Fourth International Conference on Construction in the 21st Century (CITC-IV)
"Accelerating Innovation in Engineering, Management and Technology"
July 11-13, 2007, Gold Coast, Australia

Evaluating the Design of Mobile Computing Systems in Construction through Notational Support

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Abstract
Mobile computing in construction should enable smooth integration of computer capabilities into the physical objects that populate the workspace of construction workers to reach high levels of performance. Despite the growing importance of mobile computing technologies for construction, there is little tool support for usability evaluations. This paper presents a systematic tool support — Mobile computing Evaluation Notation for Usability (MENU), which is developed to capture usability-significant features of mobile systems by considering the nature of construction. This tool could guide the development of new mobile systems and the improvement of existing systems. This paper applies MENU to describe and evaluate two real cases of mobile computing systems in construction: a mobile computing system for bridge inspection and a mobile Augmented Reality-based equipment management system. Suggestions for improving the usability of these two systems were developed based on the described methodology.

Keywords:
Mobile computing, evaluation, usability, case illustration

1. Introduction

Garnter Analysts (2004) predict that by 2014, more than 30 percent of mobile workers will combine the virtual and real world using Augmented Reality and wearable environments such as heads-up displays. Mobile computing technology holds great potentials in this regard and has been explored to improve construction processes (Reinhardt et al. 2004; Hammad et al. 2003; Magdic et al. 2002; Saidi et al. 2002). Mobile computing systems should be developed to enable smooth integration of computer capabilities into the physical objects that populate the workspace of construction workers. A number of studies on the adoption and usage of mobile computing technologies have been conducted in the area of business management, which has typically been based on empirical research (Kim et al. 2004; Scheepers and Scheepers 2004). There has been little research noted in construction, which incorporates thorough considerations of usability issues of the technology in the context of typical construction operations. A mobile computing system based on its initial conceptual design might fail to reach its maximum potentials in the absence of implementing usability evaluations. In order to carry out such effectiveness evaluations, it is necessary to thoroughly identify and capture all the possible usability issues involved with the system. Despite the growing importance of mobile computing technologies, there is little tool support for the usability evaluations of mobile computing systems. In order to effectively and thoroughly identify usability issues involved in a conceptual design for a mobile computing system, a Mobile computing Evaluation Notation for Usability (MENU), is developed to capture usability-significant features of mobile computing systems. MENU is a notation for describing the physical properties of the interaction entities and the relationship of physical with informational entities. Different system design alternatives can be described by MENU and subjected to analysis in terms of human factors issues related to the interaction (perception, cognition, action). The design of mobile computing systems demands new notational tools to deal with the central role in mobile computing systems, and mobile systems design, of the physical properties of the interaction entities and the relationship of physical with informational entities. This paper also presents an empirical study of the use of MENU with design problems of two realistic mobile computing systems in construction: a mobile computing system for bridge inspection and a mobile Augmented Reality-based equipment management system. MENU provides a framework to support the reasoning about different design issues for mobile computing system not covered by conventional design solutions for interactive systems.

Related models describing interactive systems include Presentation-Abstraction-Control model (PAC), multiple-facetted agents (Tarpin-Bernar et al. 1998), interactor (Patero 2002), Model-View-Controller (MVC), MCRpd (Ullmer and Ishii 2000), "Instrumental Interaction"—for Post-WIMP interfaces (Beaudouin-Lafon 2000), and a Model-based approach for Augmented Reality systems (Trevisan et al. 2003). The notation presented in this paper is developed based on the relevant work and derived specifically from the activity theory originated by Fjeld et al. (2002). MENU is more geared towards its applications in the context of mobile construction.

2. Notational Support: MENU

2.1 Major components of mobile computing systems

Input device is used to manipulate the digital information displayed over the real environment. Most of the input devices used in virtual environments can also be applied in AR systems. A poor input metaphor may create a number of problems for the user. For example, Intermediate devices such as joysticks actually place themselves between users and environments, which require much user cognitive mapping to perform tasks. A more direct, natural form of interaction may be achieved through tangible and gestural input. Voice input, a more direct, natural form of interaction, can be achieved as an extra input to increase input capability of the whole system. Also, haptic devices can also be input module through devices like Phantom.

Display devices can be generally classified as visual display (head-mounted displays), acoustic display (3D localized sound systems), and tactile display (force feedback devices). Visual displays are the most popular one. For auditory displays, rather than isolating the participant from all sounds in the immediate environment, by means of a helmet and/or headset, computer-generated signals can instead be mixed with natural sounds from the immediate real environment. For haptic displays, information pertaining to sensations such as touch, pressure, etc. is typically presented by means of some type of hand held master manipulator (Brooks et al. 1990) or more distributed glove type devices.

Tracking, also called position and orientation tracking, is used where the orientation and the position of a real physical object is required. Trackers are used to measure the motion of the user's head or hands, and sometimes eyes. Most tracking technologies are context-aware approaches and different technologies are available for tracking depending upon the application. For mixed environments that require large user-roaming areas, sophisticated ultrasonic tracking systems may be used to increase user range. Magnetic trackers are typically limited to a range of a few meters, yet do not require line-of-sight. Magnetic is suitable for Mixed environments with small working volumes and minimum electromagnetic interference. Body-mounted magnetic transmitters are powered through small cables, resulting in some user tethering. Ultrasonic, optical, and infrared tracking systems avoid tethering and thus allow greater freedom of motion. However, a possible tradeoff is the fact that these systems are susceptible to body interference since line-of-sight is required. Each class of tracker has their own advantages and disadvantages.

2.2 MENU

MENU models an interactive mobile system as a set of various entities, called components: *Computer*-provided entities such as computing systems (component C), *User* of the mobile system (component U), real object involved in the task as *Tool* (component T), real object involved in the task as constituting the *Object* of the task (component O), Input Device (component D_{input}), Display Device (component $D_{display}$), Transmission Device (D_{trans}) for communication and Tracking Devices ($D_{tracker}$). MENU can also incorporate multiple collaborating users with mobile computing systems to address the scalability of mobile computing infrastructure. An interaction link is defined as a relation between a component and the user. A relation between two MENU components may describe an exchange of information (represented by any one or two way arrow) between two components. The most useful aspect of MENU is the identification of the interaction links with a set of characteristics of the user's interaction with a particular mobile computing system. The characteristics along each interaction link form a basis for the evaluation of usability properties. More details can be found in Wang et al. (2006).

3. Case Illustrations

Two case illustrations are presented in this section by applying MENU to describe two existing mobile computing systems in construction: a mobile computing system for bridge inspection and a mobile Augmented Reality-based equipment management system. Suggestions for improving the usability of these two systems were developed based on the described notation.

3.1 CASE 1: MIA—Mobile Inspection Assistance System for Bridge Inspection

MIA (Mobile Inspection Assistance) is a wearable computer system that helps bridge inspectors collecting multimedia information in the field and producing the inspection report (Sunkpho et al. 1998). MIA allows an inspector to fill out the inspection form, access previous inspection reports, make sketch(s) of the bridge element(s), take photograph(s), and produce the inspection report via a voice or pen interface. The system runs on a computer with 133 MHz Pentium processor and a 1.2 GB disk (see Figure 1). The software for the system consists of the following components: (1) a graphical user interface that presents overlapping panels with tabs for viewing previous inspection reports, the current inspection form, the collection of sketch templates, the photo album, and the information about monitored elements; (2) a speech recognition tool that allows the user to invoke commands via speech and make comments and annotations; (3) a database for storing the information of the bridge; (4) a tool for sketching; and (5) a tool for viewing/editing photos.

Figure 1. Illustration of Mobile Inspection Assistance (MIA) system (Sunkpho et al. 1998)

The diagrammatic MENU representation of the system is presented in Figure 2. In terms of MENU, the bridge inspector is the component U; a bridge inspection component is an object (O_1) observed by the inspector ($U\text{->}O_1$); the database that contains organizations and storage of inspection forms is represented by O_2 and located on the notebook (C). The display device, LCD screen for output ($D_{display}$) is required so that the inspector perceives the guidance information to follow the chosen procedure. From this component, one relation is connected to the inspector (U), denoting the transfer of information, related to the inspection procedure: $D_{display}$ ($D_{display}\text{->}U$). Furthermore, a relation from the component C to the component $D_{display}$ is required because information visualized by the LCD display ($D_{display}$) is provided by the database (component O_2): $O_2\text{->}D_{display}$. Wireless communication (D_{trans}) is used to communicate and transfer data ($D_{trans}\text{->}C$). Finally, once the inspector has checked certain components on the bridge and read the additional inspection information provided by the system, the inspector has to "validate" this step, so that the system can record whether to fix it or go to the next component on the bridge. For this interaction with database O_2 on the notebook C, an input device (D_{input}) is required to interact with the notebook for accessing and recording data ($D_{input}\text{->}C$). In this system, there are two types of D_{input}: pen-input and touch screen (D_{input1}) and speech recognition (D_{input2}). They are both linked to the computer (C). Dinput1 is linked to sketch and hand-writing programs located on the C. Likewise, the speech cognition program is directly linked to D_{input2} as well. The fact that the acknowledgment and information visualization occur on the same C is encoded by a double-relation between the components D_{input1} (pen-input device) and $D_{display}$ (screen of the notebook).

Concerning the interaction links, five relations are highlighted in the MENU diagrammatic description of the situation. The inspector perceives the digital inspection information via display ($D_{display}\text{->}U$). The inspector perceives the physical bridge component ($O_1\text{->}U$). The tracker gets information from a tracked area. The inspector documents and annotates the inspection results into the notebook ($U\text{->}D_{inout1}$ and $U\text{->}D_{input2}$). The first relation ($D_{display}\text{->}U$) carries information expressed in a textual mono-dimensional language, in a frame of reference linked to the inspector so that the inspector can read it. The second relation ($O_1\text{->}U$) denotes the natural inspection or observation of a bridge component which is observed in a user-centered frame of reference. The inspector document on the notebook by pen-based input ($U\text{->}D_{input1}$) and acknowledge to the system by speech recognition ($U\text{->}_{Dinput2}$).

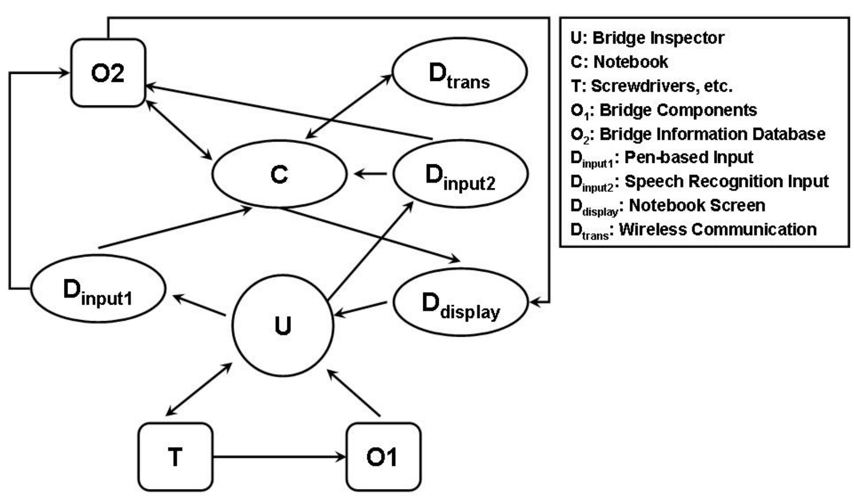

Figure 2. Illustration of MENU Representation of MIA

The display device (screen on notebook) and the real entities (bridge component) apparently have incompatible perceptual environments. In order to perform the task of compare the inspected bridge component with data/image of sample defects stored in database, the inspector has to look both at the bridge component to extract its features and at the screen of the notebook to get the reference information. The required switch between the screen and the bridge component was disturbing to the inspector because it introduced much attention switching, thus increasing cognitive load. Inefficiency increased due to the necessity of also looking somewhere else than at the screen. Head-up display is suggested to reduce such information access cost. The current use of speech recognition is ideal because the inspector’s hands need to be engaged in other tasks. Such hands-free input technology is much more robust to traditional input devices. Speech recognition should be extended to input more types of textual information into the database.

3.2 Case 2: AR EMS—Augmented reality-based equipment management system

The second mobile computing system to analyze with MENU is Augmented Reality-based equipment management system (AR EMS) developed by the author. AR EMS provides AR scenes that are annotated with types of information that are normally acquired through training and, in essence, support humans in procedure-related tasks. These capabilities include obtaining information, domain expertise, procedural knowledge, etc. The approach can alleviate much of the information overload and training required from maintenance personnel, which can improve maintenance procedure efficiency. In the AR EMS prototype shown in Figure 3, the user is able to browse spatially correspondent digital information about a task within a specific operational procedure. Wireless communication and collaboration with office personnel could also be realized to aid the effective search for “right” information from large amounts of technical specifications that are otherwise cumbersome for the mobile user to carry. The platform has been developed with the following major components: display, mobile computing unit, and tracker. The display system (see Figure 3) used in AR EMS is a lightweight ARvision-Stereo head-mounted display (HMD) with a built-in color video camera that is used to capture the real scene for video-based tracking algorithm. The cameras act as the eyes of users and their position and orientation are tracked by special tracker. The tracking approach adopted by AR EMS makes use of the ARTag system (Fiala 2004), a 2D fiducial marker and computer vision system for Augmented Reality. Fiducial marker systems consist of patterns that are mounted in the environment and automatically detected in digital images using an accompanying detection algorithm. A high-performance, light-weight tablet PC (see Figure 3) was used as the mobile computing unit that consists of Local Database and AR program. Existing imagery and data about equipment can be collected in order to compile a comprehensive, equipment-specific database of information. The way that the system adds labels is that the fiducial beside an object or component identify the component. As the component is identified, the system sends a query to the Local Database, which returns any labels matching the object’s features. The AR program is the core technical component for rendering pipeline for the whole system, just like the brains of the system.

Figure 3. Illustration of User’s Setup of AR EMS (Wang and Dunston 2006)

Here, we study the compatibility at the perceptual and cognitive levels based on the ergonomics analysis of the AR EMS system. Figure 4 shows how AR EMS can be described by MENU for usability evaluation. Concerning the interaction links with the maintenance (U), four relations are highlighted in the MENU diagrammatic description of the situation that can reveal potential usability issues: perception of digital procedural information via display ($D_{display}$–> U), perception of the mechanical components (O–> U), the crew's pen-based touch input to the tablet (U–>D_{input}), perception of tracking markers ($D_{tracker}$->U), and interaction with the mechanical maintenance tools such as screwdrivers (U<–>T). Thus, MENU provides a framework to support the reasoning about different design issues for mobile computing system. The example just demonstrates how MENU can be used to describe the system and capture the potential usability issues that could be further studied through experimentation.

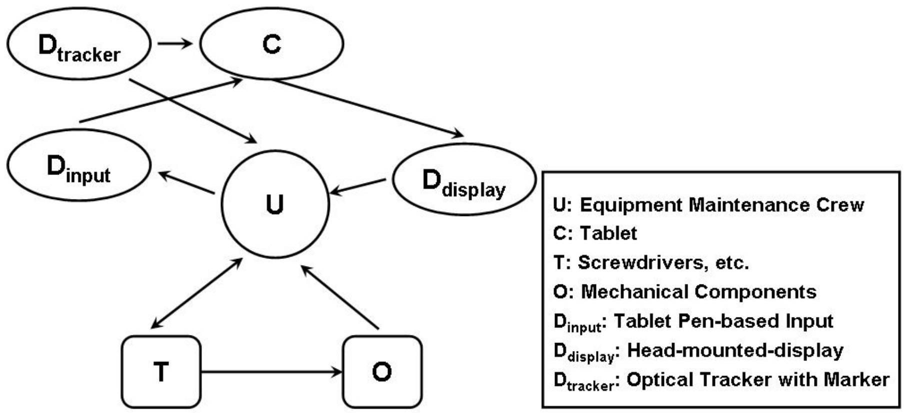

Figure 4. Illustration of MENU Representation of AR EMS

The display mechanism (head-mounted display, D) and the real entities (a tracking marker, D) apparently have compatible perceptual environments. In order to perform the simple task of following the virtual instructions, the user can directly look both at the real tracking marker and tracking marker. Otherwise if the screen of the tablet at hand is used as the primary display instead of head-mounted display, in order to perform the simple task of relating specific real tracking marker to its virtual annotation, the user has to look both at the real tracking marker to keep track of what tracking marker is targeted on and at the monitor to get the virtual annotation corresponding to the real targeted tracking marker. The required switch between the tablet screen and the tracking marker was disturbing to the user because it introduced much attention switching, thus increasing cognitive load. Inefficiency increased due to the necessity of also looking somewhere else than at the monitor.

4. Conclusions and Future Work

This paper presents initial development of a systematic methodology for evaluate the usability of implementing mobile computing systems in construction. The current method consists of a Mobile computing Evaluation Notation for Usability (MENU) notation for usability analysis. This method has also been applied in describing and evaluating usability issues o two real cases of mobile computing systems in construction: a mobile computing system for bridge inspection and a mobile Augmented Reality-based equipment management system. The results shows that MENU is effective and complete in modeling mobile computing systems and suggestions for system improvement can be produced from the analysis. This method can benefit both construction industry and mobile computing technology developers and researchers in two ways: 1) generic guidelines for the constructors to choose appropriate commercial technological components for creating an effective mobile computing system for a particular project/operation; and (2) a reference for mobile computing device designers and developers to develop more customized and ergonomic devices for similar users/tasks across multiple industries.

The future work will (1) complement the development of a systematic and thorough framework/tool support for linking related aspects of designs, comparing alternative designs, and carrying out analysis of realistic mobile computing system design problems and (2) improve the MENU notation by adding to the expressiveness of each notation, looking at the effects of handling multiple collaborating users and augmented artifacts, dealing with scalability issues. The ultimate goal is to develop a systematic approach to mobile computing system design: a design method.

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