CRC Construction Innovation
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Final Report
Enabling Team Collaboration with Pervasive and Mobile Computing

Research Project No: 2002-057-C-05 R

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EXECUTIVE SUMMARY

The research project has successfully implemented the application of mobile computing in the construction sites and the use and development of intelligent rooms based on sensed environments and new human-computer interfaces (HCI) for collaboration in the design office. The issues related to the use of pervasive computing technologies which focused on defect management system in the construction industry environment have been identified and documented.

An intensive review of the latest technologies of mobile computing with the varieties of hardware and software available and the application of Information and Communication Technology (ICT) in the construction industry has been conducted. The use of ICT and especially mobile computing devices in construction industry has been widely recognised by numerous practitioners and researchers over recent years and it has brought significant improvements in project collaboration, communication and data transmission between construction sites and off-site offices. Improved project collaboration and communication amongst all participants can be achieved by equipping construction site personnel with mobile and wireless technologies which enable them to gain access to correct, accurate and up-to-date project information.

To perform an analysis of the costs and other benefits that could be realised by the deployment of mobile computing devices in the construction sites a cost benefit analysis (CBA) methodology was carried out. The CBA methodology primarily involved four stages of analyses: planning and defining analysis; engineering analysis; economic analysis; and evaluating analysis, which were then broken down into ten steps. This will assist stakeholders to identify clearly the whole of life cycle costs and the expected benefits of the implementation of mobile computing devices on-sites.

The measurement of the time taken to transmit various types and sizes of data of construction defects which included digital imagery and text was conducted by using WiFi and GPRS. Data transfer rates over GPRS through Telstra network and WiFi over a private network were compared. It is important to note that the transmission speeds vary considerably when using GPRS and could be significantly slower compared to WiFi. With the GPRS facility, it was proved that image sizes greater than 50kb would require users to wait more than one minute to transfer the image. However, by using WiFi, the image sizes would not be an issue.

The capabilities and potentials of the telematic workbench system in construction defect management were demonstrated. The on-site crew uses a handheld mobile device to collect defect information and transfers the information to the design office through wireless communication by sending the information to a database listener. The digital workbench application monitors the database and synchronizes the location of the visual information on the site with the 3D model on the server. Integrated with 3D viewing capability in a CAD system, designers can interact with the combined model/site data using a horizontal and vertical screen effectively. A case study compared the telematic digital workbench against paper-based and Pocket PC-based methods for defect management in a controlled laboratory experiment. The experimental results show that the telematic digital workbench is effective in both time and accuracy for defect management and site-office collaboration.

1. INTRODUCTION

This is the final report of research project 2002-057-C: Enabling Team Collaboration with Pervasive and Mobile Computing. The research project was carried out by the Australian Cooperative Research Centre for Construction Innovation and has two streams that consider the use of pervasive computing technologies in two different contexts. The first context was the on-site deployment of mobile computing devices, where as the second context was the use and development of intelligent rooms based on sensed environments and new human-computer interfaces (HCI) for collaboration in the design office. The two streams present a model of team collaboration that relies on continues communication to people and information to reduce information leakage.

This report consists of five sections: (1) Introduction; (2) Research Project Background; (3) Project Implementation; (4) Case Studies and Outcomes; and (5) Conclusion and Recommendation. Introduction in Section 1 presents a brief description of the research project including general research objectives and structure. Section 2 introduces the background of the research and detailed information regarding project participants, objectives and significance, and also research methodology. Review of all research activities such as literature review and case studies are summarised in Project Implementation in Section 3. Following this, in Section 4 the report then focuses on analysing the case studies and presents their outcomes. Conclusion and recommendation of the research project are summarised in Section 5. Other information to support the content of the report such as research project schedule is provided in Appendices.

The purpose of the final project report is to provide industry partners with detailed information on the project activities and methodology such as the implementation of pervasive computing technologies in the real contexts. The report summarises the outcomes of the case studies and provides necessary recommendation to industry partners of using new technologies to support better project collaboration.

2. RESEARCH PROJECT BACKGROUND

Background

Developments in pervasive computing technology including mobile computing, wireless networks, and human-computer interfaces, have matured and decreased in cost such that it is now possible to deploy them reliably in the construction industry. These technologies enhance the ability for teams to collaborate in the office, on the construction site, and from remote offices by providing un-tethered access to building construction information and new types of interactions with collaboration software that were not possible with a keyboard and mouse. Mobile computing devices now include lightweight tablet PCs, handheld devices such as Palm Pilots, and mobile “super” phones. High-speed wireless networks such as Wi-Fi and GPRS make it possible to use these devices without the need for cables to connect to the Internet. New developments in human-computer interfaces are innovating ways in which we can interact with information. The pervasive computing paradigm could enable beneficial applications for the construction industry such as intelligent rooms with novel interactive devices for use with design collaboration software, and digital hard hats incorporating handheld computers (wearable computing) for data entry on construction sites.

To advance the pervasive computing paradigm, we must carefully consider this technology's potential and constraints. This project is a first step in creating opportunities to study and enhance the use of pervasive computing technologies, beginning with mobile computing and novel HCI devices.

Objectives and Significance

The main stream of this research project was the use of pervasive computing technology in the construction industry – focusing on the implementation of mobile computing devices in the construction sites. It presented a model of team collaboration that relies on continuous communication to people and information to reduce information leakage.

The research project aimed to improve the costly and time-consuming process of data collection and analysis/processing at the interface between physical site operation, construction management activities and consultancy practice – project activities that are generally considered by contractors and consultants to be tedious and error-prone due to extensive information leakage.

The objectives of the research project were to:

- Examine recent developments in information and communication technology (ICT) focusing on mobile computing technologies.
- Collect mobile computing devices information suitable for construction industry.
- Identify mobile computing software available with application to construction industry.
- Survey of information needs of construction sites.
- Identify relevant human-computer interfaces, and wireless mobile computing devices for the use in construction sites.

Consolidating research from several authors (Capgemini, 2004; Done, 2004; Haas et. al, 2002; Eisenblaetter, 2001; Jadid and Idress, 2005; Rebolj et al. 2000) when mobile computing is used properly in the construction industry, some benefits can be achieved such as improved business productivity, reduces paperwork, eliminates redundancy in project task operations, reduces response waiting time, greatly limits revision of the job tasks, enhance worker efficiency, increase knowledge-sharing amongst workers, customers and partners, improve quality of decision making by informing employees. Using mobile computing devices remote team members can communicate and access up-to-date information including specifications, standards, regulations and etc. Other benefits of using mobile computing was reported by Daito in Rebolj et al. (2000) and Jadid and Idress (2005) such as eliminating redundancy in project task operations, reducing waiting time respond and limiting job tasks revision.

A recent research project funded by the Office of the Deputy Prime Minister in UK (Capgemini, 2004) identified the potential benefits of the implementation of mobile computing in the six National Projects. On average, by implementing mobile computing, the national annual value added was £150m. Other significant benefits reported by the Council were the reduction in paperwork by over 80% and reduction in response time to service requests by more than 50% (from 45 days to 12 days). Another research conducted by Haas et. al (2002) reported that a significant benefit of using handheld computers in construction was achieved. Handheld computers application could potentially reduce the delay time by approximately 50 to 95% for different types of activities during the construction process.

Methodologies and Deliverables

The Enabling Team Collaboration with Pervasive and Mobile Computing research project started in September 2004. This research project was divided into three phases:

- **Phase 1: Case analysis**

  The case analysis was related to industry analysis with the following activities:

  - Review of wireless data access providers focusing on coverage in Australia, bandwidth, cost of bandwidth, network reliability, and physical environment limitations.
  - Review of mobile computing devices focusing on feature sets relating to business needs of construction industry and off-the-shelf applications.
  - Survey of industry needs of construction sites with a focus on type/nature, format, frequency, size and length, quality of services, workflow, security, etc.
  - Survey mobile computing software with application to construction industry.

- **Phase 2: Technology adaptation**

  Phase two was to adopt and adapt existing human-computer interface and mobile computing technology to enable remote data acquisition and novel interaction with design construction data. In this phase, training material for mobile computing devices was to be created.

- **Phase 3: Uptake analysis**

  Phase three was to test actual information delivery capabilities of mobile computing devices to theoretical given framework from phase one and validate framework, with the following activities:

  - Identify construction site and specific aspects of a case study.
  - Create study protocol and test equipment.
  - Train users on mobile computing devices.
  - Run study and collect data from retrospective protocols.

By implementing mobile computing devices in the construction sites several potential deliverables were identified such as streamlining and making more efficient the normal day-to-day consulting and construction-related business activities leading to reduce effective cost of data transmission and improve communication to all project participants.

3. PROJECT IMPLEMENTATION

All research activities have been completed as per work plan approved by the CRC CI in the six monthly project review meeting in March 2007. The following is a summary of the activities have been carried out.

Existing Mobile Computing Technology

An intensive review of existing mobile computing technologies has been completed in March 2006. The review explored the latest technologies of mobile computing with the varieties of hardware and software available and the application of Information and Communication Technology (ICT) in the construction industry in order to support project collaboration within project participants. The application of ICT in construction industry has been widely recognised by numerous practitioners and researchers over the last several years. It is evident from the literature review that during the 1990s, the international construction industry started using information and communication technology with increasing confidence. One of the important applications of the ICT in construction industry was the use of mobile computing devices to achieve better communication and data transmission between construction sites and offices.

Generally, a mobile computing device is designed for mobile workers who wish to have real-time connection between a mobile device and other computing environments. The term mobile computing encompasses three components: computer hardware, mobile networks, and mobile services (Magdič et al. (2002). It is important to note that the selection of the appropriate hardware was identified as an important factor in the successful implementation of mobile computing construction, especially on-site.

Accurate information at the right time and at the right place is crucial for successful completion of a construction project. Generally, information in paper form is circulated to project participants during the construction process, and often information is not available when needed. Obviously, information requirements and the transmission of information amongst project participants increases as projects become more complex**.** Therefore, it is essential that communication is managed to ensure that everyone is in the "loop". Collaboration amongst project participants can be supported electronically by using web-based project collaboration, affording significant improvements in an organisation's performance. Another evident derived from literature review confirmed that improved project collaboration and communication amongst all participants can be achieved by equipping construction site personnel with mobile and wireless technologies which enable them to gain access to correct, accurate and up-to-date project information.

Mobile computing offers many benefits then can improve construction processes. The most significant benefit is the ability to provide construction workers with real-time access to relevant information on construction sites. On the other hand, the limitations of using mobile computing are related to technical, financial, cultural, organisational and legal aspects.

Wireless Data Throughput Testing

This research activity presented the results of a study on wireless communication data transfer rates for a mobile device running a custom-built construction defect reporting application. The report of Wireless data Throughput Testing on a Mobile Device Using WiFi and GPRS was completed in November 2005. The study measured the time taken to transmit various types and sizes of data of construction defect, which included digital imagery and text. Data transfer rates over GPRS through Telstra network and WiFi over a private network were compared. Based on the data size and data transfer speed, the rate of the transfer was calculated to determine the actual data transmission speeds at which the information was being sent using the wireless mobile communication protocols. The report found that the transmission speeds vary considerably when using GPRS and could be significantly slower that what was advertised by mobile network providers. While WiFi was much faster than GPRS, the limited range of WiFi limited the protocol to residential-scale construction sites.

By using GPRS as a method of wireless connectivity, the studies recommended the maximum size of a digital image was approximately 50kb with a throughput of 9-13kbs. It was proved that image sizes greater than 50kb would require users to wait more than one minute to transfer the image. However, by using WiFi, the image sizes would not be an issue.

Project Workshop

A workshop was conducted on 15 February 2006 at the University of Sydney which aimed at introducing preliminary outcomes of the research project. All industry partners and the research project team fully participated in the project workshop. The output of the workshop was used to guide further work and has assisted the team to maximise the value of project outcomes.

The project workshop covered two important issues as follows.

- Review of existing technologies which presented a concise review of existing technologies on mobile computing and communication technologies, web-based collaboration, the flow of information during the construction process, and the usage of mobile computing in construction.

- Demonstration of a developed digital workbench in order to view construction defect images that were captured and sent from construction sites by using a handheld computer device.

An open discussion followed after presentation and demonstration. The discussion focused on the future direction of the project and finding a demonstration project. Workshop participants were given a handout of potential project ideas based on the pilot application demonstrated during the workshop and decided to focus on developing an application of construction defect management system that associated with the digital workbench model.

Defect Management Process

Defect management is identified as a method of capturing information where any defect occurs in construction projects and transferring the information to off-site offices. When people are working in a collaborative environment, there is a need to resolve the inevitable defects that occur during the construction process rapidly. This traditionally was a labour-intensive process where defects are documented, broken up into sub-tasks and assigned to the appropriate department to resolve them. The application offered a defect management solution which assists industry to track defects and more efficiently manage resolution through the use of mobile computing and digital workbench devices.

On-site Defect Reporting Application and Telematic Digital Workbench

We have developed an approach to construction defect management as a demonstration of a concept for the real-time sharing of visual data between a construction site and an off-site design office. This approach uses a telematic digital workbench that incorporates mobile computing, wireless communication and a horizontal table-top interface. The system structure can be divided into three tiers: clients (mobile phone and workbench), communication channel (wireless network) and the server (database). The data flows in this system are illustrated in Figure 1. With mobile computing and wireless communication, our approach intends to improve the visual data flows between the building site and the design office. Using a horizontal table-top interface for localising and displaying defects, designers, constructors and clients can understand access and make use of defect information collaboratively.

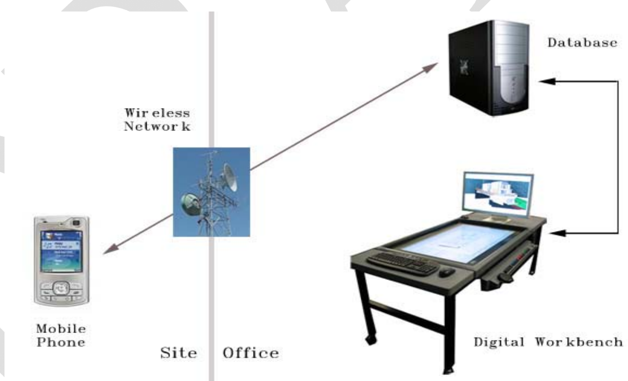


Figure 1. System Architecture.

3.5.1 On-site Defect Reporting Application

The defect reporting application supports the capability of capturing digital images of the defects, annotating a note regarding each defect, defining the locations the defects, as well as sending the above information to an off-site database to be accessed from the design office. The mobile device provides a software platform for the construction defect reporting application as well as the hardware supports for taking digital images of the defects and transferring the data through a wireless network to an off-site database. The hand-held mobile device chosen for our demonstration is the Nokia N80 mobile phone (Figure 2 (a)). This mobile device was selected because its supports a variety of wireless communication protocols such as WiFi and Bluetooth.

Additionally this device is capable of capturing digital images and videos with its inbuilt camera.

We developed the software which can be installed and operated on the mobile phone to provide a graphical interface for entering defect information, transferring data to an off-site database, as well as retrieving and viewing feedback from the design office. Each defect punch list includes a project name, an inspector's name, a photo of the defect, the location of the defect, the detailed description of the defect, the responsible party and the action required. The location of the defect is represented by a zone number, a common method for localization during the construction phase. Compared to the traditional approach relying heavily on manual inputs, this mobile application approach will be more efficient for the workflow in defect management by providing synchronised data transmission and visualization.

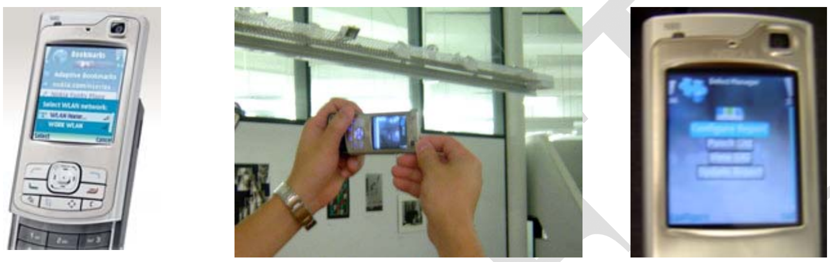


Figure 2. The Nokia N80 Mobile Phone and Defect Reporting Application

3.5.2 Telematic Digital Workbench in the Design Office

In addition to the applications of mobile computing and wireless communication, we developed a digital workbench system consisting of a SmartBoard touch screen as the horizontal table-top work surface, and a large-scale flat-screen monitor as the vertical display mounted across the horizontal work surface. The future development of the workbench will enable the vertical screen to be flexibly positioned to show different views of the 3D model. The horizontal work surface is used for displaying 2D design drawings and the vertical display is used for displaying 3D views. The SmartBoard as shown in Figure 3 supports tangible interactions on the telematic digital workbench through a pen (finger) interface. In order to control more detailed functions and to type text descriptions in CAD drawings, a wireless mouse and keyboard are also employed for the workbench.

Figure 3. The Digital Workbench.

After the defect information is received from the construction site, each defect can be automatically mapped, located and displayed in the 3D model of the CAD drawings according to the zone it belongs to. By using APIs (Application Programming Interfaces), we developed a set of software features that extend the current CAD platforms for defect management. For demonstration purposes, we use ArchiCAD as a base for the development. These features can be categorised into the following three groups: defect synchronisation, defect viewing and design collaboration. A detailed list of software features is shown in Table 1.

Table 1. Add-on ArchiCAD Features

Features	Descriptions
Synchronise with defect database	(1) To connect to the database where the defect information received from the construction site is stored; (2) to retrieve all defect information from the database; and (3) to add or remove Defect Markers from elements in the 3D model accordingly.
View defect information	To open a window showing details of the selected defect including digital images and textual descriptions.
Add defect marker	To manually add a Defect Marker to the selected element in the 3D model.
Remove defect marker	To manually remove a Defect Marker associated with the selected element in the 3D model.
Examine defect (defect only)	To examine a specific defect in the 3D view without displaying other elements of the 3D model.
Examine defect (3D model)	To examine a specific defect in the 3D view in relation to the whole 3D model.
Rotate 3D view	To continuously rotate the camera to inspect the surrounding environment of a specific defect in the 3D view.

The defect synchronisation features initially enable each defect in the database to be mapped and located in the 3D model based on the zone it belongs. During design collaboration, these features also modify the defect database to reflect any changes that are made to the 3D model. The defect viewing features provides tools to view and examine defect information (digital images, 3D objects and textual descriptions) in the 3D model. The design collaboration features enable users to add, delete and modify defect information in the 3D model. To provide real-time feedback from the off-site design office to the construction site, an image capturing application is also incorporated in the digital workbench. This application is capable of automatically capturing the defect displays in the 3D model as digital images and storing the images. Using the same mobile phone, the defect inspector can instantly retrieve the feedback whilst at the construction site.

4. CASE STUDIES AND OUTCOMES

Case studies were conducted as an examination of the software application in conjunction with adopted handheld and pervasive computers in the construction site to dealing with defect management activities. Two case studies have been carried out in October 2006 and January 2007 in terms of the application of mobile computing on-site and digital workbench,

Case Studies 1: Mobile computing

4.1.1 Introduction

This case study project was used as an exemplar for the trial/demonstration of the adopted pervasive computing devices in the realistic contexts which involved the use of selected mobile computing (Nokia N80) and digital workbench devices. The devices were used by members of the research team and industry partners to dealing with defects management activities. When people were working in a collaborative environment, there was a need to resolve the inevitable defects that occur during construction process rapidly. This traditionally was a labour-intensive process where defects were documented, broken up into sub-tasks and assigned to the appropriate department to resolve them. Our developed application offered a defect management solution which assisted organisations to track defects and more efficiently managed resolution through the use of the above devices. Issues such as devices and/or process effectiveness, usability, and time consuming were measured and assessed. The potential impact of the use of mobile computing devices on-sites in conjunction with a digital workbench device in the office was explored.

The objectives of the case study were to implement and test the capabilities of mobile computer devices to transferring information from construction sites to off-sites offices and the effectiveness of digital workbench as an HCI device to support team collaboration activities.

4.1.2 Methodology

This case study sought to obtain an industry–wide perspective of how mobile computer devices and digital workbench with their latest technologies could support the construction project activities. The initial approach of this case study was to conduct on-site interviews and site observations and followed up by implementing a developed software application focusing on defects management in the building construction projects in Australia. To get familiar with the application and devices, training was given to the construction personnel before conducting case study.

Interviews have been conducted with people involved in both management and construction activities such as IT/Group Managers and Site Engineer/ Construction Manager/Project Manager. The interviews aimed at identifying existing defect management processes including information flow, data characteristics, communication network, integrated management system and human resource characteristics. As a result of interviewing IT/Group Managers, an internal defect management process was mapped. This included information flow and data characteristics of defect management process; communication network and internal integrated management system of the company. At the construction site, the interview was conducted with Construction Managers/Site Managers. A detailed process of on-site defect management was observed.

Software Application

The software application was an automated inspection process that allows field supervisors to improve their productivity by streamlining the operation of the construction process. By using a single mobile device in the field, construction personnel were able to remotely communicate defect data to its main office. The application allowed field construction personnel to capture a digital image of a defect, enter location and description of the defect, and also the responsible organisation for the defect. Furthermore, the personnel were able to retrieve an existing defect report to verify its completion. The software application procedures can be viewed in Figure 4.

Location and Time

Case study was conducted on 30 November 2006 between 10am and 12pm at John Holland's construction project which was located at Holsworthy Army Barracks - NSW, 40Km on the East side of the Sydney centre.

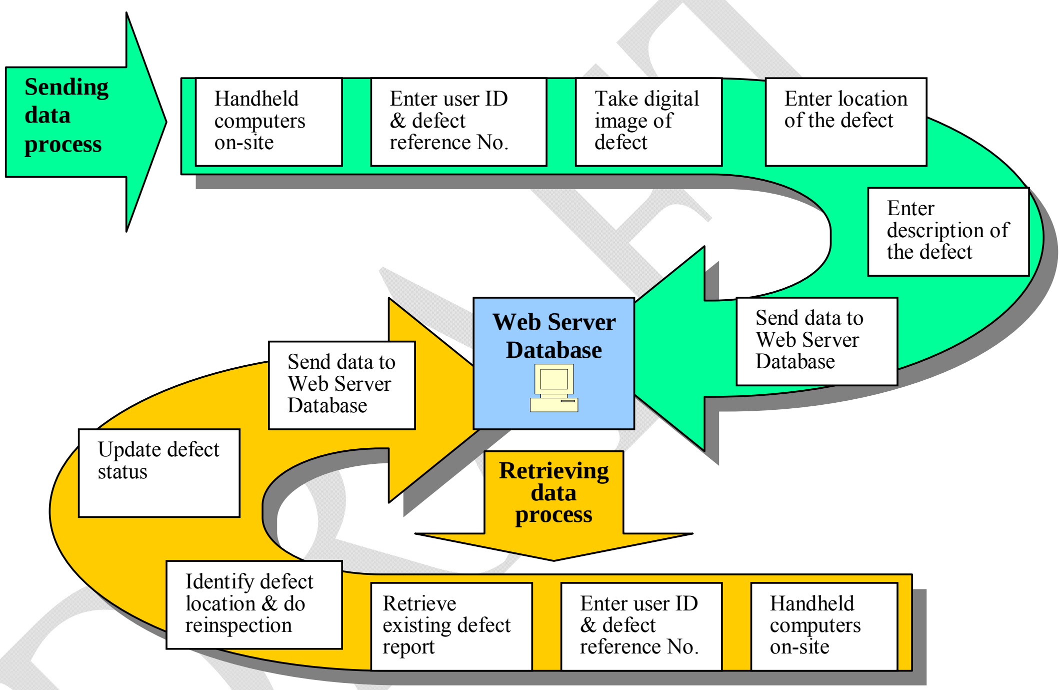


Figure 4. Software Application Procedures

4.1.3 Outcomes

The trial use of the mobile computing device in a realistic setting was successfully carried out. Two mobile computers, Nokia N80, were used with two different providers – Optus and Telstra. Two construction site people were involved in the case study. By using Nokia N80, they captured digital images of defect in the construction site and entered necessary data related to the defect images (e.g. location and description) and sent the data to the server which was located in the University of Sydney. The outcomes of the case study are as follow.

- Optus and Telstra networks with a 3G facility were used during the case study. It was found that during the data transmission the Telstra network worked better compared to the Optus one. In a certain location, the Optus network was not available.

- The speed of data entry into the handheld device depended not only on the computer knowledge base, but also on other issues. These included the location of the defect whether it was located outside or inside the building. The clarity of the handheld screen might be affected by very bright sunlight or dim light. Construction safety environment and the severity level of the defect (major/minor defect) were other significant factors influencing the speed of data entry. The speed of data entry increases in a good construction safety environment.
- The use of work codes for defects was recommended by users instead of describing the type of defect by wording. The use of work codes would make data entry easier and faster.
- The time required to input the descriptions of the defect completely into the handheld device ranged between 195 and 330 seconds per item of defect, with the average time being 273 seconds.
- The size of the image file sent from construction sites was approximately 72 KB. However, the data size will depend on complexity of the images.
- Data transfer time from construction site to the web server, which was located off-site, depended on the network's speed (Optus or Telstra). The speed of the data transfer varied from time to time – whether it is sent in the morning, afternoon or evening. Based on the previous project team's report "Wireless data Throughput Testing on a Mobile Device Using WiFi and GPRS", on average the data transfer time of a 72 KB image file was 1.15 minutes.
- A handheld device equipped with a built-in camera allowed users to capture images of defects and send the defect image in conjunction with other data to the off-site office. The users agreed that a larger handheld screen size would help them to speed up the process.

4.1.4 Conclusions

Based on the case study conclusions can be derived as follows.

- The trial of the software application and handheld device in the real context was successfully carried out. All data could be sent and received properly by the web server database located at the University of Sydney, NSW. This trial needs to be followed up by a more detailed case study in order to compare data transfer times between existing and new applications.
- The limitation of the software application and the handheld's characteristics did not allow users to view construction drawing on the handheld's screen. In addition, taking pictures at outdoor locations was found to be another important issue. In very bright circumstances, pictures could not be captured perfectly.
- To be effectively used in the construction sites, handheld devices should be supported by appropriate device characteristics. This includes the use of rugged cases.

Case Studies 2: Pervasive computing

4.2.1 Introduction

To confirm the efficacy of the telematic workbench concept for construction defect management, a case study was conducted. The case study was a comparative study undertaking a series of controlled laboratory experiments using both traditional media and digital media for defect management. Prior to the final experiments, we conducted a pilot study using a pair of architects, in which we were able to investigate whether the research instruments were working properly. Experiments could be conducted with different stakeholders, such as builders and site managers, to better understand the efficiencies and potential benefits of the technology. Thus, for the final experiments three pairs of architects and constructors were recruited, and each pair of them participated in a complete experiment and collaborated on different defect detection tasks with similar complexity using a different defect management method for each task. It was anticipated that the comparison of the same subjects in different defect managements would provide a better indication of the effects of the methods than using different subjects and the same defect task.

4.2.2 Methodology

The experiment consists of three defect methods sessions: paper-based method; Pocket PC-based method; and telematic digital workbench method. The paper-based session represents the traditional way of defect management on a construction site. IDMS was selected as representative for existing commercial defect management systems via a pocket PC and the telematic digital workbench is our prototype integrating mobile computing and wireless communication.

Paper-based method

This traditional method typically includes inspecting the building site, discovering defects, documenting defects by paper (See Figure 5), and communicating the information to designers and builders in a face-to-face mode requiring the physical presence or electrically such as email, fax, phone etc. In terms of visualization of the defect information, most firms record defect information using notes and textual descriptions on a drawing. The collected defect information is inputted into database by secretaries who have no expertise on construction or design domains. This paper-based tradition method can sometimes lead to missing defect information, misunderstandings and arguments among different parties due to human input errors. We investigate this session as the base line for the study.

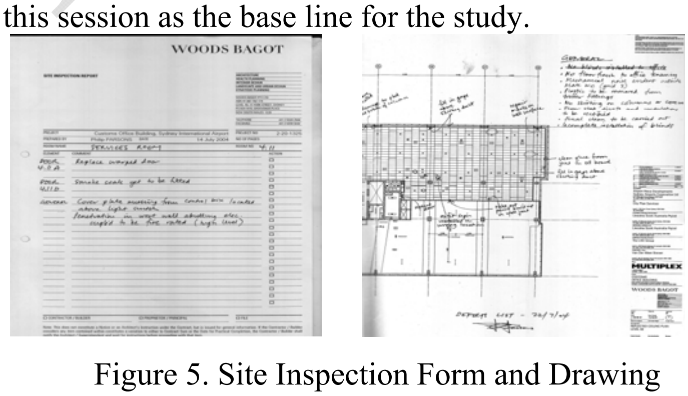
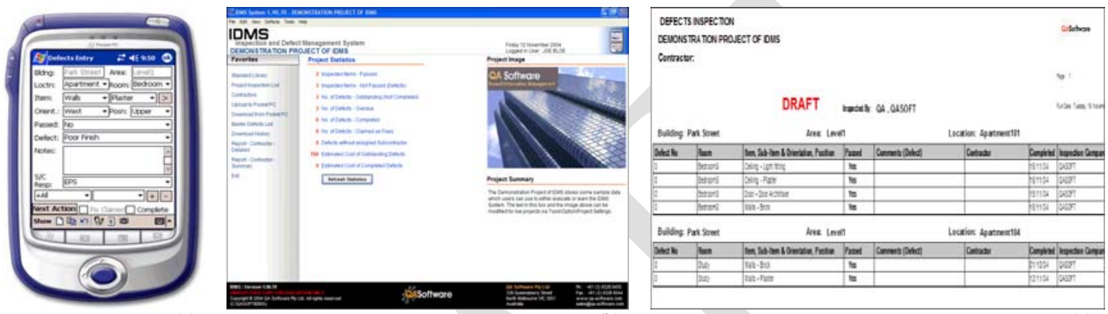


Figure 5. Site Inspection Form and Drawing

Pocket PC-based method

IDMS (Inspection & defect management system) is a PC + Pocket PC-based system for managing building inspections and recording of defects. It provides detailed project inspection list and maintains a photographic record of defects using a Pocket PC camera (See Figure 6). Thus, users just need to choose one of the items from the list step by step. For example, it says 'Ceiling–light fitting, West-Upper'. The defect information is recorded using a Pocket PC and on returning to the office the inspection results are downloaded to the PC and automatically emailed to the relevant contractors who are required to fix the defects. IDMS provides automatic data input and camera function via the handheld Pocket PC. However, IDMS does not satisfy an increasing need for synchronous design collaboration since it does not use the wireless network for the data transmission. Further, IDMS does not provide 2D or 3D CAD drawings in terms of visualizing the defect data.



(a) (b) (c)

Figure 6. IDMS (a) Pocket PC; (b) PC; and (c) the Final Defect Data

Telematic digital workbench method

During defect inspection an on-site defect inspector takes digital photos of defects using the mobile phone. The defects can also be documented into the punch list using textual descriptions. The defect information of the punch list can then be transmitted to the off-site design office through the wireless mobile network. Once the data are received at the design office, the localization of the defect information is realized through the zoning system in the 3D model of the CAD drawing. Designers in the office can examine the defects and make necessary modification using the digital workbench. Further, the inspector can retrieve and view feedback from the off-site design office using the same device. These two reversible defect data flows thus enable synchronised design communication between the construction site and the design office. The process of defect management process is shown in Figure 7.

(a) (b)

Figure 7. (a) Taking a Digital Image of a Defect Using Mobile Phone; and

(b) Explore the Defect Information using Digital Workbench.

When we compared the defect management methods, we investigated three defect management processes (See Table 2) in order to demonstrate the capabilities and potentials of the telematic workbench: a recording process in inspection; a transmission process between the construction site and the design office; and a visualisation process of the defect information. Through the recording process, inspectors collected defect information, where the paper-based method relies heavily on manual inputs and the other two methods rely on automatic inputs via the hand-held devices. In terms of the data transmission process, the paper-based and Pocket PC-based methods communicate between the construction site and the design office asynchronously while the workflow in defect management using the telematic workbench is synchronous. For visualisation, compared to the paper-based and Pocket PC-based methods, the telematic workbench method provides 2D & 3D defect information in a CAD model. It was expected that different features of the three processes would determine the efficiency and accuracy of the defect management.

Table 2. Three Focused Processes

Processes	**Defect Management Behaviours**		
	Paper-based	Pocket PC-based	Telematic workbench
Recording	human input: (drawings & report)	automatic input via a pocket PC (camera)	automatic input via a mobile phone (camera)
Transmitting	in person, email or phone	pocket PC ↔ PC & email to the office	wireless network using a mobile phone (synchronisation)
Visualisation	Papers	digital database	digital database and 2D & 3D defect information in a CAD model

4.2.3 Experiment

The experiments were carried out in two simulated places in the Wilkinson Building at the University of Sydney. One architect was located in the design office and the other constructor was in the construction site for the simulated situation in each experiment. Two experimenters were required for each experiment.

Design Office

The simulated design office was set-up in a lab, in which the telematic digital workbench was located as shown in Figure 8(a). The workbench consists of a SmartBoard touch screen as the horizontal table-top work surface, and a large-scale flat-screen monitor as the vertical display. The horizontal work surface is used for displaying 2D design drawings and the vertical display is used for displaying 3D views. The SmartBoard supports tangible interactions on the telematic digital workbench through a pen (finger) interface. In order to control more detailed functions and to type text descriptions in CAD drawings, a wireless mouse and keyboard are also employed for the workbench. In the paper-based method and the Pocket PC-based method sessions, the designer used the horizontal surface of the workbench as a conventional desk for reviewing defect information after the touch screen was turned off. A video camera was used to monitor a designer's behaviour for a reference and one experimenter stayed in the design office for assistance.

Figure 8. (a) The Simulated Design Office; (b) A SmartBoard Touch Screen

Construction Site

There was no special setting for the simulated construction site since we defined certain areas on level 2 of the Wilkinson Building for the construction site. The inspector carried a pen, a Pocket PC and a mobile phone and performed the construction site tasks in the designated place (See Figure 9). Instead of recoding the inspectors' behaviours, the other experimenter observed and noted their specific process, behaviours, time etc. In addition to the total session time, the time taken to complete individual tasks at the construction site was measured.

Figure 9. The Simulated Construction Site.

Table 3 shows the outline of the experiment set-ups. For the telematic workbench session, no physical drawing was allotted to the architects in the design office because of the ArchiCAD drawing given.

Table 3. Outline of the Experiment Set-ups

	Paper-based session		**Pocket PC-based session**		**Telematic workbench session**	
	on site	Office	on site	office	on site	Office
Drawing	O	O	O	O	O	X
Photo	X	X	O	X	O	X
Instrument	site inspection report (paper & digital version)		pocket PC & PC	PC	mobile phone	digital workbench
Application	None		IDMS		CRC 6.0 & ArchiCAD	
Network	None		Internet (email)		wireless network	

Site	the entrance area	the Hearth area	the Hearth area
Design Office	The Sentient room in level 2		

Participants

Each pair consists of one constructor and one architect from our industry partners, John Holland and Woods Bagot. Three participants for the construction site have over 10 years-working experience in the construction engineering area and the other participants for the design office are competent in using ArchiCAD ranging from 4 to 10 years-working experience in the architecture practice. It was observed in the pilot study that the architect is not familiar with the keypad of the Nokia phone, so he pushed a wrong button several times and lost all data. In order to overcome the unfamiliar keypad problem, for the final experiments we recruited constructors who are good at text input in the mobile phone. Three architects are also early adopters, so they had no difficulty in using the telematic digital workbench.

Defect tasks

Appropriate defect management tasks had to be devised carefully in order for the experiment to proceed realistically. We invented riddle-like defect tasks for which the architects in the office had to figure out the defect information such as text descriptions and digital images sent by the inspectors on the construction site. For each session the lists of three specific defect items such as a wall, a door and a window were given to the inspector. Each defect item included several features to be found. These defect items were devised to stimulate architects' perception of the defect information. This framework seemed to be the most relevant for the experiment since we could monitor how the defect information was delivered or understood by the other partner according to the three different defect management methods. In the paper-based session, only text descriptions of the defects were provided to the architects in the design office, and in the Pocket PC-based session, digital images were provided in addition to the text descriptions of the defect data. For the paper-based session, we made a paper version and a digital version of 'site inspection form'. The former was for the inspectors to record the defect information on site and the latter was for the secretary to put them into the database. Through the vertical screen and horizontal surface of the digital workbench, the designer in the design office can view the defect images superimposed on a 3D CAD model as well as the text descriptions.

Experiment Process

Prior to the experiments, by request of the University's Human Ethics Committee, the participating subjects were provided a 'subject information form' regarding information about the experiment. However, no indication was given to them of the hypotheses that would be tested. In accordance with policies of the University's Human Ethics Committee, all subjects completed and signed a 'subject consent form' allowing us to utilise the recorded data and reproduce the results in the form of reports and papers, provided their anonymity was preserved. The defect information they would expect in the sessions was given and the procedure of the experiments was explained to the participants together. The participants were given time to practice using the systems and related software in the training session, which was assisted by each experimenter individually. They were asked to work on a defect management task collaboratively for each session and completed a post-questionnaire at the end of the experiment. Each pair performed the three sessions in one day and no time limitation was allotted to the participants for performing their defect management tasks. In the paper-based session, the manually transcribed sheets were typed by the experimenter in an Excel database and printed out and then delivered to the architects in the design office. Two types of questionnaires were provided as the subjective measurement because the participants' experience might be different according to their roles in collaboration. Each session was conducted simultaneously in the two simulated places.

4.2.4 Analysis and Outcomes

For the data collection, we used three methods: observation, video recording and questionnaire. The first two methods are concerned with objective measurement that address the issue that the telematic digital workbench deploys a more efficient and less time-consuming method to collecting, transmitting and visualising & documenting defect information. The questionnaire is concerned with participants' subjective perception of their experience using three different defect management methods.

Observations

This section describes the observations of the three sessions in the two simulated places in order to provide the overall understanding of the task performance and participants' behaviours rather than detailed analysis of the defect management process. The results are shown in Table 4.

Table 4. Overview of the Task Performance

	Session	**On site** (recording)	**Input/ docking** (transmission)	**Office** (reviewing)	**Total time**	**Answer** (accuracy)
Exp 1	Paper-based	20 mins	16 mins	15 mins	51 mins	1 correct/ **2 incorrect**
	Pocket PC	27 mins	10 mins	8 mins	45 mins	3 correct
	Telematic	24 mins		12 mins	35 mins	2 correct/ 1 incorrect
Exp 2	Paper-based	12 mins	14 mins	7 mins	34 mins	3 correct
	Pocket PC	16 mins	14 mins	8 mins	39 mins	3 correct
	Telematic	14 mins		13 mins	22 mins	3 correct
Exp 3	Paper-based	13 mins	14 mins	25 mins	53 mins	**3 incorrect**
	Pocket PC	23 mins	10 mins	12 mins	45 mins	2 correct/ **1 incorrect**
	Telematic	20 mins		15 mins	33 mins	3 correct
Exp (average)	Paper-based	15 mins	15 mins	26 mins	46 mins	
	Pocket PC	22 mins	11 mins	9 mins	43 mins	
	Telematic	19 mins		13 mins	34 mins	

The recording time in inspection for the paper-based session was shortest because the inspectors are most familiar with the paper-based method and they did not need to spend time in manipulating new input devices. Inspectors noted the defects' location on the drawing first and then finalized text descriptions in the defect information sheets. The average time to describe each data in the paper-based session was around 4 minutes whereas the average time for recording using a Pocket PC or a mobile phone was around 7 minutes.

Although the transmission process for the paper-based and pocket PC-based methods were shorter than they would be in a real situation, the total time taken for the telematic workbench session was still shortest among the three methods due to the synchronous communication between the construction site and the design office. For an additional transmission process, the experimenter inputted the defect data into database in the paper-based method, and the inspectors docked the Pocket PC to PC, downloaded and emailed the defect data to the design office in the Pocket PC-based method. The experimenter has no design background, which was planned for simulating the data input by a secretary in a real situation. As expected, there were several input errors in the paper-based session, which might cause the architects' to misunderstand the defect information. For example, the inspector transcribed 'brick wall alignment is out by 12 degrees…', but the experimenter inputted 'alignment' as 'assignment'. The inspector said 'height of wall does not extend to the ceiling', but the experimenter typed 'extend' as 'extact' incorrectly. The experimenter with no expertise found it hard to understand the inspectors' handwriting correctly.

In terms of accuracy, architects in the design office produced more incorrect answers in the paper-based session compared to the other two sessions. They were confused which parts the other inspectors described as defects since the descriptions of defects did not provide sufficient information. This could be caused by the experiment's input errors or no digital image of the defect information in the paper-based session. Table 4 shows that the time taken to review the defect information in the telematic workbench session is longer than that in the pocket PC-based session. However, the real time taken for the review and rectification in the telematic workbench session was only 2 minutes for each item since the visualisation of the defects in a 3D view of the CAD system helped the architects figure out the defect information. The time shown in Table 4 included the waiting and checking time for the defect information from the workbench. Further, the reason for the incorrect answer in the telematic workbench session is that the inspector captured a wrong photo of the item, so the architect was not able to produce a correct answer for it.

Figure 10. Paper-based, Pocket PC-based and Telematic Workbench Sessions On-site

Analysis of Post experiment questionnaire

We investigated subjective rankings of the participants' impressions on productivity and workflow, and how well they collaborated with their partner through the post questionnaire. The questionnaire was categorized into four groups: perception (3 questions), performance (8 questions), collaboration (3 questions) and suggestions & comments regarding defect management processes, tools and applications (5 questions). The perception and the collaboration categories were given to only designers in the design office. The others were provided for all of them. Each participant rated the three methods for defect management by marking with a cross at the position along the five scales. We gathered the responses of each question directly from three pairs of participants, and synthesized the average results to identify common perceptions and trends.

Perception

The perception category represents users' attending to visuo-spatial features of the defects. We investigated architects' perception of defects, global spatial relations and local spatial relations while they were reviewing the defects. For example, if they noticed a defect in the context of the whole of the building, this could signal their perception of a global relationship. On the other hand, if they understand the spatial relationship between the defect and immediately surrounding building elements, this can be their perception of the local relationship. We expected that their perceptive ability for spatial knowledge would be different according to the available displays for visualization. Figure 11 shows the levels of their perception for three sub-categories.

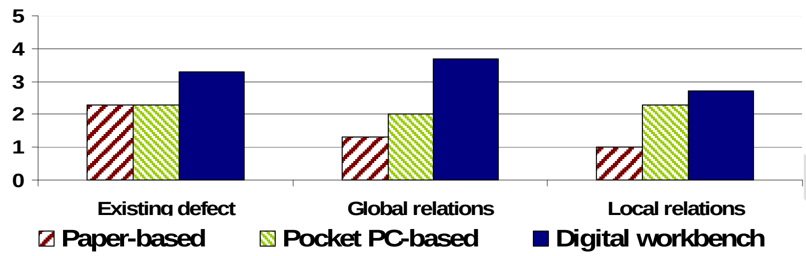


Figure 11. Perception: Office

Compared to the other two methods, in the digital workbench method they exhibited higher levels of perception. The next is the Pocket PC-based method with digital images. This result indicates that media-rich and interactive systems for visualization of defect information may stimulate the architects to perceive more defects and spatial relationships when reviewing.

Performance

The performance category represents the defect management process brought by the systems. Participants' evaluation for the performance was investigated in terms of positive and negative aspects. The positive aspect includes 'ease of use', 'efficiency of the defect management process', 'integration into construction workflow', 'representation of defects' and 'satisfaction with performance'. Figure 12 and 13 show the results of inspectors' evaluation and architects' evaluation respectively.

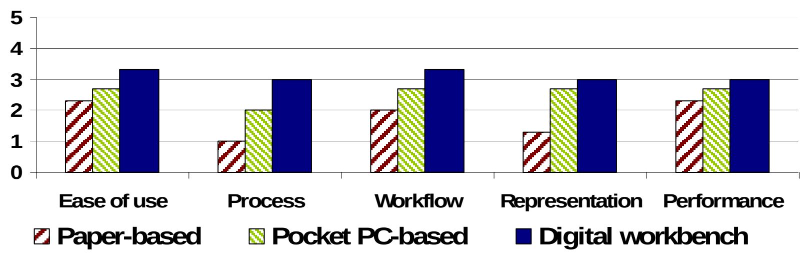


Figure 12. Positive Aspects of Performance: Site

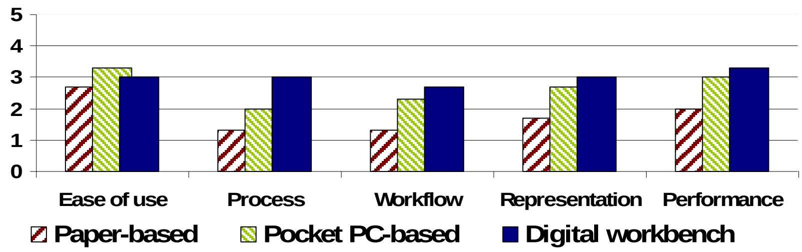


Figure 13. Positive Aspects of Performance: Office

Inspectors used different input devices such as a pen and papers, a mobile phone and a Pocket PC. They had a more positive attitude to the digital workbench method. Similarly architects evaluated the performance of the digital workbench method more highly than the other two methods except a sub-category 'ease of use'. The unfamiliarity to the digital workbench may affect their evaluation regarding the ease of use. The above positive results are consistent with the high percentages of architects' correct answers in the digital workbench session. Figure 14 and 15 show the results of inspectors' evaluation and architects' evaluation respectively in terms of the negative aspect.

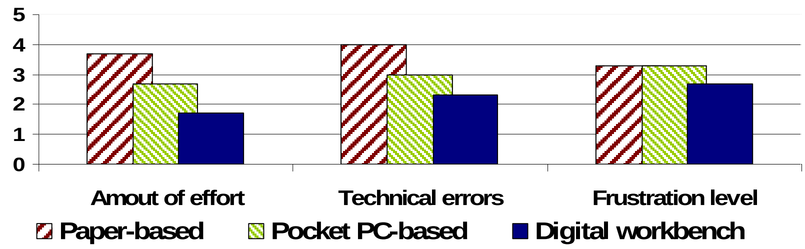


Figure 14. Negative Aspects of Performance: Site

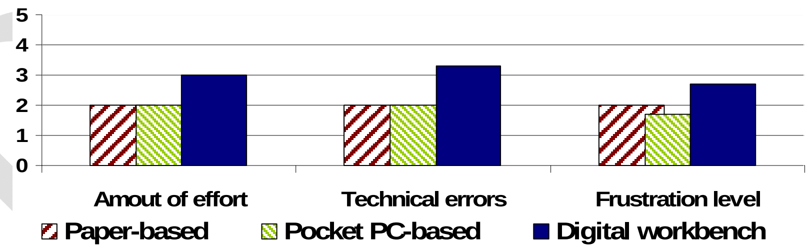


Figure 15. Negative Aspects of Performance: Office

Contrary to the result of the pilot study, while using a mobile device for recording, inspectors put less effort, produced less technical errors, and were frustrated less time compared to the other two methods. These might be caused by the recruitment of constructors who are good at text input in the mobile phone. We interpret the above findings that the telematic digital workbench is more efficient for the recording process from the inspectors' perspective compared to other methods. On the other hand, architects committed more errors and experienced higher levels of frustration when using the digital workbench. These are consistent with their answer regarding 'ease of use' for the digital workbench.

Collaboration

The collaboration category represents the communication on the defect information between the inspectors on site and the architects off site. This category was measured only from architects' perspective and the focus was on how architects understood the defect data made by inspectors. The category was divided into three sub-categories: 'speed of decision-making in fixing defects'; 'ease of communication with the other partner'; and 'effectiveness of collaboration with the other partner'. Figure 16 shows architects' evaluation. Compared to the other two methods, architects' evaluated the collaboration using the digital workbench method more highly than the other two methods, which is similar to the results of the perception category.

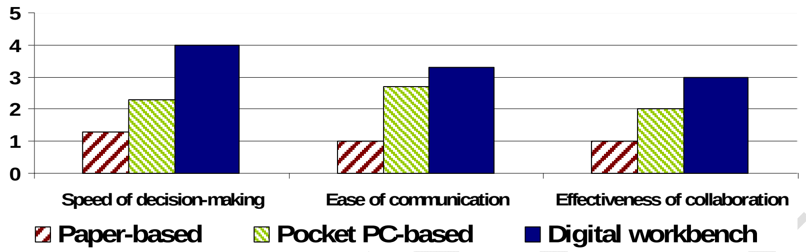


Figure 16. Collaboration: Design Office

Suggestions & Comments

Participants expressed their opinions for the following five open-end questions: 'relevant context for the defect management systems'; 'frustrating features'; 'promising features for effective defect management'; 'promising features for effective collaboration'; and 'any comment on their experience regarding defect management processes, tools and applications'.

In terms of the relevant context, inspectors and architects expected that the Pocket PC-based and digital workbench systems may be helpful for managing larger projects, specifically sites far away from the office, whereas the paper-based method suits much smaller projects that need little time or funds to set up for a short duration. Inspectors said that the stylus allows easier data entry for people rather than the mobile phone and architects agreed that the 3D modelling view in the digital workbench is helpful to assist in describing issues.

In terms of frustrating features, inspectors complained about disorganising defect description and handwriting styles that may cause misunderstanding of the defect information in the paper-based method. They also pointed out the problem of time and level of detail to capture the defect. In the Pocket PC-based method, inspectors said that having to repeat the configuration for each data entry was frustrating. For the telematic workbench method, inspectors complained about the painful typing on a phone and the small size of keyboard. Architects complained about technical errors and poor quality of photos as frustrating features. They said that the defect locations when indicated in the ArchiCAD model were not very precise, so it was hard to understand them.

In terms of promising features for effective defect management, inspectors recommended voice annotation in addition to typing for the Pocket PC-based method and the digital workbench method. They proposed that the recording process needs to be simplified in the Pocket PC-based method by limiting to capture only the necessary field and using the wireless network instead of docking using PC. Architects said that the ability to locate defects on plan precisely rather than by zone is necessary for the telematic workbench method. With regards to promising features for effective collaboration, architects proposed that the ability to edit the photos on site to more clearly demonstrate the defect is necessary. Finally, participants concluded that the digital workbench is easier to use and a very satisfactory collecting tool for the defect management in the comment category.

4.2.5 Conclusions

The case study presented a telematic digital workbench incorporating mobile computing, wireless communication and a horizontal table-top interface for the defect management. We assumed that the real-time sharing of defect data between a construction site and a design office in the telematic digital workbench may reduce the time taken, human errors, misunderstanding etc. In order to explore the potentials and constraints of the digital workbench, a comparative case study was carried out using three pairs of constructors and architects. Through the observations and the analysis of the post-questionnaires, we found that the participants' perception, performance and collaboration are different according to the defect management methods. The inspectors using the telematic workbench method exhibited the following behaviours than the other two methods:

- more 'ease of use', 'efficiency of the defect management process', 'integration into construction workflow', 'representation of defects' and 'satisfaction with performance'; and
- less effort, errors and frustration experience

Compared to using the other two methods, the architects using the digital workbench method exhibited the following behaviours:

- higher levels of perception of the defects such as existing defects, local spatial relationships and global spatial relationships;
- more 'efficiency of the defect management process', 'integration into construction workflow', 'representation of defects' and 'satisfaction with performance';
- more effort, errors and frustration experience; and
- faster decision-making in fixing defects, easy communication and effective collaboration with the other partner

The total time, the data transmission time and the defect review time in the digital workbench method were less than those of the other two methods while the recording time in inspection for the paper-based session was shortest among the three methods. In terms of misunderstanding, the digital workbench and Pocket PC-based methods produced less wrong answers compared to the paper-based method due to the automatic data input entry. All above results show that the telematic digital workbench is effective in both time and accuracy for defect management and site-office collaboration, and produce more effective performance and process.

5. CONCLUSION

The report marks the completion of the CRC for Construction Innovation research project No. 2002-057-C. The project has served to demonstrate the successful practical application of pervasive and mobile computing in the realistic context in the construction industry and also the use and development of intelligent rooms based on sensed environments and new human-computer interfaces for collaboration in the design offices.

A defect management software application to support case studies was developed. The software application allowed users in the field to remotely communicate defect data to its main office through a wireless mobile network by capturing digital images of a defect, location and description of the defect, and also the responsible organisation for the defect. Digital workbench system consisting of a Smartboard touch screen as the horisontal table-top work surface and a large-scale flat-screen monitor as the vertical display mounted across the horisontal work surface was developed for displaying 2D design drawings and 3D views, respectively.

The case studies have described the possibilities of the real application of pervasive and mobile computing devices in the construction industry that promised significant benefits in challenging construction defect management. The most significant benefits were the devices' ability to provide construction personnel with real-time access to relevant information at the construction sites, and to send real-time information back from sites to the appropriate decision makers.

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