FRAMEWORK FOR IMPLEMENTING MOBILE COMPUTING INFRASTRUCTURE FOR CONSTRUCTION OPERATIONS

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ABSTRACT

Construction projects generate large amounts of data and information that must be accessed by numerous parties, from numerous locations, and under varied conditions. Currently, a field crew's project information retrieval, information manipulation, and collaborative decision-making are predominantly limited to paper-based media. As the industry moves towards more digital information management and more information technology (IT) tools become available, the adoption of proper IT technologies and development of an effective IT infrastructure for executing and managing construction field tasks becomes essential. Mobile computing technology can be an effective means for information access by enhancing and maximizing human abilities involved in performing construction tasks, and in collaborating among numerous parties. This paper presents a framework for establishing fundamental principles for developing effective mobile computing systems that would accelerate construction field operations. This framework is developed to relate appropriate technological components in mobile computing systems to specific construction activities from the perspective of two user-centered human factors concepts: feasibility and usability.

KEY WORDS

Computer-aided construction, mobile computing, information technology, usability

INTRODUCTION

Construction projects invlolve the generation and use of large amounts of data and information that must be available to numerous individuals and organizations who are often remotely located from one another in both field and office settings. Currently, a field crew's project information retrieval and manipulation and collaborative decision-making are predominantly supported by paper-based media. However, as economics drive the industry towards more digital information management, more information technology (IT) tools are needed for accessing, storing, and conveying digital project information. Garnter Analysts (2004) predict that by 2014, more than 30 percent of mobile workers will combine the virtual

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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). The focus of this paper, distinguished from others' research, is to provide a fundamental framework for implementing mobile computing infrastructures for supporting the tasks that are typically performed in construction field operations, thus facilitating technology transfer to the construction area.

A number of studies on the adoption and usage of mobile computing technologies have been conducted in the area of business management, which have 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 feasibility and usability issues of the technology in the context of typical construction operations. The objective of this framework is therefore to provide a theory of task-technology mapping for mobile information systems. For the specific purpose, the authors only focus on the human factors issues related to hardware devices and collaboration and intentionally omit other issues like strategies for system development, development cost, and infrastructure standards. This framework could 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.

TECHNOLOGY-TASK MAPPING THEORY DEVELOPMENT

Based on Goodhue and Thompson's (1995) general theory of task• technology fit and on Zigurs and Buckland's (1998) specific theory for task• technology fit for group support systems, a specific task• technology mapping is proposed for mobile computing use in construction operations. The technology-task mapping is determined as a three-way match between mobile computing device capabilities, the profiles of the tasks, and individual's usage context. In order to obtain a better understanding about mobile computing technology to support construction tasks, the idea of task-technology mapping provides a suitable starting point and will be used to extend the future framework. Factors and characteristics of mobile computing technology and task profiles have been extensively investigated for business management (Zigurs and Buckland's 1998). It is therefore a reasonable starting point to explore relevant factors in the context of construction field. Identification of these factors as presented below should also take into account unique features of construction operations like high mobility, large roaming areas, and signal barriers.

MOBILE COMPUTING DEVICE CAPABILITIES

The design and implementation of mobile computing systems involves decisions about how the user interacts with each technological component of the proposed mobile computing system. The authors define generic mobile computing systems as user-centered systems incorporating various kinds of computing devices (PDA, laptop, wearable computers, pocket and tablet PCs, etc.), feedback displays (head-mounted-display, hand-held display, haptic display, aural display, etc.), interaction tools (keyboard, touch-screen pen, 3D mice, data glove, etc.), trackers (GPS, RFID, inertial, optical, etc.), and transmission technologies (Personal Area Network, Satellite-based, Bluetooth, IRDA, Wi-Fi, paging system, etc.).

The factors that need to be considered in determining their promise in construction field use should be identified as the first step. Three capability characteristics of those mobile computing components have been identified: technical functionality, portability, and situational awareness. Results from this assessment lay the foundation for formulating technology-task mapping. The descriptions of these factors and the "high" and "low" end device examples are given in the Table 1.

Table 1. Characteristics of Mobile Computing Device Capabilities

Device Capability	Descriptions	"High" End Examples	"Low" End Examples
Technical Functionality	Technical features such as limited processing, memory and communication capacities, mobile communication, personal touch, time-critical services (Yuan and Zhang 2003)	Wearable computers, bluetooth	PDA
Portability	Devices differ in size, weight, performance, storage capacity, display and input mechanism, and other form factors. As a general rule, intuitive user interfaces and simple menu structures should be deployed (Chan et al. 2002).	Pocket PCs, head-mounted-display, data glove	Laptop, keyboard, mice
Situational Awareness	Includes location-awareness and identity-awareness. Location-awareness refers to situations where information about the location of a user or collaborators is important. Identity-awareness refers to the situations where the identity of a user or collaborators matters (Junglas and Watson 2003).	GPS	Paging system, cell phone

PROFILES OF CONSTRUCTION TASKS

Task requirements have to be identified and generalized as well. From a thorough observation of mobile computing systems used in the architecture, engineering, and construction (AEC) industry and other related domains, many factors regarding task requirements have been identified, some of which, if not considered, may yield a failed mobile computing system. These factors should be considered in the design of mobile computing systems. Each factor can influence the feasibility and usability of proposed mobile computing systems. These factors are discussed in Table 2.

INDIVIDUAL'S USAGE CONTEXT

In order to address potential personal limitations from each working individual, the individual use-context should also be accounted into the design of mobile computing systems. Three factors identified as relevant in describing the individual use context for mobile information systems are distraction, mobility, and previous experience, as described in Table 3.

Table 2. Profiles of Construction Tasks

Task Profile Factors	Profile Factor Descriptions	Construction Cases
Mental Requirements	Relevant to perceptual and cognitive tasks involved in performing a construction task. Perceptual tasks are those attributable to sensory comprehension. Cognitive tasks are those involved in the reasoning and volitional processes that translate between perception and action.	Identifying and detecting an object of interest among a cluster of objects could impose influence on the user's focus of attention. A highlighting method is then necessary to direct worker's attention to specific workpiece features.
Physical Requirements	The wearing of mobile systems while performing a construction task may increase physical occupancy.	A worker with hand(s) preoccupied by an assembly task may have difficulty in simultaneously using mobile computing systems.
Working environment	Factors include situational awareness requirements, indoor/outdoor location, noise level, work area hazards, working volume, etc.	Aural display and speech recognition devices do not work in noisy working environments.
Task Difficulty	Refers to the degree of difficulty for performing a task. The difficulty of the task could be as high as strategic planning which is characterized by unstructured decision making and the application of creativity. It could also be as low as operational tasks characterized by the fact that tasks, goals, and resources have been carefully defined.	Upper management who are involved in the strategic planning routine might need high sophistication of mobile computing devices in every regard, especially the coordination functionalities among different parties.
Task Interdependence	The degree to which a task is related to other tasks, and as a result the extent to which coordination with other tasks is required (Thompson 1967).	Tasks with high interdependence, such as project management, generally require a significant amount of coordination.
Hazards issues	Safety issues can play a role and limit the attention that a user can devote to a mobile system, such as when they are driving a vehicle (Tarasewich 2003).	If the construction task is to be performed under potentially dangerous conditions, where workers need to keep high situational awareness and update knowledge of the surroundings in real time, the peripheral devices should be wearable enough so that they may not occupy too much of the worker's mobility .
Time Criticality	Defined as the importance with which a task needs to be performed promptly (urgency).	Some mobile systems can support urgent tasks by providing the notification of maintenance staff about such emergency situations as equipment breakdown.
Physical disposition	The physical disposition for the work task should be considered in terms of such factors as motion, body position, etc. The physical disposition may determine the appropriateness of certain interaction tools or mechanisms.	In a clustered or congested working volume (e.g., HVAC piping corridor or around special equipment), a body-based human-mobile system interaction metaphor is not as appropriate.

Table 3. Characteristics of Individual Usage Context

Usage Context Factors	Context Factor Descriptions	Construction Cases
Distraction	Mobile users tend to be distracted more often because many activities compete for their limited time, and cognitive resources (e.g., attention). Also, the use-context tends to change frequently when users are mobile, leading to a situation where a user's attention and priorities can change rapidly and unpredictably (Tarasewich 2003).	A worker performs the construction task at hand while accessing information from the mobile system and meanwhile communicating with other collaborators.
Mobility	Related to the fact that a user attempts to use a mobile computing system while being in motion.	A user moves from an outside location, e.g., a construction site, to a room in a building, e.g., on-site office. Such location transitions might break connections and affect the quality of the network connection, which can become an issue in usage.
Previous Experience	Prior experience includes individual and vicarious exposure, and accumulated experience. There is a relevance of previous experience with mobile systems (applications and devices) to system success (overall compatibility of the technology).	A worker who is familiar with mobile applications might have a perceived ease of use for another similar mobile system setup, which leads to the quick success of technology adoption.

TECHNOLOGY-TASK MAPPING

To assess the mapping between construction tasks and mobile computing technologies, mapping of task requirements regarding performance into system functions and features is necessary in order to design mobile computing systems that satisfy user's expectations. A specific technology-task mapping is developed for mapping mobile computing technology to construction tasks. The *technology-task mapping* is determined as a three-way match between mobile computing device capabilities, the profiles of the tasks, and an individual's usage context. The task-technology mapping is considered as a predefined profile, which is developed in three steps. In the first step, an ideal mapping between construction tasks and mobile computing technology is proposed. The second step establishes a mapping between the individual use context and the mobile computing technology, and in essence addresses the feasibility of mobile computing systems in situations of mobile use. The third step combines the propositions of step one and step two and proposes a mapping between construction task and mobile computing technology that is moderated by the individual use context. This framework of technology-task mapping theory is depicted in Figure 1.

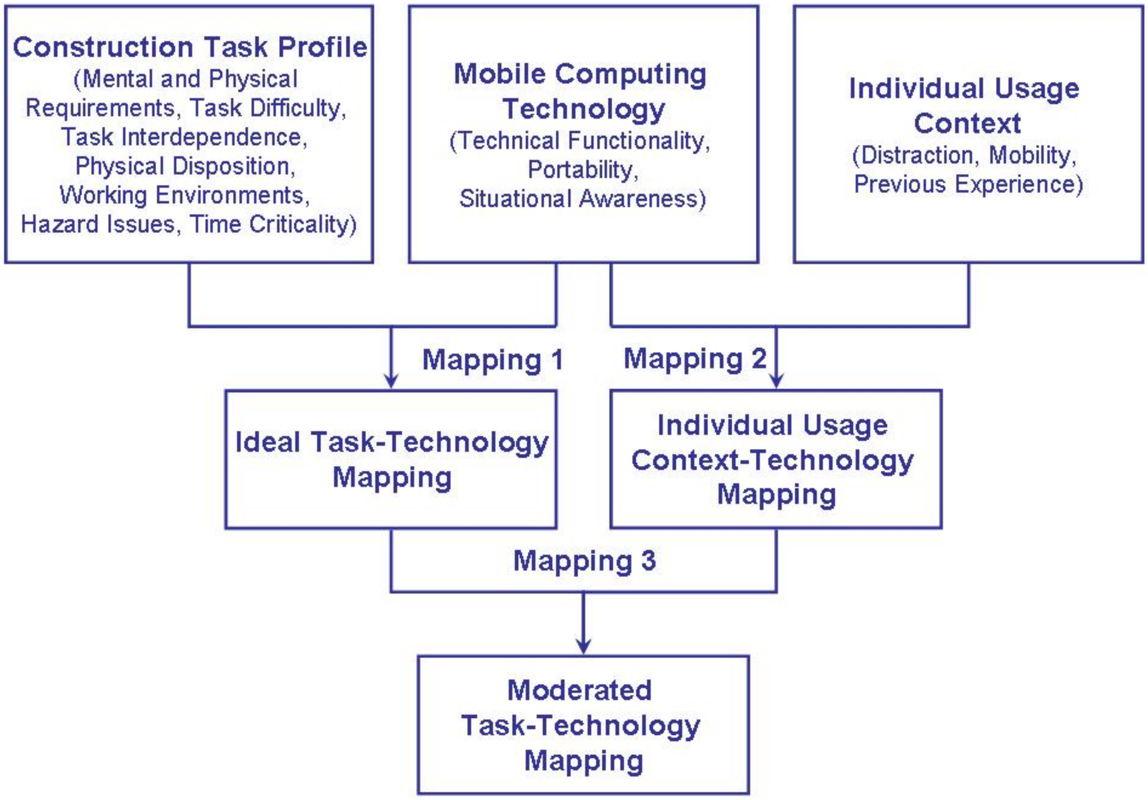

Figure 1. Framework of Task-Technology Mapping for Mobile Computing Systems Usage in Construction Processes

NOTATIONAL SUPPORT FOR USABILITY DESIGN OF MOBILE COMPUTING SYSTEMS

The task-technology mapping proposed above is not an end unto itself. Rather, it has the goal of producing practical mobile computing systems with high levels of performance. Therefore, the next step, designing conceptual mobile computing systems for particular construction operations, should be explored by developing corresponding solutions from the task-technology mapping theory. This step focuses on the conceptual design of mobile computing systems, the selection of computing devices, feedback devices, interaction tools, trackers, and transimission devices. However, 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 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. These identified usability issuse can then be evaluated and addressed through designed experiments. 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 thoroughtly identify usability issues involved in a conceptual design for a mobile computing system derived from task-technology mapping theory, a Mobile computing Evalaution 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. A navigational model framework developed by Reinhardt et al. (2003) was tailored for specifying conceptual and visual information representation of interactive mobile systems and offered an approach that effectively and efficiently creates and manages different views of information contained in product and process models that is thus made accessible on a mobile computer on construction sites. In contrast, MENU can capture the physical properties of components and their relationships with other 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).

DEFINITION OF 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.

CASE ILLUSTRATION

Examination of electrical contracting reveals aspects that prompt the consideration of mobile computing technology. Primary sources of information for electricians are the relevant project plans and electrical codes. Specifically, electricians must refer to the electrical drawings and schedules and to the architectural drawings. On large projects, it is not satisfactory for just the foreman or superintendent to carry the drawings. If enough copies are available, individual workers clearly benefit from direct access to these information sources. In order to minimize this paper burden, reduced scale drawings are often distributed, but even these are still bulky for large projects. In addition to the project plans, each worker must have his or her own copy of the electrical code. The current version of the National Electrical Code is about a 780-page volume. The need to access digital sources of information is a strong motivator for mobile computing.

With regard to communication or collaboration for electrical contractors, high-rise buildings present a promising opportunity for implementing mobile computing infrastructure. If it not unusual for an electrical foreman or superintendent to be many floors removed from the worker who has a question about, say, the circuit breaker schedule. Even if the worker does have a radio to contact the supervisor, that individual may have to refer the question to a higher level manager and perhaps ultimately to consult with the project engineer. This need for documentation and the need to have very specific decisions in the field make electrical construction a suitable domain for implementation of mobile computing solutions.

Figure 2 gives an example of a conceptual design of a mobile computing system for electrical construction operation which is represented by MENU for capturing usability issues. This conceptual design is merely an example to show MENU can describe all the components invovled in a mobile computing system. The device/technology associated with each component are not fully validated yet and presented only for the purpose of case illustration. 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. Concerning the interaction links with the electrician (U_1), five relations are highlighted in the MENU diagrammatic description of the situation that can reveal potential usability issues: perception of digital information via display ($D_{display}$–> U_1), perception of the electrical wires (O–> U_1), the electrician's input to computing sytem (U_1–>D_{input}), interaction with the electrical construction tools (U_1<–>T) and the electrician's communication with the foreman via certain transimission device (U_1<–>D_{trans1}). Thus, MENU provides a framework to support the reasoning about different design issues for mobile computing system.

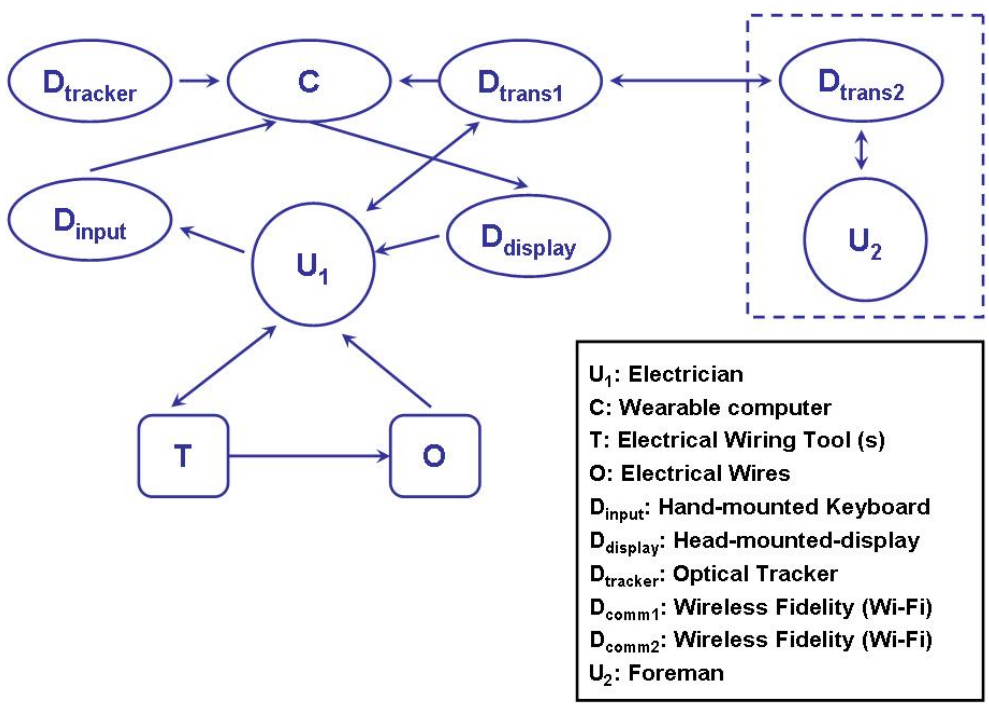

Figure 2. Illustration of MENU Representation of a Mobile Computing System for Electrical Construction Operation

CONCLUSIONS

This paper presents initial development of a framework for evaluate the feasibility and usability of implementing mobile computing infrastructure for construction processes. The current framework consists of the development of a task-technology mapping theory for feasibility issues and a MENU notation for usability analysis. The future work will 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. The ultimate goal is to develop a systematic approach to mobile computing system design: a design method.

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