vision for how mobile devices might be integrated with other forms of embedded and robotic sensors systems to support civil infrastructure inspection contexts is presented. Then, an overview of the objectives and mission of our research in the area of mobile and wearable computer-aided engineering (m/w CAE) systems is presented. Finally, three specific research projects, at various stages of completion, are briefly presented: (1) the Java Inspection Framework (JIF) for rapidly creating and field-testing speech controlled inspection applications; (2) Situation-aware Interface Design: finding the right interaction for mobile and wearable computer systems; and (3) Information representations and data structures that support efficient data access and data collection on construction sites.

2 Vision for Mobile, Embedded and Robotic Systems in Civil Infrastructure

Imagine that a team of bridge inspectors is inspecting a large highway bridge. Some inspectors are visually inspecting the more accessible parts of the structure. They rapidly record what they are seeing using a speech interface to their data collection device. They compare the current condition to that reported during previous inspections by viewing any of the previous inspections reports stored in a central database. Some inspectors are querying sensor systems embedded in, or attached to, specific locations on the structure using a mobile device for interfacing with these various sensors. The inspectors are able to access the loading conditions and corresponding structural responses, and any changes in local material properties, of the structure since the last inspection period. Other inspectors are operating mobile inspection devices from a remote position somewhere on the bridge. They are able to move these devices to different locations so as to view and sense the condition of the underside of the bridge superstructure. They are also able to control and interpret the information being provided by these devices. Finally, other inspectors are using advanced condition assessment technologies, such as laser scanning, video imaging, infrared thermography and ground-penetrating radar to inspect certain elements of the structure, such as the bridge deck. As these inspectors are collecting and viewing the results collected from these various sensor systems, they are evaluating the conditions of the structure and the need for additional tests, with the help of decision support systems.

Each inspector is providing input directly into an inspection report being compiled as they perform different aspects of the inspection. In other words, they are all using some form of mobile IT device to efficiently and effectively support their specific field-oriented tasks. Nobody is sitting at a desk; they are on the bridge and moving about, climbing, and conducting their inspection tasks and visually confirming what the various sensors and condition assessment technologies are reporting.

In addition to being easy to use, the mobile IT systems provide intelligent, supportive functionality. For example, they help locate possible damage sites and assess their states of damage. When a defect or damage is found, the location, nature and extent of the damage must be accurately described by the inspector. An intelligent inspection assistant presents the inspector with a detailed, context-specific description of the procedure to follow in assessing the damage once it has been discovered. For example, the system advises the inspector about where and how many times the rust and scale should be scraped from the girders on a superstructure so as to measure the remaining section. Knowledge Discovery in Data (KDD) techniques are used to help inspectors identify common damage locations on the bridge being inspected based on the data collected on other bridges in the database. Based on the locations and extent of damage on other similar bridges, under similar loading conditions, exposed to similar weather conditions, the system could relate these damage locations to the current bridge.

3 Mobile and Wearable Computer-Aided Engineering (m/w CAE) Systems

The vision driving our research in mobile and wearable computer-aided engineering (m/w CAE) systems is to make engineering information accessible when, where and how it is needed. Engineering information consists of all the information that is available for a specific artifact, such as specifications, construction and manufacturing plans, sketches, images, manuals and inspection and maintenance plans. This information would be provided for the different stages (construction/manufacturing, inspection, maintenance, etc.) of the life cycle of engineered systems (buildings, automobiles). Mobile workers need engineering information not only at the office, but especially at the construction site, on the shop floor and at maintenance facilities. To access engineering information away from the desktop, the mobile workforce needs mobile IT support that is natural, easy to use, and truly supportive of the task.

Our mission for our m/w CAE research is to do enabling research on mobile and wearable CAE systems that addresses the following tasks:

- Determine necessary levels of detail of information for given tasks or contexts;

  Effective support must offer as much necessary information as possible, with the least information overhead possible.

- Develop and assess tools for rapid, knowledge-based development of mobile IT support;

  Rapid prototyping enables early field-testing opportunities and thus validation and verification of the envisioned system. Therefore, we see the need for standardized tools and frameworks, which support developers to create systems based on experiences made in previous projects.

- Identify and characterize commercially available hardware components for building cost-effective, context-appropriate mobile and wearable CAE systems;

  One of our key concepts is to test and incorporate commercially available components and to integrate and enhance them with customized software to usable, effective systems. Part of this effort is to foresee which of these components will become standard products that can be included in long-term IT strategies without quickly becoming obsolete or outdated.

- Identify, develop and test appropriate user interfaces and interaction means;

  Using mobile and wearable computer systems in an engineering context means to see these systems as "Tools", rather than toys or high-tech gadgets. Only in applying appropriate user interfaces for effective interaction, we can make IT support an essential part of the "Toolbelt".

- Test with real engineering applications and users.

  Finally, we are committed to learn from real-world examples and implementations. We can only accomplished this by field-testing at the actual job site and getting feedback from the people who will use the systems in the future.

4 Several m/w CAE Systems Research Projects

In this section, three specific research projects in the area of mobile systems research are presented: (1) the Java Inspection Framework (JIF) for rapidly creating and field-testing speech controlled inspection applications, developed by Jirapon Sunkpho; (2) Situation-aware Interface Design: Finding the Right Interaction for Mobile and Wearable Computer Systems being developed by Christian Bürgy; and (3) Information representations and data structures that support efficient data access and data collection on construction sites being developed by Jan Reinhardt.

4.1 JIF: Java-based Framework for Rapidly Creating and Field-testing Speech Controlled Inspection Applications

The Java Inspection Framework (JIF) provides a partial solution to the development of field inspection support systems by capturing the common components presented in several field inspection support systems. One can think of JIF as an application or environment that is able to interpret the necessary information about a particular inspection process described in a text file, complying with a set of predefined grammars, then use the information in the text file to produce an application to support that inspection process. Thus, development time can be greatly reduced since most of the common elements have been implemented and JIF users only need to describe the inspection information in a required textual format to develop an inspection application without requiring any coding tasks. JIF is implemented using JAVA to ensure platform independence and Internet support.

JIF is developed based on the concept of Object Oriented Application framework or framework for short. A framework is an abstract design that describes the interaction between interacting objects to provide a skeleton of an application in a particular application domain [3, 4, 8]. It incorporates knowledge that is common to applications in the domain. The low level details are left to the framework user, since these are the features that vary among systems in the application domain [7].

The key characteristics of an application framework are *extendability*, *inversion of control,* and the use of *design pattern as building blocks* [7]. A framework is extensible because it consists of abstract classes and interfaces that can be extended and specialized. These abstracted classes and interfaces are also called *hot spots* of the framework. Inversion of control means that the control of the flow of the execution often resides in the framework, not in the application. Finally, a framework uses design patterns as its building blocks because patterns are appropriate for designing parts of frameworks and particularly designing hot spots within frameworks because many design patterns enhance flexibility or extensibility [6].

JIF is composed of a set of cooperating classes that make up a reusable design for a field inspection support system. This set of cooperating classes can be separated into three main layers: *inspection domain objects*, *tasks*, and *application*. Figure 1 shows the components that make up JIF.

The inspection domain objects represent the concepts and entities required in order to model the inspection process. These concepts include the *inspection elements* or items being inspected, the *inspection data* being collected, the *instruments* or technologies that are used to collect the data, and the *knowledge* about a specific inspection process. A detailed discussion of these concepts and how they were implemented can be found in 10].

Inspection domain objects are managed and controlled by a task object in the task layer. A task represents an activity that needs to be performed during an inspection. Examples of an inspection task are collecting inspection data about a specific inspection element, selecting the element for inspection, and performing an action on some inspection element.

Two forms of *task* were introduced: *atomic task* and *group task*. An atomic task is a task that does not contain other tasks within it, while a group task is a task that contains other tasks within it. For example, a task of inspecting a deck element is a group task that contains three atomic tasks: inspect the top of the deck, inspect underside of the deck, and inspect drainage system of the deck. A group task is initialized and executed according to a *plan*. A plan controls the order of initialization and execution of the tasks within the group. Four plans for initializing and executing a group of tasks are *sequence*, *menu*, *batch*, and *choice*. A sequential plan allows an inspector to perform all inspection tasks in a group in a specific order. A menu plan allows an inspector to perform zero or more tasks in the group in any order. A choice plan allows only one task in a group to be performed. Finally, a batch plan allows an inspector to perform all inspection tasks in a group in any order.

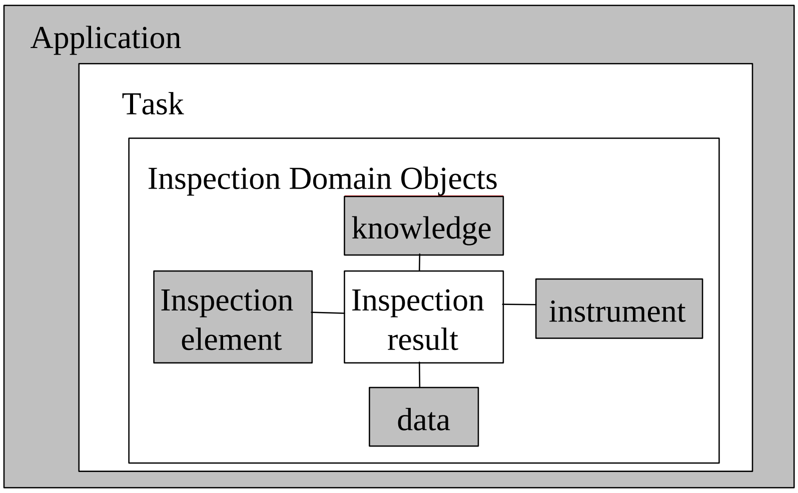

Figure 1: JIF Architecture

An inspector interacts with the system through the application layer of the framework. The application layer manages and controls a set of tasks and provides an interface for an inspector to interact with the system. In JIF, the application layer is implemented according to model-view-controller (MVC) paradigm, which separates the data from its representation and the controller. The data for the application are simply a set of tasks to be performed. This set of tasks is created by a task builder. The controller and the view are represented by the *task manager,* which initializes and executes the tasks, and the *application view,* which provides the visual interface of the application.

By having such a framework that provides the environment for integrating different pieces of inspection information, a new inspection support system (such as in bridge inspection support system) can be developed efficiently and effectively without requiring significant amount of effort. JIF also leverages the effort in developing a new inspection support system by separating inspection information into groups (knowledge, elements, and tasks) and allows this information to be provided by different groups of people without having to know about other information that is not in their base of expertise. In bridge inspection, the knowledge needed by JIF can be developed by a bridge engineer who does not have to worry about the actual bridge elements and inspection tasks. Moreover, these model implementations can be reused as long as they support the interfaces specified by the framework.

4.2 Situation-aware Interface Design: Finding the Right Interaction for Mobile and Wearable Computer Systems

On construction sites, we see ever-changing *work situations* that differ in their *work locations* and *work activities*. Mobile and wearable computer systems can support workers in these work situations. But to be useful tools, these systems need to offer specific user interfaces that are appropriate for the location and the activity being performed. The design of user interaction with mobile and wearable computers is often redone from the beginning each time a new system is created. In this research project, we are attempting to develop an "Interaction Constraints Model" that aids system designers in choosing the right interaction means for specific tasks with respect to the environment in which the task is performed and the kind of mobile or wearable computing system that supports this task. With the Interaction Constraint Model, we are developing a methodology that supports the design of a mobile system interface, based on experience from previously developed systems. The model is built on the premise that the application or the domain are not as important as the constraints that affect the system for determining the right human-computer interaction with mobile or wearable computer systems. By categorizing and documenting these constraints and the feedback on chosen human-computer interactions for existing mobile system interface designs, we will have a means by which to make manual, and in the future automated, decisions about the user interface designs for these mobile and wearable computer systems.

For computer-aided engineering applications, mobile IT support helps to improve construction processes and enables mobile workers to perform their tasks better, faster, and with higher quality, i.e., with higher data consistency (less manual data entry and reentry), shorter data access times (connection to the company's intranet and to online manuals), and better communication means (Internet telephony, short messages, expert forums). However, mobile workers usually perform several different tasks in ever changing environments. This generates different constraints on the system design of the mobile IT support with respect to:

- the kind of the **task** to be performed;
- the **application**, for which the task is performed;
- the influences caused by the **environment** on the execution of the task;
- the **device** chosen as the supporting hardware platform; and
- the abilities and work patterns of the **user.**

Each situation demands that the user and the mobile or wearable computer system adapt their interaction with respect to the task, the application, and the environment. Many mobile input devices have been developed for use "on the move", such as mobile, body-worn pointing devices or keyboards, scanners, or data gloves. But these interactions still involve using at least one hand. Some tasks, however, have to be performed using both hands, which makes the manual operation of an IT device distracting or even impossible. Based on this need for hands-free user interfaces and our experience in developing speech-controlled wearable computers, we are attempting to formalize the design process for user interaction with wearable computer systems in industrial environments. In order to formalize this design process, we are taking a more detailed approach and investigating tasks of different domains. The intention of the interaction model is to help in choosing the most appropriate and effective forms of interaction (e.g., speech) for a specific task with respect to the given constraints. Since these constraints occur in repeating patterns within different domains we can formalize and re-use them in the design process of future software applications.

4.3 Information representations and data structures that support efficient data access and data collection on construction sites

The information about construction projects that is needed by workers on a construction site is often not available in a form that is usable on that construction site, even if it is in electronic form. Moreover, current mobile computing solutions for complex data acquisition and data access tasks do not have sufficient ability to capture data in the field efficiently and integrate that data in the overall knowledge base of the construction project [2].

Human Computer Interaction (HCI) research has shown that appropriate interaction styles with mobile computing devices can make data access and data collection tasks in the field effective and efficient [9]. However, apart from solutions for single, isolated tasks, general data access and data collection tasks for construction projects are complex and extensive. The provision of spatial information, as it is often needed for tasks on construction sites, and data collection support of extensive data sets in external environments, are still not sufficiently solved [1].

This research project currently aims at three goals to enable effective and efficient user interaction with mobile devices on a construction site:

1. Providing data structures to the user that resemble the semantic links of the task the user executes on the construction site. By using data structures that link objects on which the user is likely to execute operations closely together, will minimize navigation needs between desired data sets.

2. Providing controls that execute the desired operations on multiple data sets.

3. Enabling the user to interact with the computing device in a higher-level descriptive style. Semantically-rich descriptions of desired operations on data sets and data retrieval requests minimize the amount of interactions that are necessary to fulfill a data update task. Furthermore semantically rich requests for data limits the amount of data sets that qualify for a request and can therefore minimize the navigation steps that are necessary to retrieve a desired data set.

If the three stated goals are achieved, the user may be able to interact with complex data sets on a computer in a field-based setting more efficiently. Being able to retrieve and annotate complex data sets on the construction site will enable the user to interact with integrated product and process models on the construction site. If computer-based solutions are able to retrieve and capture all the information a user on a construction site may need or want to document, paper-based solutions will become obsolete. IT-system-based product and process models can handle construction-related information more consistently than paper-based solutions, which will avoid mistakes made due to the usage of outdated documents, regeneration of data that is already available and enable a unified way to access and retrieve data.

Our approach to make interaction with complex data sets on construction sites more efficient is to organize these data sets into hierarchical structures in order to allow generalization and specialization of data sets.

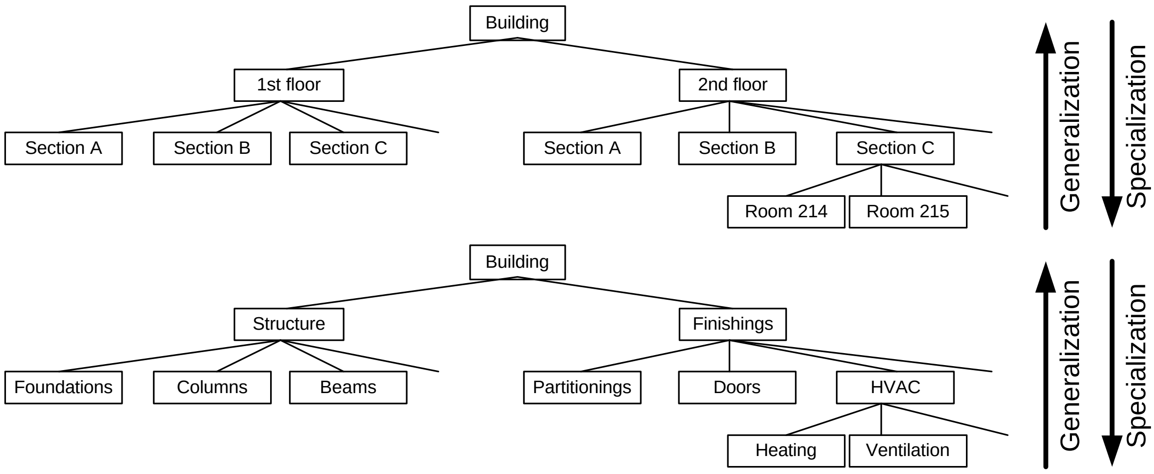

Figure 2: Hierarchies of objects in a product and process model

Operations that are executed on higher-level nodes of the data set hierarchy will affect all lower data sets as well. This aggregation of operations has the potential to execute operations on a large number of lower level data sets with a single interaction with only one node of the overall data set.

The configuration of lower level data sets in groups will be specific for different tasks and may even change for one task during the course of a construction project. The challenge of this approach is to create and use object hierarchies dynamically that group data sets that are eligible for joined, aggregated operations. This research will focus on the interaction with customized data structures for data acquisition and data access tasks on construction sites as well as the efficient generation of desired data structures from existing data representations.

For example, a desirable data structure for a window inspection task that is to be done on a certain floor of a building would be an upper level grouping of windows per floor and a lower level grouping of the directions of the building. This data structure will enable the user to select the floor he or she is currently on and avoid navigation through window items that relate to different floors. In a different scenario, the user stands with a mobile computing device in front of the building and inputs information about the completion of the windows in the facade of the south side of the building. For this task, a data structure that has higher-level groupings of windows according to direction and lower level groupings of the windows according to floor-level is more desirable. By selecting the direction the user is able to see, he or she can eliminate navigation through all the atomic window elements that cannot be seen, and therefore cannot be updated. If, for instance, all windows on one side are installed, an operation SET 'INSTALL WINDOWS' COMPLETE could be executed on the grouping of the windows by direction rather than having to select every atomic window element. By applying algebraic operations between datasets of different levels, desired selections of data sets can be created and joined operations can be executed. This will eliminate the need to touch every single atomic element but will still enable the user to input detailed information.

The stated approach will facilitate a minimal yet sufficient amount of interactions with mobile computing devices on the construction site. In conjunction with current HCI methods such as multi-modal user interfaces, which optimize interaction with a mobile device on the level of a single operation, we hope to make data access and data acquisition tasks on construction more efficient.

The proposed approach will be implemented and tested for data acquisition tasks that relate process information to building elements of a product model. This process information needs to be updated through an operation that is applied to building elements. By grouping building elements that are semantically related and will have similar update operations, the total amount of necessary updates can be reduced significantly.

5 Summary and Conclusions

Mobile computing is becoming more desirable and prevalent on construction sites. Reliability-based approaches to monitoring and maintaining infrastructure will also demand mobile data collection support. Tools, techniques and knowledge will be needed to assist in the rapid development of interfaces and application software for tasks to be supported by these mobile devices. This paper presented several specific areas of research being conducted in the mobile systems area in the Advanced Infrastructure Systems Lab at Carnegie Mellon. The first project developed a Java-based tool to assist in the rapid prototyping of an inspection application, but did not give much guidance on the specific design of the interface that would work best for the task and environment. The second project is exploring the nature of the knowledge and constraints that drive the selection of user interaction mechanisms for a specific task in a specific environment. The third project is exploring the underlying representations of data needed for supporting field-based construction applications. The premise is that if the appropriate data representations are used, the amount of user interaction with a mobile computing device can be greatly reduced. The research in the M/W CAE Lab is not so much aimed at the development of a specific mobile application as it is aimed at the development of tools, techniques, representations, and knowledge that will better, and more knowledgeably, support the development of such mobile systems for infrastructure-oriented applications.

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