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Using a real time integrated communication system to monitor the progress and quality of construction works

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CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

LEUNG Sze Wing

Abstract

The endeavor of this thesis focuses on designing a monitoring system to provide a cost-effective solution on quality assurance for construction projects. The construction site monitoring system integrates a long-range wireless network, network cameras, and a web-based collaborative platform. The users of the system could obtain the most updated status of construction sites, such as behaviors of workers, project progress, and site events anywhere with Internet connectivity. It was carefully configured in order to maintain the reliability under the reactive conditions of the construction sites. This thesis reports the architecture of the monitoring system and reviews the related technologies. The system has been implemented and tested on two construction sites and promising results were obtained.

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Chapter 1

Introduction

Quality control represents increasingly critical concerns for the practitioners of the construction industry. The aim of it is to provide a product quality that is satisfactory to the stakeholders of different parties, compliant with the recognized standards in the industry, completed on schedule, within budgets and so on. Research reports show that up to 12.4 percent of construction cost is wasted due to rework of defective components detected late in the construction phase (Burati et al., 1992; Josephson and Hammarlund, 1999). In the worst case, some defects may cause injuries or fatalities. Even with minor defects, re-construction may be required and facility operations impaired. Increased costs and delays are the result. Indeed, most construction defects are related to human factors such as unskilled workers or insufficient supervision in construction projects (Atkinson, 1999; Opfer, 1999). Therefore, the faster and more information of site activities and worker behaviors the project stakeholders know about, the higher possibility to avoid undesirable outcomes. If project team members could obtain the site information instantaneously, it is believed that some human errors could be prevented.

Therefore, one of the indispensable procedures in assuring construction quality may be site monitoring. It does not only minimize construction defects and human errors but also supports project team members making strategic decisions like contingency plans at critical points throughout the construction phases. In practice, quality control procedures are conducted by the contractor, client's representative or consultant. They have to ensure the quality of materials and work on site is in accordance with the agreed specifications and accepted standards. However, due to the limitation of manpower and the reactive environment of a construction site, where unplanned changes to work regularly occur (Ward, 2004), it is rather infeasible to monitor site activities, behaviors of workers and progresses effectively from time to time. Furthermore, the construction industry is widely considered as a fragmented industry such that massive amount of organizations and stakeholders are involved in a construction project. When quality problem is observed, stakeholders from different companies, or even from different geographic locations have to make critical decisions and consolidate a contingency solution as soon as possible. The efficiency of this kind of collaborative tasks intensely relies on the approach of communication. Remarkably, communication difficulties or disorders in construction projects could directly lead to a sharp increase in the volume of unnecessary expenditure, and also affect the progress and quality of the projects (Anumba et al., 1997; Anumba and Evbuowan, 1999; Higgin and Jessop, 2001).

Conclusively, in order to achieve site quality control, the construction industry requires not only a site-monitoring infrastructure, but also an efficient communication and collaborative environment. This thesis presents a cost-effective construction site monitoring system integrating a long-range wireless network, network cameras, and a web-based collaborative platform. The system supports simultaneous user access therefore project team members could view real-time captured images or video of a construction site, discuss and exchange ideas with gadgets such as video conference, text and shared whiteboard at a distance via the Internet. It was carefully configured in order to maintain the reliability under the messy and muddy environment of construction sites. The system has been implemented and tested on two construction sites and promising results were obtained.

The thesis includes the studies on common construction site monitoring practice, rationales of the design of the proposed system, implementation process, difficulties encountered as well as the testing results. This thesis is organized as follows. Firstly it reviews the major technologies used in this study and work that has been done by others. Then it reveals the architecture of the system and the rationales on hardware selection. It will discuss the implementation experience and results in two construction sites. Finally the paper ends with conclusions and future research directions.

Chapter 2

Background and Objective of Research

2.1 Challenges in the Construction Industry

The construction industry is well known as being a fragmented and divisive industry in that multitude of companies, professions, and occupations involved in the construction project life cycle (Kanji and Wong, 1998; Milakovich 1995). As a result, the achievement of building quality inevitably relies on the cooperation, communications, as well as negotiations among the stakeholders, such as the representatives of owners, architects, contractors, subcontractors, suppliers, and so on. The owner perceives a need to invest in a building project then he employs consultants, architects and engineers to start the project. After that, a main contractor will be employed to implement. Indeed, construction projects are becoming increasingly complex and dynamic in their nature (Carr and Tah, 2001). Winch (1987) even criticizes construction projects as one of the most complex of all undertakings. Because of the complexity, there are dozens of factors affecting the success of a construction projects. Chan et al. (2004) identifies the critical success factors from 43 literatures and summarizes them into five categories, namely, (i) project management, (ii) project procedures, (iii) project-related factors, (iv) external environment, and (v) human-related factors. The authors argue that project management is a key for project success, which is also confirmed by other researchers (Hubbard, 1990; Jaselskis and Ashley, 1991; Walker and Vines, 2000; Chiang, 2008). Noticeably, although not mentioned by Chan et al., four of the nine factors under project management category are related to the communication and interactions between project team members; namely (i) communication system, (ii) control mechanism, (iii) feedback capabilities, and (iv) control of sub-contractor's works. As suggested by Jaselskis and Ashley (1991), in order to maximize the project's chance of success, stakeholders should adopt management tools. In this information age, appropriate and adequate use of information and communication technology (ICT) can be an effective tool to facilitate a communication and interaction environment among construction team members.

In construction project management, because of the highly fragmented nature of the industry that caused by geographical distribution of projects team members, the different responsibilities of various parties, and different time to join the construction teams, it has highlighted the importance of communication. Communication difficulties or disorders during the projects process can directly lead to a sharp increase in the volume of unnecessary expenditure, and also affect the progress and quality of the project (Anumba et al., 1997, Anumba and Evbuowan, 1999; Higgin and Jessop, 2001). In Hong Kong, the fragmentation characteristic is perhaps more prominent because of the multiple layers of subcontractors. They are typically very small firms but collectively undertake most of the works. Chiang (2008) suggests that the extent of subcontracting is even larger due to further subcontracting down the stream by subcontractors with or without the knowledge or consent of the contractors or the clients. This kind of partnering relationship may cause quality issues due to the temporary or one-off nature of construction projects, where the project team members may not be familiarized with the competence, especially the practice behavior of each other. In fact, the construction industry is persecuted by some common partnering problems such as ineffective communication, limited trust, and lack of cooperation

(Chan et al., 2004). This kind of adversarial relationship between stakeholders could cause project delays, cost overruns, difficulty in resolving claims, litigation, and a win-lost climate (Moore et al., 1992). Therefore, it could be foreseen that if a party has more knowledge about its partner(s), the some risks could be reduced.

As the construction industry is so complex, the above-mentioned challenges are possibly not the exhaustive collection. However, according to the literature reviewed, one major challenge is the lack of effective communications. Theother one is uncertainty, that is, not havingsufficient knowledge of party and project status. The following two sections will further investigate the said challenges.

2.1.1 Uncertainty and Interdependence

The complex procedures and party relationships may cause inefficiency of operations (Cox and Thompson, 1997) and there is a trend of increase in degree of complexity (Gidado, 1996) that brings negative effects to the industry. For example, by comparing the level of acceptance in adopting new techniques with other industries, Shammas-Thona et al. (1998) argue that the construction industry has failed to adopted quality management techniques that have improved performance in other industries, while Vrijhoef and Koskela (2000) and Cox (1996) believe the supply chain management in the construction industry lags behind others. Gidado (1996) concluded that the complexity in the industry originates from several causes, namely, the environment of construction sites, the quality resources employed, the level of scientific knowledge, and the number and interaction of different parts of the workflow.

"The contractor needs to gauge a price for a project not yet built, for which he may not have seen the detailed drawings, on a site of which he may have no knowledge, and with a labour work force not yet organized" (Hillebrandt, 1974)

Although Hillebrandt (1974) gave the above comment over three decades ago, the situation still exists today. The complexity in the construction industry, according to Gidado (1996), could be divided into two categories. One is related to "uncertainty" and deals with "the components that are inherent in the operation of individual tasks and originate form the resources employed or the environment". Dubois and Gadde (2002) further explain that there are four factors in this category: (1) management is unfamiliar with local resources and the local environment; (2) lack of complete specification for the activities at the construction site; (3) lack of uniformity of materials, work, and teams with regard to place and time; and (4) unpredictability of the environment. Factor (2) and (3) are related to the organization of construction-based records that shared amongst the team members (Beastall, 1998), where the effect of them could be alleviated through the adoption of content management systems or CRM (Craig and Sommerville, 2007). During the last decade, the construction industry has widely adopted the use of IT and the concept of managing projects using web-based technologies is closer to reality than ever before (Nikas et al., 2007) because it could simplify the methods for recording information generated throughout the life cycle of a project (Rankin and Froese, 2002). Stewart (2007) further explains that these systems are capable to reduce the high levels of waste on construction projects usually caused by information that is inadequate, inappropriate, and inconsistent. Although these systems increase the efficiency of storage, organization, and retrieval of construction information and documents, they lack the capability to capture the status of the environment of a construction site instantly. Factor (1) and (4) are related to construction environment – an environment that changes dynamically with project progress, parties involved in, unexpected incidents, and so on. Therefore, an active and instantaneous site inspection mechanism may be required in order to assist stakeholders to acquire site status and make decisions in a timely fashion.

Another category relates to "interdependence" among tasks, and represents the sources of complexity that "originate from bringing different parts together to form a workflow". There are also three factors causing the "interdependence": (1) the number of technologies and the interdependences among them; (2) the rigidity of sequence between the various main operations; and (3) the overlapping of stages or elements of construction Gidado (1996). Simply speaking, in a construction project, stakeholders implement their own parts independently but they have to cooperate with each other in a rigorous workflow. As a result, inordinate amounts of information are not only existed within an organization, but also shared between organizations. Although Inter-organizational information and records management systems are now being used for this purpose (Caldas and Soibelman, 2003), and some researchers believe that an effective information and records management system could solve many of the information related problems (Lam and Chang, 2002; Mak, 2001), over 90 percent of company documentation exists on paper only (Veal, 2001). Loesch and Theodori (2004) further comment that the records and documents are locked in drawers and filing cabinets with no global access to the information contained within. The findings reveal that the industry greatly focus on paper work but the information on papers are rarely shared within organizations. The closed, and to a certain extent, protective practice may lead to another challenge: ineffective / inefficient communication.

2.1.2 Ineffective / Inefficient Communications

In addition to the challenge of complexity, ineffective communication between organizations is another critical factor causing fragmentation. Some researchers argue that the construction industry could be treated as a system (Ozel and Kohler 2004, Dubois and Gadde 2000, Love and Gunasekaran, 1997). Shoesmith (1991) described it as a Temporary Multi-Organization (TMO). To a certain extent, it could be considered as a loosely coupled system (Dubois and Gadde, 2002) because the stakeholders tend to implement their works independently. In other words, the industry strongly relies on localized decision-making and financial control. However, when the construction parties focus on paying the attention to conform their contractual requirements, they are actually informatively and even financially linked with each other. According to Wong and Fung (1999), to a contractor, the overhead or preliminary items of a project only take up about 18 percent of the total construction costs, while 82 percent is represented by materials and services provided by the subcontractors and suppliers. Research also reveals that communication between parties is critical to the success of an alliance (Wikforss and Lofgren, 2007; Hau et al., 2005; Cheng et al., 2001). Nevertheless, in practice, various stakeholders usually handle different stages of the building life cycle independently and overlook the importance of communications, which results in incomplete and loosely-coupled construction processes. Bateman and Snell (1999) reported that only 20 percent of the information passed down the hierarchy from the top management might reach the site workers. The Gartner group also agrees the communications between stakeholders are limited and identifies that the highest level of interaction across organizations generally occurs between the middle level managers in an organization (Alshawi and Ingirige, 2003). Cheng et al. (2001) explain the possible factors of poor communication in the industry may be inappropriate / inefficient / ineffective channels, unexpected communication breakdown, and not having open lines of communication protocols.

In order to tackle the communication problems, researchers suggest that online collaboration tools can facilitate not only easier management of the construction project, but also allows better access and exchange of project records resulting in time and cost savings and streamlining the overall construction processes (Nikas et al., 2007). Moreover, Tai et al. (2009) recommend that the industry should make full use of existing ICT tools to explore the possibility of new organizational forms for the construction project teams and establish a uniform communication standard for construction information across the whole industry. Meanwhile, stakeholders of the industry also perceive the importance of adopting ICT as a communication media. In a study involving a combined group of 22 contractors, consultants, and some industry associations, over 55 percent of the organizations believe collaborative and multimedia applications are vital applications that can contribute to the future performance of the industry (Sarshar and Isikdag, 2004). Unfortunately, in practice, construction professionals are still quite attached to their conventional means of communications such as paper documents (Stewart, 2007). Emails are already considered as the most "sophisticated" use of the ICT for the majority of the construction firms (Bjork, 2003). Samuelson (2002) comments that the lack of effective applications for the core business of the construction industry may be one explanation of the low ICT adoption rate. This is synonymous to Acar et al. (2005)'s suggestion that there is no single "magic" ICT solution for the industry. It implies that the construction industry has the demand of a custom-made ICT solution. A system that is simply “borrowed” from other industries could not gain the applause of the construction practitioners.

2.2 Research Motivation and Objective

The above-mentioned challenges may not be the exhaustive collection of challenges that the construction industry encounters. Instead, they simply represent the most concerned problems in the industry. While there is no panacea to solve all these problems immediately, according to the literature reviewed, a tailor-made system that facilitates a site monitoring function and provides an effective communication channel for project team members may be one of the solutions.

In construction quality management, site monitoring is a critical process that provides information in developing contingency plans and prevents structural disaster to occur. For instance, the rate of defects in construction projects could be minimized if the construction processes are closely monitored and examined throughout the construction stages. Research reports show more than 12 percent of construction cost is wasted due to rework of defective components detected late in the construction phase (Burati et al., 1992; Josephson and Hammarlund, 1999). Indeed, most construction defects are related to human factors such as unskilled workers or insufficient supervision in construction projects (Atkinson, 1999; Opfer, 1999). All these statistics reveal that construction site monitoring and instantaneous actions could enable significant cost saving and avoid project delay. This is particularly important for large-scale projects that involve many organizations coming from different geographical locations. Effective site monitoring, surveillance and communication among project team members become very challenging. Raftery et al. (1998) suggested that the trend of globalization in construction project has resulted in an increase in foreign participation in the construction industries in many countries. And these are mostly developing countries. The challenge is that the stakeholders from different geographical locations need a way to monitor the current status of a construction project, and to effectively communicate among themselves to make timely decisions.

The research in the use of ICT for monitoring purpose is not vey prevalent in the construction industry. As it is not a new technology, a stereo vision system with two cameras was proposed for recognizing bricks (Slivovsky et al., 1996) a decade ago. In more recent literature, researchers tried to combine cameras with robots to identify defective tiles (Navon, 2000) and used digital images to analyze the coating surface of bridges (Lee et al., 2006). In order to obtain large quantities of figures describing the as-built conditions, laser scanners and embedded sensors are the target of research (Foltz, 2000; Tepke and Tikalsky, 2001). The above-mentioned technologies capture site information and data but they cannot visualize what is happening in the site, including the behavior of workers, project progress, or other unexpected events. For the applications in video monitoring, Cheng and Chen (2002) attached a V8 video camera to a tower crane to monitor an erection operation of prefabricated structural components and the video signal was sent to the site office using a coaxial cable. However, there are two drawbacks in this approach. Firstly, it is costly for the data cable installation; and secondly, project members or stakeholders outside the site office could not use the proposed system to monitor the site in real-time.

Conclusively, the research question of this thesis is:

How to facilitate a construction site monitoring environment using information and communication technologies so that team members could view real-time site status and communicate with each other anytime and anywhere?

Therefore, this thesis proposes a system that aims to speed up decision-making process, especially when unexpected site incidents happen. It is because the team members could discuss the monitored results through the Internet instantly. In addition, the system could reduce uncertainties, risks, the complex processes incurred from fragmentation as well as outturn costs. The research plan, design and implementation details of the system are presented in subsequent chapters.

Chapter 3

Research Planning

After the challenges and the objectives are known, the next step is to start the design processes. One of the main objectives of this thesis is to design and implement a cost-effective construction site monitoring system with real time collaborative functions. Stakeholders could monitor a site and meet together not only within the site area, but also at any place with network connection. Since the proposed system allows many users to access it and interact with each user simultaneously, it is essential to involve the users in the design phase in order to achieve higher usability. For a more systemic design and implementation flow, User-Centered Design approach (Vredenburg et al., 2001) was adopted in this study. User-centered design can be characterized as a multi-stage problem solving process that not only requires designers to analyze and foresee how users are likely to use an interface, but to test the validity of their assumptions with regards to user behaviors in real world tests with actual users. In general, the design phase includes four processes, namely, i) Establish requirements and Identify needs; ii) Design / redesign; iii) Prototyping; and iv) Test and evaluate. The relationships between the stages are illustrated in Figure 1.

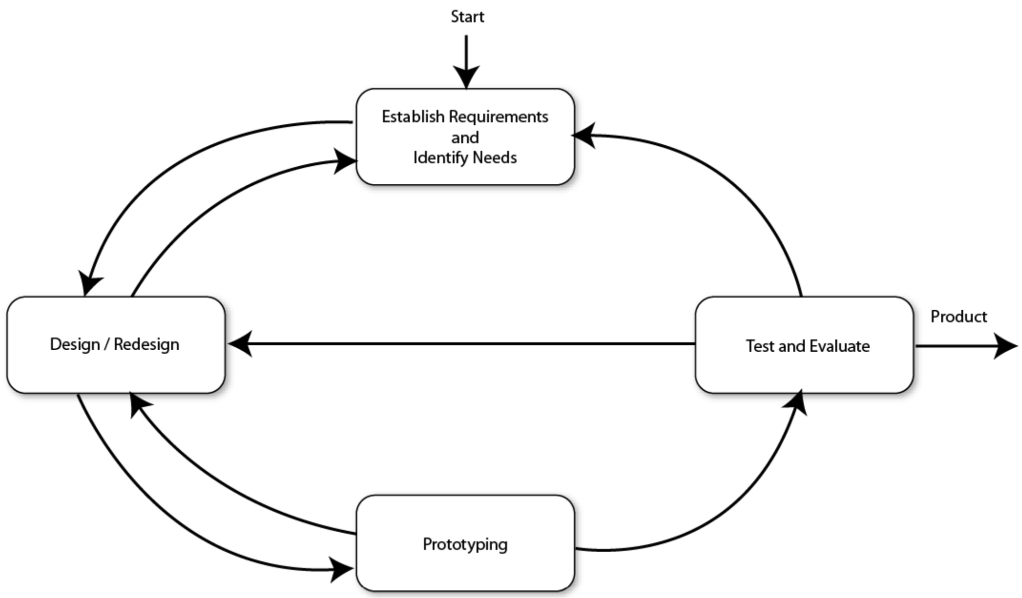

Figure 1. User-centered design model

As shown in Figure 1, the processes of the user-centered design approach are iterative, that is, the flow of a design process may not be unidirectional. In most projects, designers may go through the processes back and forth until a stable and satisfied design is obtained. It is called "user-centered" because the process involves the potential users who will ultimately use or intend to use the system (Vredenburg et al., 2001). This chapter focuses on establishing requirements and identifying the needs of the stakeholders.

3.1 Identify Needs and Establish Requirements: users' view

There are various kinds of requirements such as functional requirements, data requirements, environmental requirements, user requirements, etc. Usually some of the requirements are provided by users but most users do not know exactly what they want and have fewer ideas about what the product concretely looks like. They often have rich abstractive ideas in mind and thus the designers of a project have to "establish" the requirements together with the users before going through the actual design processes. Therefore, before system design, semi-structural interviews were conducted with the practitioners of the construction industry, including owners, contractors, engineers, and IT supporting staff in order to collect their expectations and user requirements. Suppose there is a system that allows project team members to monitor site activities, according to the interview scripts (Appendix), they wish the system to:

1.) allow them to keep their eyes on different parts of a construction site;
2.) let them focus on a particular region so that they can take immediate actions before an unexpected incident happens;
3.) be able to use the system anytime and anywhere;
4.) provide a clear image, especially at night, to act as a security surveillance system;
5.) be able to archive the monitored results for future / further reference;
6.) provide a user-friendly interface (some of the subjects raised a concern that some people in the industry are still not keen on computing);
7.) be inexpensive; although the subjects usually could not tell their willingness to pay because they have never tried any similar solution before; and
8.) be technologically secure to ensure the system only allows authenticated users to access;

Based on each of the expectation or user requirement, a list of system requirements is established as followings:

A.) The effective viewing angle of the system should be large enough in order to cover the entire construction site area. In other words, it provides a “bird’s view” of a construction site.

B.) In addition to a bird’s view, the system can concentrate on part of a site and let the users monitor an activity in detail. Technically speaking, the viewing angle is smaller but a closer image is obtained.

C.) The system works stably, reliably and continuously in a 7x24 fashion.

D.) The optical quality of the system is good enough in order to maintain a good quality image source and in particular in low light environment. Moreover, during image transmission, the image quality should not be distorted too much. Therefore the image compression rate and the bandwidth of the transmission media are the critical considerations of this requirement.

E.) The system has to have a mechanism for storing a large amount of images and log data. They should be accessible by the users easily.

F.) The system should be easy to use, including the installation. The interface of it should be very similar to popular computer applications, such as a web browser. The aim of this requirement is to make minimize the need for user training.

G.) The system has to be innovative but it is not essential to use the components that are the most technically superior. In fact, mature and second-superior components are dramatically cheaper. Most importantly, they are more stable and reliable.

H.) Secure measures should be taken, both physically and digitally. The hardware, especially the one that stores archived results should not be placed in a location that is reachable by unauthenticated parties. Also, all data transfer through the network should be encrypted.

3.2 Identify Needs and Establish Requirements: system designer's view

From the view of the users, they are more concerned about the functions of the proposed system rather than the implementation difficulties. There may be some system requirements that are induced from the use environment, technology limitations, component integration, etc. Therefore it is essential to figure out more system requirements before designing the system.

The fundamental difference of the design consideration between a construction site monitoring system and an ordinary surveillance system is that the former works in a relatively reactive area, where the stability of the system is probably influenced by external factors such as weather conditions (temperature, humidity, rain, wind, etc.), dirt, and even flying debris. Therefore:

I.) The system should be protected by durable and sturdy material, especially for the components that are located outdoor and within the construction site.

Another major design concern is the cables of the monitoring system. To site workers, any visible cable could cause disturbances such as safety and performance issues; to the monitoring system, a single and small defect of a cable could cause the entire system malfunctioned. Most importantly, the existence of cables makes the relocation of the system costly and problematic. For example, along with the progress of a building project, the number of floors built increases with time so that part of the system has to be repositioned in order to maintain the viewable area. The long cables that link between the components definitely introduce cable-fixing and signal attenuation issues. Take 100Base-Tx, still a common Fast Ethernet connection standard nowadays, as an example, the maximum segment length of the network cable is just 100 meters (IEEE, 1995). This may be too short for connecting the components that are far apart within a construction site (e.g., between the roof of a building and site office). Adding a repeater between two segments is a solution but it causes more problems in cabling, as a repeater requires power supply. Therefore:

J.) The system should use as less cable as possible. The cables could not be too long and should be protected in order to decrease the probability of defection.

There are ten requirements (A-J) gathered before the system design stage. As depicted in Figure 1, this set of requirements may not be the final and stable one and it may need further refinements after the design stage.

Chapter 4

System Design

This chapter describes the design process that is based on the ten requirements specified in the previous chapter. Through analyzing the requirements, related technologies are studied with literature review. On one hand, some of the technologies are commonly adopted in the construction industry and have proved to be working reliably in construction sites such as local communications using wireless networks. On the other hand, some of the studied technologies could not be found in the literature of the industry, such as the use of unidirectional and omni-directional antennas to solve the cabling problems.

4.1 From Requirements to Technologies

4.1.1 The Internet

The proposed system aims to facilitate an environment for users to monitor site activities anywhere and anytime, which is also one of the user requirements. Obviously the Internet is a convenient and economic solution because it is maturely developed and is accessible by the public at a very low cost. Recently, a concept of how the Web and its associated technologies can be used to manage construction projects has attracted much attention by construction practitioners (O'Brien, 2000). Moreover, Engineering News Record (ENR) in the United States reports that the number of construction firms using web-based project management has risen by 16 percent within year 2001 to 2002

(Hurtado, 2003). It is also estimated that the number of construction firms prepared to set up a web-based system is doubling every 6 months. All these statistics reveal that many construction firms are well prepared to adopt any new web-based applications, in terms of computer equipment and knowledge. It is also implied that the perceived ease of use of a new system by a user may be correlated to the knowledge and experience that the user has. As discussed in Chapter 3, one of the requirements of the system is "easy to use". Therefore the proposed monitoring system is a web-based product, where the users would find it easy to use if they get used to the interface of a web browser. It is noted that although the Internet is indispensable for the proposed system, technical discussion of Internet is left behind in this thesis because the Internet infrastructure is not configurable by users.

4.1.2 Wireless Network

Another critical requirement is to reduce the disturbances that could be caused by cables. Long cables do not only affect the safety and performance of site workers but also the reliability of the system. "Using fewer cables and wires" is a solution but "using no cables and wires" is an even better solution. In practice, current electricity technologies only eliminate power cables of a device that requires little energy, such as a micro-machine. Moreover the distance between the power source and the consumption device must be very short in order to minimize power low during transmission in air (Scheible et al., 2002). Fortunately power cable is not a major concern in this system since it is indispensable in a construction site and power source can be obtained easily. Apart from power cables, another kind of cable is network cable to transmit data. It is relatively inconvenient to ubiquitously connect a device to the Internet within a construction site. Nowadays it is common to have Internet connectivity in construction site, but for site office only. Most importantly, according to one requirement, the effective viewing angle of the system has to cover the entire construction site area. Under this circumstance, the devices and components such as cameras may have to be separated in long distances. Therefore, using no network or data cables and wires to implement data connections within a construction site may be the one and only one solution in this project.

The use of wireless technology in the construction industry is not uncommon. Researchers of the industry studied several common wireless communication models, such as General Packet Radio Service (GPRS), Bluetooth, and Wireless Local Area Network (WLAN), where their coverage, power consumption, and data bandwidth were compared (Delsing et al., 2004). Ward et al. (2004) implemented a wireless system using WLAN to collect various kinds of data of a construction site such as casing and drilling information. Recently the Radio Frequency Identification (RFID) technology has become a hot topic in information and communication application of the industry. For example, Goodrum et al. (2006) studied the feasibility in using RFID technology to track tool inventory and tested the performance under different temperature conditions. In general, wireless technologies offer a cost-effective solution in connecting heterogeneous network devices and computers because the installation is relatively simple. It is particularly suitable for construction sites since there is no network cable affecting operations and safety.

There are several types of mature wireless technologies available nowadays, including Bluetooth, WLAN, 3G, and WiMax. They can be coexist because they are designed to serve different applications having different constraints such as power consumption, transmission range, speed, radio frequency, and so on. By summarizing the literature reviewed (Scheible et al., 2002; Delsing et al., 2004; Ward et al., 2004; Goodrum et al., 2006; http://www.ieee802.org), they are briefly described and compared in the following paragraphs.

Bluetooth

Bluetooth is a wireless networking standard that provides short-range (about 10 meters) connectivity to electrical devices such as mobile phones, computers and their peripherals, PDA (Personal Digital Assistant), etc. Data is transmitted via small radio transmitter/receivers installed in each electronic device. There are several benefits to using this technology. Firstly, it does away with all the wires, connectors, and attachments needed to connect several peripherals to a computer system - whether a user is using them indoors or on the go. This technology is also easy to use with little user input. Finally, Bluetooth devices need very little power to operate and therefore they are particularly suitable for data transfers among low-powered handhelds where battery life is critical. However, the trade-off is that the bandwidth of Bluetooth connection is only about 1 - 3Mbits/sec nowadays (Version 2.0), which may not be sufficient to handle multimedia data such as images and motion pictures.

Wi-Fi (WLAN)

Wi-Fi is a wireless technology that can support a wireless Local Area Network (WLAN) and provides high-speed access to the Internet with data transmission rates approaching 54Mbps (or higher specified the draft standard). The most popular Wi-Fi standard is 802.11b/g. Wi-Fi networks operate over a limited range within 110 meters. Now almost all laptops and desktop computers come with built-in Wi-Fi transmitters.

Most Wi-Fi access points are run privately within homes or businesses, but there are also numerous public Wi-Fi access points or “hotspots”. According to ABI’s research report (2008), by the end of 2008, global hotspots grew by 40 percent over 2007. Now Wi-Fi is currently available at more than 220,000 public hotspots and tens of millions of homes, corporations, and university campuses throughout the world. Therefore, Wi-Fi is a relatively mature, stable and widely accepted technology, when comparing with other similar technologies.

3G

3G is the third generation of mobile phone network standards and technologies. With 3G, network operators can offer users a wide range of advanced services within a mobile environment including: wireless voice telephony, video calls, broadband wireless data and HSPA data transmission. In contrast to Wi-Fi, 3G networks are wide area networks, which means users can hook up from virtually anywhere with coverage of mobile phone network. This added flexibility, however, comes with a higher price tag and a problem of stability. It is because the connection relies on the services provided mobile phone carriers, which are usually charged on pro rata basis and the bandwidth may be shared with a huge amount of mobile phone users.

WiMAX

WiMAX means Worldwide Inter-operability for Microwave Access. It is an emerging technology that provides high-throughput broadband connections to a large geographic area. Considered the successor to Wi-Fi, WiMAX provides improved performance and usage over much greater distances. WiMAX supports peak data speeds of about 74Mbits/sec, with a transmission range of a few kilometers. Obviously this is an ideal technology for long-range communication and high bandwidth data traffic, but unfortunately, this service is still not available in Hong Kong (up to March 2009).

By considering services availability, data bandwidth and cost (power consumption is a minor consideration because a construction site can provide sufficient electric power easily), Wi-Fi (WLAN) is used as the major wireless solution in this thesis. The standard transmission range of Wi-Fi (110 meters) may not be long enough to be used in a construction site, but with additional components, it can offer a wider coverage area up to several kilometers. Detailed information will be described in Section 4.1.4.
In addition, 3G (or its predecessor, GPRS) is used as an optional connection for ubiquitous site monitoring using mobile phones, more information is revealed in Section 4.2.

4.1.3 Network Camera

For any surveillance system, camera acts as its "eye" and the entry point, that is, the scene being monitored is visually input to the camera. Conventionally the camera outputs the captured images to a display device (e.g., monitor) or / and a storage device (e.g., video recorder). Nowadays some cameras can be connected to computer networks so that the captured images could be transmitted to anywhere via Internet connectivity. Network cameras can be used for very cheap surveillance solutions. The basic hardware requirement for such a system is just one network camera, some Ethernet cabling, and one computer. In this thesis, network cameras are connected wirelessly in order to avoid the annoyance and infeasibility of cables. The still images and video could be shared to any authenticated parties who have Internet connectivity.

Technically, network cameras are analogue or digital video cameras, plus an embedded video server having an Internet Protocol (IP) address, capable of streaming still images, videos (note that a video is actually produced from a sequence of images), and sometimes, even audio. Due to the fact that network cameras are embedded devices that do not need to output an analogue image, the resolution or, the perceived sharpness of a digital camera is often higher than that of a closed-circuit television (CCTV) analogue camera. A typical analogue CCTV camera has a PAL (768x576 pixels) or NTSC (720x480 pixels), whereas network cameras may have VGA (640x480 pixels), SVGA (800x600 pixels) or XGA (1280x960 pixels, also referred to as "mega-pixels") resolutions. An analogue or digital camera connected to a video server acts as a network camera, but the image size is restricted to that of the video standard of the camera. However, optical components including lenses and image sensors, and image compression rate (the lower the better) used in the network camera, are the factors that determine the image quality.

Except the issues of image quality, according to the requirement list, the system should be able to monitor the entire region of a construction site. This requirement is definitely related to the field of view (FOV) of the lens of the network camera. As illustrated in Figure 2, FOV describes the angular extent (horizontal, vertical or diagonal) of a given scene that is imaged by a camera (Guy, 2006). In other words, the value of FOV (in degrees) represents the amount of sight that the user can see at a moment. The larger the FOV is, the more comprehensive view the user can obtain. Ultra wide-angle lenses, also known as fisheye lenses, can cover up to 180 degrees. However a fisheye lens produces an image with a large amount of barrel distortion so the image looks like being mapped around a sphere.

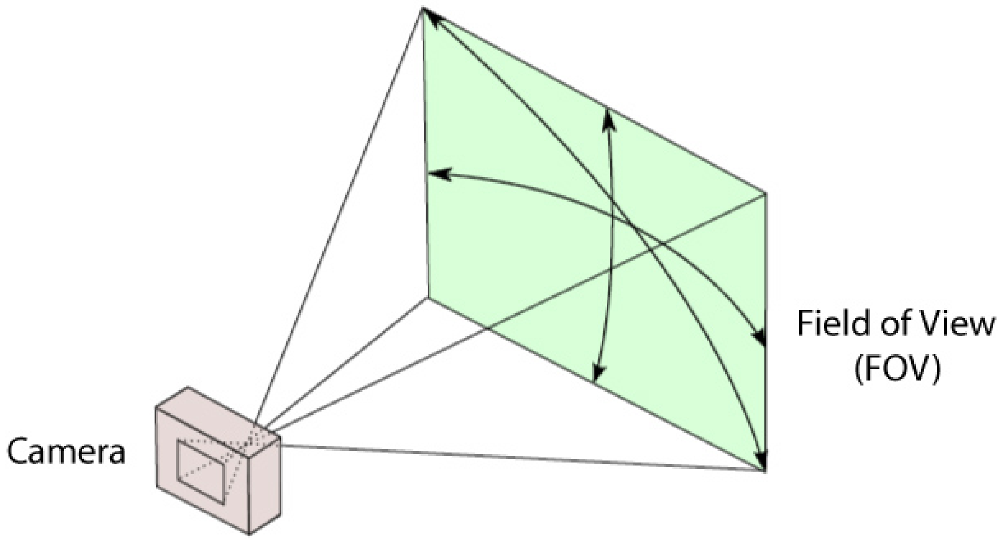

Figure 2. Field of View of a camera

There is always a trade-off between level of detail and comprehensiveness. Another drawback of using a too-wide lens for monitoring purpose is that the users could always have a rough idea about the activities happen in a site but lack of detail information of a specific event. For instance, a safety manager may not be interested to know if all site workers are working hardly. Instead, he may be delighted to know if they are always wearing the necessary safety gears, without walking around the site frequently. Figure 3A and B contrast the image outputs of an ultra-wide lens with approximate 180 degrees of FOV and a standard lens with about 48 degrees of FOV, respectively. It is observed that the ultra-wide one has a barrel distortion and gives an overview of the site while the standard one provides a close-up image view but only focuses on a smaller region.


Figure 3A. Image taken by a fish-eye lens with 180 degrees diagonal FOV

Figure 3B. Image taken by a standard lens with 48 degrees diagonal FOV

In order to enable both overview and a specific view, the camera should have the capability to change its FOV, that is, the zoom function. Nevertheless, it is not sufficient by only employing the zoom function. When the camera is zoomed in (FOV decreased), only a smaller area of the construction site could be seen. In order to view different parts of the site with the FOV is small, the camera must be able to turn around, i.e. pan and tilt. Panning refers to the horizontal rotation motion of a camera on the vertical axis while tilting means the rotation on the horizontal axis, as shown in Figure 4. Noticeably the amount of angular movement of pan / tilt again affects the entire viewable area. Finally, one camera may not be enough to cover the whole construction area, therefore the system should preferably have the capability to attach and manipulate multiple network cameras simultaneously.

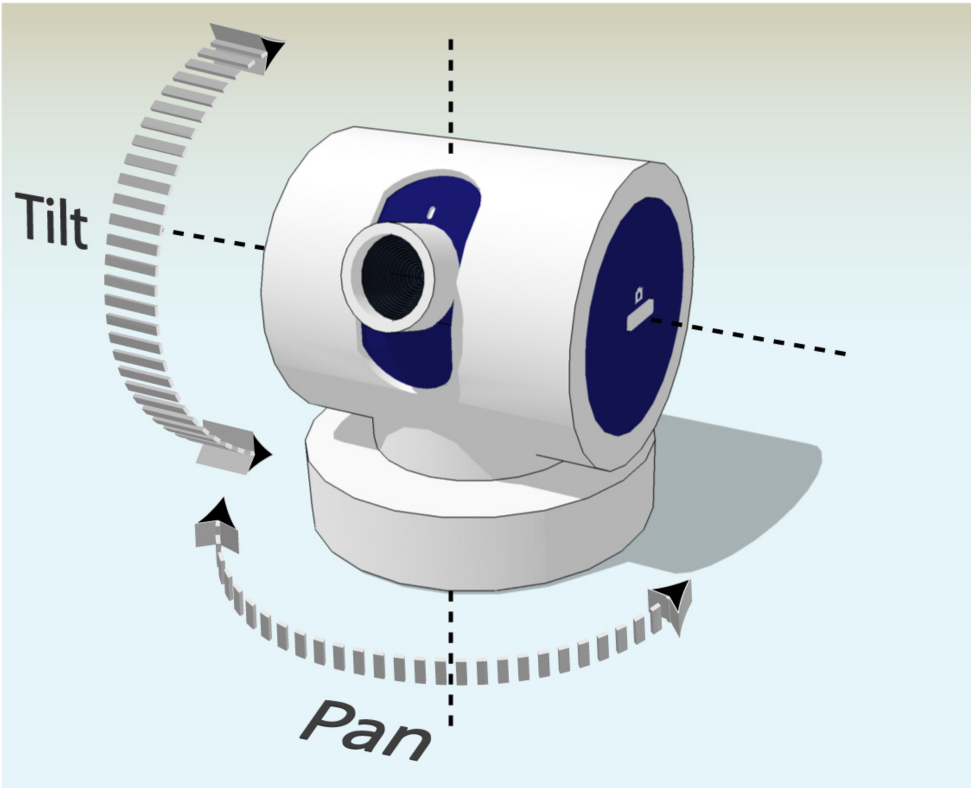

Figure 4. Pan / Tilt motions of a camera

4.1.4 Signal Transmission

As specified in section 4.1.2, in order to minimize the annoyances caused by cables and wires, signal transmissions of the system within a construction site are in wireless mode. Nowadays, the embedded technology of Wireless Local Area Network (WLAN) is based on the IEEE 802.11 standards, which is also commonly known as Wi-Fi (Wireless Fidelity), a brand licensed by the Wi-Fi Alliance (IEEE, 2007). The latest version of the IEEE 802.11 standard is IEEE 802.11n, but it is still under development. Instead, IEEE 802.11**b** and IEEE 802.11**g** are widely used in mobile devices such as laptop computers, personal data assistants (PDA), mobile phones, portable video game consoles, etc. They use the 2.4GHz frequency band, operating legally under the rules and regulations in most countries. Table 1 shows the summary of IEEE 802.11 standards. In this project, Wi-Fi is adopted because it is more cost-effective, faster in transmission speed, and able to offer a relatively long communication distance for network devices, when comparing with several common wireless standards (Delsing et al., 2004). Nevertheless, the standard transmission range of Wi-Fi is still not broad enough to cover most construction site. Take IEEE 802.11g as an example, its outdoors theoretical maximum transmission range is about 110 meters, but the indoor theoretical transmission range dramatically drops to about 35. These figures imply the transmission performance of IEEE802.11 standards is very sensitive to obstacles, while a construction site might be full of obstacles.

Standard	Release Date	Operation Frequency	Data Rate (Max)	Range (Indoor)	Range (Outdoor)
Legacy	1997	2.4-2.5 GHz	2 Mbit/s	~Depends on walls	~75 meters
802.11a	1999	5.15-5.25/5.25-5.35/5.745-5.825 GHz	54 Mbit/s	~30 meters	~100 meters
802.11b	1999	2.4-2.5 GHz	11 Mbit/s	~35 meters	~110 meters
802.11g	2003	2.4-2.5 GHz	54 Mbit/s	~35 meters	~110 meters
802.11n	2007 (draft 2.0) Ratification timeline pushed to late 2008.	2.4 GHz and/or 5 GHz	248 Mbit/s = 2x2 antenna	~70 meters	~160 meters

Table 1. Summary of IEEE 802.11 standards

Therefore it is not very feasible to implement the project by adopting the current Wi-Fi technologies without signal amplification. For the devices that communicate using radio frequency, generally there are two ways to amplify the signal. The first approach is to increase the signal power amplifier by connecting a power amplifier into the existing antenna. The power amplifier, or called "range extender amplifiers", which is a small device that aims to add around half to one watt of power to the antenna. Although these power amplifiers offer a cheap (around HK$1,500 – HK$ 2,500) and minimal setup that can be easily added to any existing network, they need extra power supply and therefore cause the problem of weather proofing. Another drawback is that it gives only about two to three times of range extension theoretically, which is still not strong enough for use in large construction areas.

Another approach is to replace the original antenna with a high-gain antenna. Specially-shaped antennas can be used to increase the range of a Wi-Fi transmission without having to drastically increase transmission power. This low-cost approach allows Wi-Fi signals transmitting over distances of several kilometers by using very simple enhanced antennas while keeping the standard protocols and hardware intact. Two types of antennas can strengthen the signal, namely, unidirectional and omni-directional antennas. Antennas produce a three dimensional radiation pattern, but for purposes of discussion, books and literature often consider only the azimuth pattern (Ward et al., 2004; Carr, 1993). This pattern is as seen from a "bird's eye" view above the antenna. For simplicity, the following paragraphs describe these two antennas in brief with four different signals (A, B, C, and D) arriving from different directions (in actual situations, of course, the signals will arrive from any direction).

Omni-directional Antenna

The omni-directional antenna radiates or receives equally well in all directions. It is also called the "non-directional" antenna because it does not favor any particular direction. Figure 5A shows the pattern for an omni-directional antenna, with the four cardinal signals. This type of pattern is commonly associated with verticals, ground planes and other antenna types in which the radiator element is vertical with respect to the Earth's surface. The key factor to note is that for receivers all four signals (or signals from any direction, for that matter) are received equally well. For transmitters, the radiated signal has the same strength in all directions. This pattern is useful for broadcasting a signal to all points of the “compass”, or when listening for signals from all points. A simple metaphor to describe this operation is that the signal of an omni-directional antenna is like a flame of candle giving off light in all directions.

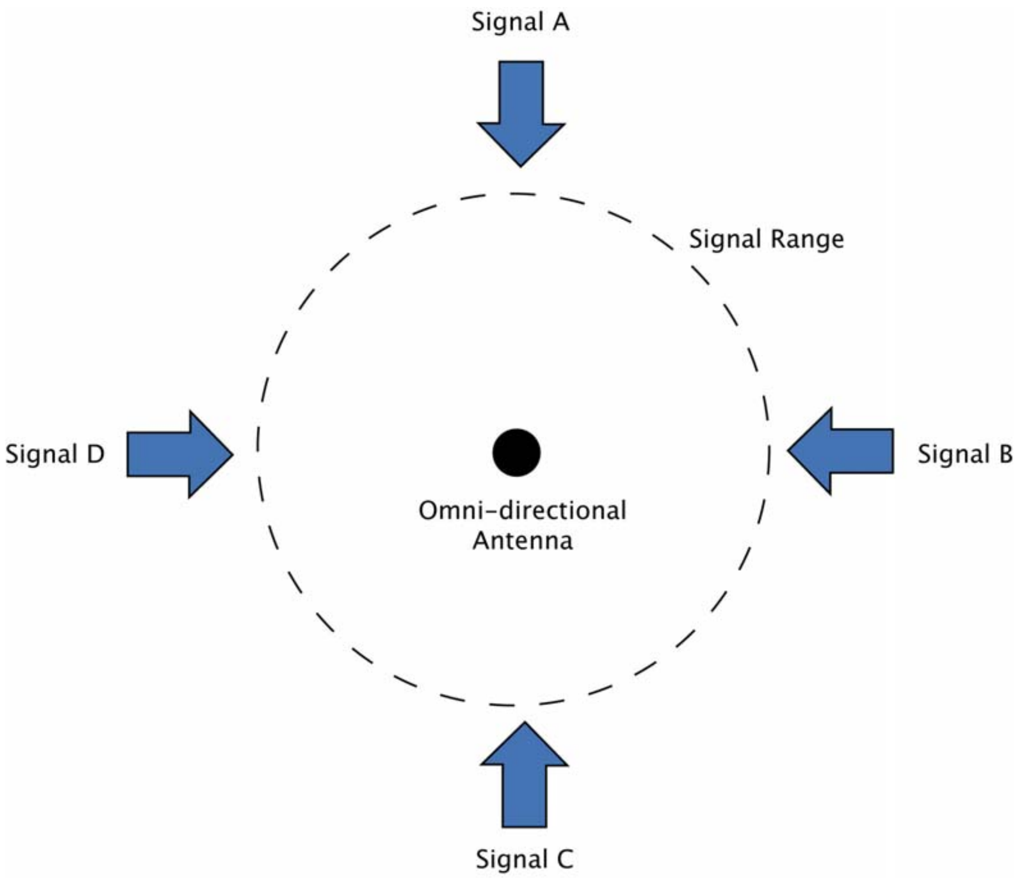

Figure 5A. Signal range of an omni-directional antenna (plan view)

Unidirectional Antenna

If the signal of an omni-directional antenna acts like a candle flame, then a unidirectional antenna works more like an electric torch that gives off light primarily in one direction. It radiates greater power in one direction allowing increased performance on transmission and reception and reducing interferences from unwanted sources. Figure 5B shows a unidirectional signal pattern. The antenna consists of a main-lobe, two side-lobes and a back-lode (Carr, 1993). The main-lobe is the direction with maximum radiation or reception, while the side-lobes and back-lode attempt to minimize the signal. As shown in the figure, only signal A is maximized (pointing to the main-lobe), other three signals are suppressed.

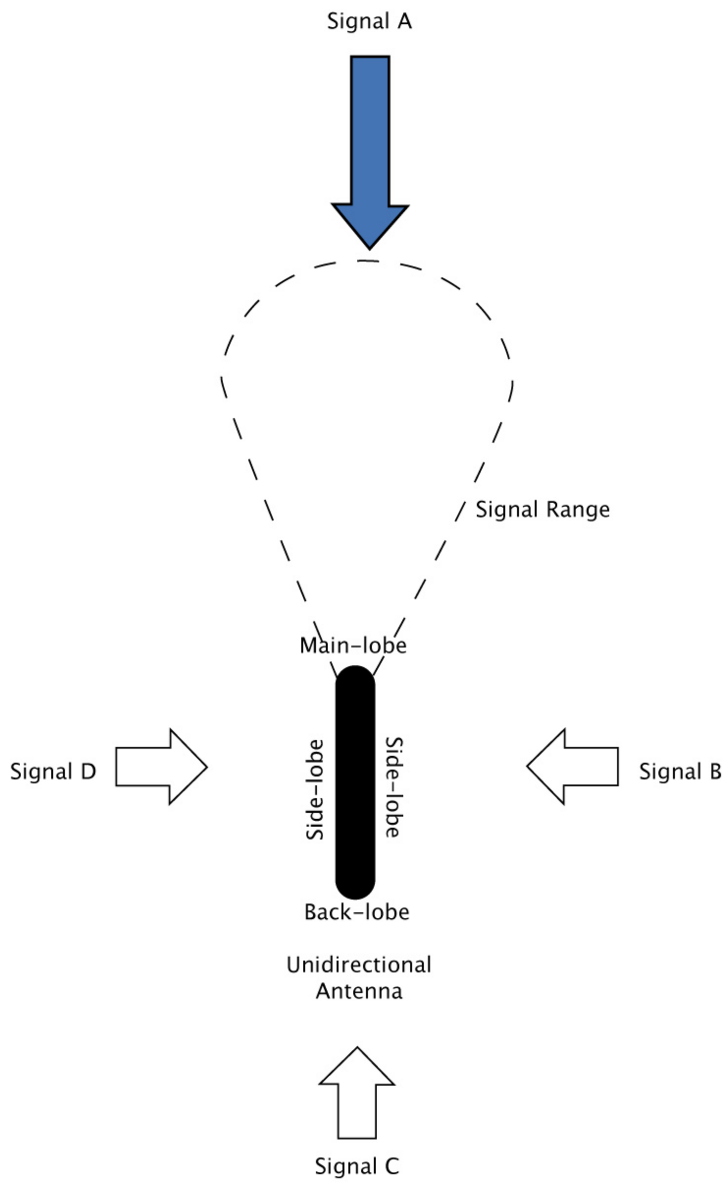

Figure 5B. Signal range of a unidirectional antenna (plan view)

It is noted that the unidirectional antenna propagates signals to one direction, with a restricted azimuth around 12 to 75 degrees (Ward et al., 2004). When comparing with the two antennas, there is no absolute winner or loser. An Omni-directional antenna has a 360-degree of signal transmission / reception region but relatively shorter in range, while a unidirectional antenna has a concentrated and long signal transmission / reception capability. Therefore, when using them together, they could compensate each other's insufficiency and contribute broader application possibilities. As one of the requirements specifies that the system should be able to monitor the entire construction site. In certain circumstances, using one camera may not satisfy the requirement, since obstacles may block the view, as well as the signal, of the camera. To tackle this problem, a point-to-multipoint network infrastructure could be used. That is, to connect two or more cameras to a single reception device (e.g., network router) that distributes the monitoring results to the users, of course, wirelessly. It is not very feasible to use only one type of the antennas. For example, when both the cameras and reception device are equipped with omni-directional antennas, the transmission range may not be long enough for use in construction sites ("candle flame"), although it is not necessary to align the antennas as they propagate the signals in all directions, Alternatively, using unidirectional antennas could overcome the problem of insufficient transmission range ("electric torch light") but it causes a problem of antenna aligning. As a signal of a unidirectional antenna can only propagates in one direction, the reception device can receive one camera output only at a time.

Figure 6 depicts a solution for a long-range point-to-multipoint wireless network. Although the communication range of "omni-*to*-uni" configuration is not as long as a "uni-*to*-uni" combination, it allows several cameras to connect to the reception point. From the perspective of construction practitioners, they may be interested to know the maximum number of monitoring viewpoint there can be. In other words, under this point-to-multipoint configuration, the number of cameras that can operate simultaneously may be a concern to the users. Indeed, this question is tricky to answer because the number is composed of many variables and factors. One of the most prominent factors is the bandwidth of the wireless network. Take IEEE802.11g as an example, its theoretical maximum transfer speed is 54 Megabits per second (Mbps). If each monitoring viewpoint (camera) requires 2 Mbps of data rate, this point-to-multipoint network theoretically supports up to 54 / 2 = 27 monitoring viewpoints. However, the data rate of each viewpoint depends on the quality of images it captures, which is basically affected by several factors such as resolution, colour depth, frame rate, compression algorithm used, etc (Shuman, 2003). In terms of human perception, those factors principally affect the sharpness and fluency of motion of images we see in a computer monitor. Using the quality of video-CD (VCD) and DVD video, the two common video media formats nowadays, as a reference, the video data rate of the former is around 1.2 Mbps, while the latter one requires around 7 Mbps in average. It is important to note the number of simultaneous working viewpoints with acceptable image quality is theoretically calculated under the condition of no signal interference, attenuation, and blockage. In fact, research reveals that the actual performance of wireless network is always below the specification, even operating in an open and less-interfered environment (Wijesinha et al., 2005). Therefore, site tests are required.

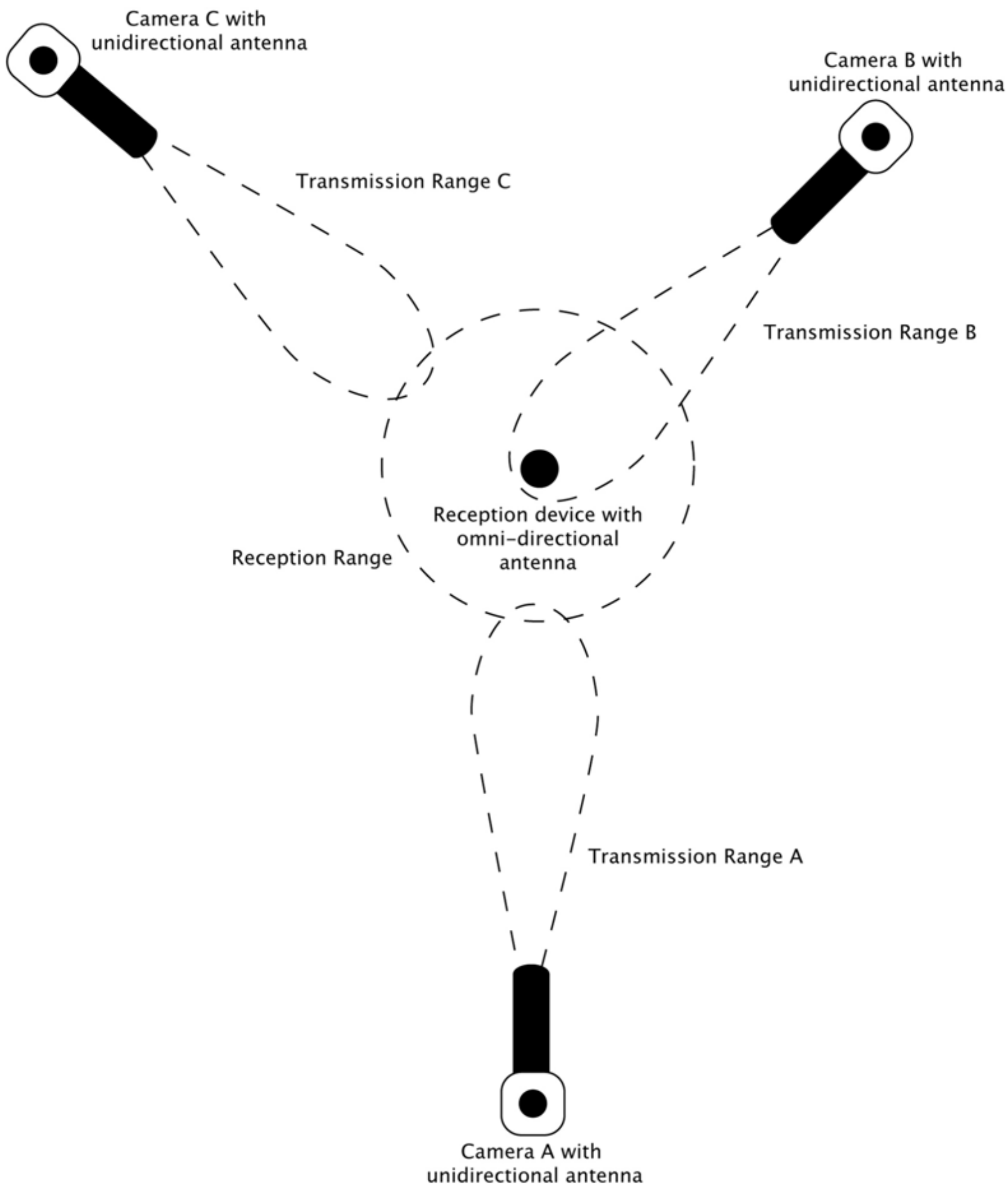

Figure 6. A long-range point-to-multipoint wireless network

4.1.5 Web-based Collaborative System

As mentioned previously, the proposed monitoring system is actually a collaborative system, which not only allows multiple users to monitor the most updated status of a construction site, but also facilities a real-time meeting environment for discussion and making immediate decisions anytime and anywhere. As the Internet interconnects computer devices worldwide, doubtlessly a web-based system is an appropriate and hands-on companion to the proposed monitoring system. The major advantage of web-based systems is that users are not required to install any special software packages. A computer with a web browser, Internet connection and probably a few free-of-charge software plug-ins are suffice. Another important benefit is that it simplifies the establishment of a collaborative environment among project team members. Researchers have been spending efforts to develop project management information systems using ICT (information and communication technologies) for the industry (Rojas and Songer, 1999; Tam, 1999; Deng et al., 2001). Nitithamyong and Skibniewski (2004) summarized and compared the features of commercial web-based construction project management systems. Recently, with the development of mobile devices, project management systems become portable and wireless. For example, Aziz et al. (2004) designed a multi-tier mobile collaboration support infrastructure and Kimoto et al. (2005) implemented a system with personal digital assistants (PDA).

The proposed monitoring system was planned to integrate with a mature web-based collaborative application in such a way that the user interface is very similar to other web applications, that is, users could find the system as easy as navigating a web page. Nevertheless, not all existing web-based collaborative platforms could be feasibly integrated with the proposed system. “Openness” of a platform is the critical consideration for the integration process because when the owner of the platform does not possess the right of accessing the core part (e.g., source code, application programming interface, etc.) of the platform, there is no way to integrate any component to other proprietary systems legally. Another issue is about the degree of customization of the platform. The higher the degree of customization, the more the suitable user interface could be provided to construction practitioners.

4.2. Architecture of the Monitoring System

After studying the major technologies and related components that may be involved in the project, the next step is to design a proper system architecture in order to link all the components together. The system mainly consists of five types of hardware components; namely, (i) network camera(s) (with zooming, panning and tilting features); (ii) wireless routers; (iii) outdoor antennas (uni- and omni- directional); (iv) media/web server (for storage and collaborative services); and (v) client devices. Since a construction site is more of a reactive environment, each component is carefully configured and protected in order to maintain the reliability and performance of the system. The architecture of the system is shown in Figure 7. The system is divided into three parts that include (i) monitoring viewpoint(s), (ii) site office, and (iii) authenticated devices and their functions are deliberated below.

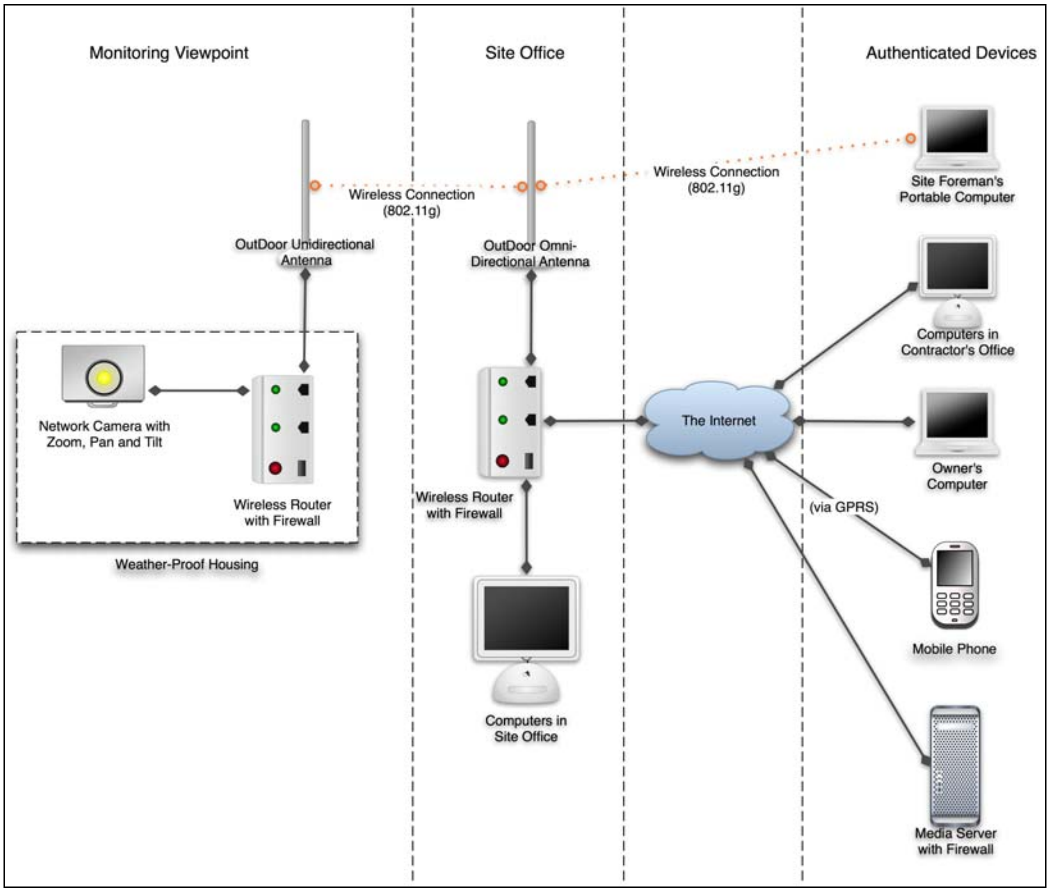

Figure 7. Architecture of the monitoring system

4.2.1 Monitoring Viewpoint

For the location of monitoring viewpoint, the three core hardware components, i.e. a network camera, a wireless router and an outdoor unidirectional antenna are connected using network cable (CAT5 UTP between the router and the camera; coaxial between the router and the antenna) in order to provide image capture and transmission functions. This segment is suitable to be placed above the construction site (e.g., on the top of the mast of a tower crane or the roof of a building nearby) to enable a bird's-eye view of the site. In order to enhance flexibility and provide sufficient viewable angles, a network camera that can zoom, pan and tilt was chosen. The camera used in this study has a 21x optical zoom, pan scans from -175 to + 175 degrees, and tilt scans from -120 to 90 degrees. It employs a VGA (640 x 480 pixels) color CCD image sensor and captures images at a speed of 30 frames per second. Last but not least, the camera has a built-in web server so that the captured image frames can be sent to the Internet through its Ethernet network interface (10-Base-T/100Base-Tx).

Since it is costly to install and maintain an Ethernet connection to the Internet on a tower crane or the roof of a building. To tackle this problem, the network camera is connected to a wireless router using an Ethernet (CAT 5 UTP) cable. The wireless router acts as a transmitter to transmit image data captured by the camera. Another wireless router located in the site office receives the data. A potential technical problem is that the communication distance between the two routers may not be long enough. Therefore, the long-range point-to-multipoint wireless configuration described in the previous section is adopted in order to extend the signal propagation distance. An outdoor unidirectional antenna is attached to the wireless router. According to the specification of the unidirectional antenna used in this project, it concentrates the signal and extends the range up to around three kilometers (assuming two unidirectional antennas are used, one for each router) and it is weatherproofed. It is noted that the unidirectional antenna propagates signals to one direction, with a restricted azimuth around 12 to 75 degrees (Ward et al., 2004), which implies the antenna of the monitoring viewpoint have to be aligned with the receiver’s antenna. The antennas that were used provide a signal gain of 14dB.

Since the monitoring viewpoint is located outdoors, the gears (i.e. the camera and router) have to be sheltered by protection housings. Although there are some weatherproof network cameras available, they were not chosen in this study because they may not be able to survive the dirty and hazardous environment in a construction site and can easily be damaged by flying debris. Instead, some durable, weatherproof and low cost metal cabinets, dome-shaped housings, reinforced plastic containers, and so on are readily available in retail stores in Hong Kong. They could be chosen and modified according to the installation location of the monitoring viewpoint. However, the choice of housing cannot be confirmed during the design stage because test construction site(s) was /were not confirmed yet (details of the housings is described in the next chapter).

4.2.2 Site Office

The ubiquitous Internet makes it easy and sometimes necessary for contractors to install broadband Internet connection in site offices, which is usually provided by telecom carriers using ADSL (Asymmetrical Digital Subscriber Line) technology via traditional telephone lines. Aziz et al. (2006) reviewed the enabling technologies of Web services used in construction sites and some of them require broadband Internet connection for better performance. In this thesis, the site office is installed with two hardware components, that is, as shown in Figure 7, a wireless router and an omni-directional antenna. The wireless router is sheltered inside a metal cabinet with rubber weatherproof sealing. It is connected to the Internet using a broadband network and attached with the omni-directional antenna. An omni-directional one extends the range of the wireless signal at 360 degrees and forms a point-to-multipoint configuration as depicted in Figure 6 (the router acts as the reception device). That means signals from multiple monitoring viewpoints could be received by using a single wireless router located at the site office. Therefore these devices installed in the site office facilitate as an Internet hub for not only all monitoring viewpoints, but also portable end-user devices such as tablet PC or PDA within the construction site area. Although the combination of uni- and omni-directional antennas decreases the communication range to around one kilometer, the range is still long enough for an ordinary construction site.

Even without Internet connectivity, the above configurations allow supervisory staff or site manager to monitor construction operations in the site office. With Internet connectivity, nevertheless, the usability of the system increases tremendously as site conditions and operations can be accessed by stakeholders off-site.

4.2.3 Authenticated Devices

In this study, any device that has access rights to the network camera(s) is considered an authenticated device. Figure 7 shows some authenticated devices such as portable computers, desktop computers, mobile phones, and a media/web server. A user could use different kinds of authenticated devices to access the network camera(s), depending on the access location. For examples, a safety supervisor may zoom and pan the camera regularly by using a computer in the site office to see if there is any implicit risk or malpractice; a site foreman could always have a bird's-eye view of the site by using his Tablet PC within the site area (connected to the wireless router of the site office), which is convenient in observing different construction tasks simultaneously when the site is large; even the owner may be delighted to view the progress of his or her properties anytime, anywhere by using a mobile phone that is compatible with the network camera and with GPRS/WiFi/3G Data connectivity.

The system employs a web-based user control interface and therefore a Web browser is all that is required for manipulating the network camera and viewing the motion image in real-time. As shown in Figure 8, the camera can pan, tilt, zoom and focus by pointing/clicking/dragging the icons in the control panel. The view of the camera is displayed on the right next to the panel and the image size (640x480, 320x240, and 160x120) and quality are configurable by the users. According to the specification of the camera, it supports up to 30 concurrent users. This means multiple stakeholders could monitor a construction site in real-time simultaneously.

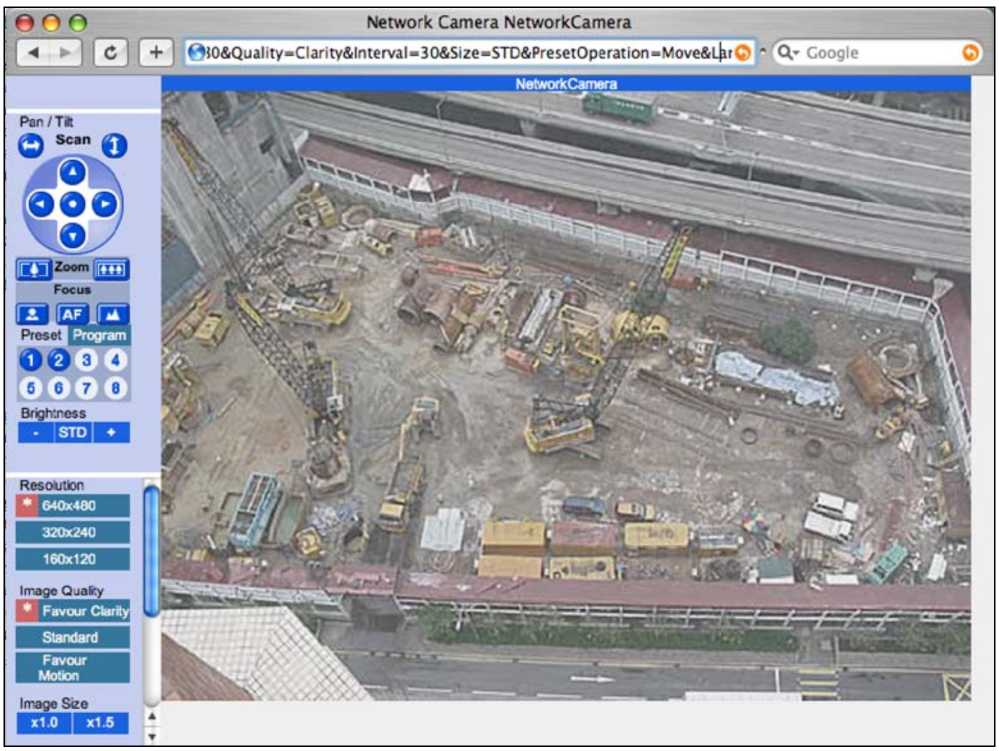

Figure 8. Web-based User Control Interface

Although having the stakeholders to view the progress of the construction is a step forward, it was considered that this is not good enough because the stakeholders are not connected with each other. As a result, they cannot communicate their ideas immediately. Moreover, as they do not always have time to use the system, to monitor a site in real-time is obviously inflexible to them. To rectify the above shortcomings, a media/web server was introduced. This server serves two major purposes. One objective is that it archives captured (still) images and facilities a collaborative environment for different stakeholders. A system administrator could configure the network camera using any authenticated device to capture and transfer snapshots of the site on a periodical basis, say one image per minute. This allows stakeholders to review what has happened in the construction site. For example, the construction manager can propose a solution to the architect or owner by using one of the images stored in the server, or images from similar projects.

Noticeably, by replacing the proposed web/media server with a higher-grade model with video streaming function and more storage capacity, it is technically feasible to record motion pictures (video). However the proposed system is not composed of the video recording feature because the cost, including human resources is too high. An experiment was done to investigate the extra cost for facilitating the video recording feature. Apple QuickTime Pro (http://www.apple.com/quicktime) was used to encode the video output of the proposed wireless camera in MPEG-4 H.264 format, a widely accepted video coding standard with efficient data compression nowadays (Lanfranchi and Bing, 2008; Marpe et al., 2006). The test video is configured with a resolution of 640 x 480 pixels (matches the native resolution of the camera), medium quality (the quality is perceived as between VCD and DVD video), 24 frames per second. It was found that the average data rate of the video is around 1.5 Mega bits per second, therefore for a 24-hour H.264 video recording, 16.2 Giga Bytes (1.5M x 60 x 60 x 24 / 8) storage is required. In other words, a 500-Giga-Byte hard disk drive is just enough to store a one-month monitoring result. Moreover, backing up such a huge amount of data without doubling server hardware cost requires extra daily manual process. For monetary cost, the server that is capable to handle streaming video data was HK$20,000 (excludes maintenance cost) more than the one for storing still images.

The other objective of adopting the server is to facilitate a collaborative environment. A new application called vMeeting was developed to integrate with the camera system, which is an online web-based collaborative platform (http://www.smile-tech.hk/html2/product.htm#vmeeting) to establish an online virtual meeting among the stakeholders synchronously. It was fortunate that the originator of vMeeting is interested in participating this project and agreed to customize vMeeting in order to integrate the proposed monitoring system. The integrated system, as shown in Figure 9, allows users to communicate through video conferencing (using low-cost desktop webcams), browsing archived photos, watching the real-time monitoring view as well as sharing text and drawings. It synchronizes the screens of all participants, that is, all computers show the same real-time monitoring view, archived photo and other information concurrently. As a result, this approach offers an efficient virtual meeting environment, which was considered by some of the users to be better than a conventional face-to-face meeting as the most-updated status of a construction site is available. Major decisions could be made immediately during a meeting, e.g. issuing architect’s instructions when the owner has made a decision on modifications.

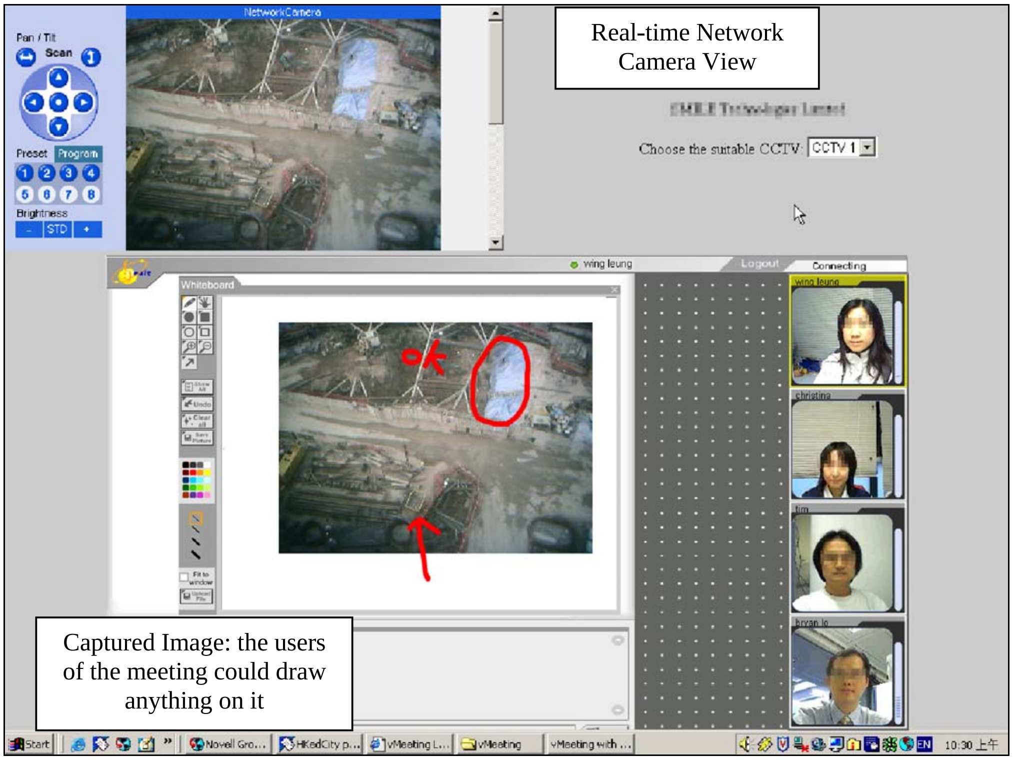

Figure 9. The integrated collaborative environment

4.2.4 Network Security Issues

Since a long-range wireless LAN connection is incorporated in the system, it is unavoidable that wireless signal propagates outside the site area and therefore it is subject to being hacked by malicious users. From the feedbacks of the user, some subjects are also concerned about the security of the system, as they are worried if any unauthorized party could obtain any monitored results.

Wired Equivalent Privacy (WEP) encryption is a popular and common practice to prevent the unauthorized access the network. However, research reveals that using WEP is insecure because by using some commonly available software and equipment, it is indeed not difficult to eavesdrop on WEP-protected networks from distances of a mile or more from the target (Cam-Winget et al., 2003). The latest practice of WLAN security is to use Wi-Fi Protected Access (WPA). One major improvement in WPA over WEP is the Temporal Key Integrity Protocol (TKIP), which dynamically changes keys as the system is used (Wi-Fi Alliance, 2004). Moreover, to further enhance the security level, some researchers suggested disabling the broadcast of the Service Set Identifier (SSID) (Ward et al., 2004). This approach reduces the chance for hackers to discover the existence of a wireless network, unless they know the SSID. In this study, except using WPA and disabling the broadcast of SSID, Media Access Control (MAC) address filter is enabled in the wireless routers. As each network device (includes computer or PDA) has a unique MAC address, the filter is capable to deny the access of any device that is not registered in the wireless router. The registration of a MAC in the router can easily be done. Some routers is capable of reporting MAC addresses of nearby devices and prompts the administrator to set "allow" or "deny" access to each device, without having to key in the 10-byte long hex codes. Using the above security measures, only the registered devices of the project team members are authorized to use the system.

In summary, during the design phase, the following system specifications were drafted in order to fulfill the system requirements established in the previous chapter:

1. The Internet is used to connect the onsite components to off-site components such as computers in contractor's company (fulfills F).

2. Wireless network is adopted for connecting components within a construction site (fulfills J).

3. A network camera acts as the "eye" of a monitoring viewpoint, which features pan, tilt, and zoom functions (fulfills A, B).

4. The outdoor gears of the system are protected by weatherproof housings, the choice of which is dependent on the installation location of the monitoring viewpoints (fulfills I).

5. The combination of outdoor omni – and uni – directional antennas strengthens the signal of the wireless network and enables point-to-multipoint connections of the monitoring viewpoints (fulfills J).

6. A web-based collaborative platform is integrated with the monitoring system, which should have a certain level of openness, in terms of usage permission and the degree of customization. vMeeting was selected because the originator of it agreed to open their platform exclusively for this project. It is installed in a web/media server that stores monitored images as well (fulfills E, F).

7. The data during transmission are encrypted so that unauthorized parties cannot access it (fulfills H).

It is noted that requirement C and D are related to stability and performance and therefore they cannot be fulfilled during the design phase. Requirement G is about the cost of building the system. Whether it is cost-effective or not depends on the construction project scale and the perception of the stakeholders. Nonetheless the price of all components of the proposed design is listed below.

Component	**Quantity Required**	**Unit Price (HKD)**	**Subtotal (HKD)**
Network camera with pan/tilt/zoom	1	7,800	7,800
Unidirectional antenna	1	2,400	2,400
Omni-directional antenna	1	1,750	1,750
Wireless router	2	460	920
Coaxial cable, 5 meters (connecting router to antenna)	2	850	1,700
Antenna wall mount plate	2	530	1,060
Weatherproof cuboids cabinet (protects routers)	2	200	400
*Weatherproof cuboids cabinet with acrylic glass (protects camera)	1	250	250
*Weatherproof dome housing (protects camera)	1	1,200	1,200
**Web / Media Server	1	9,800	9,800
Total Price (using cabinet to protect the camera)			26,080
Total Price (using dome housing to protect the camera)			27,030

* The selection of housings for the network camera depends on the installation location of the monitoring viewpoint
** If using a server that is capable to store movie files, about HK$20,000 should be added to the total price

Table 2. Price of components for one monitoring viewpoint

Chapter 5

Design Justifications

The draft design was then reviewed by the subjects interviewed before. They do not have major comment on the design but they wished to see something more concrete. Fortunately one of the subjects, who is a property owner showed great interest in the proposed system and agreed to share two of his construction sites as testing sites. Although the design supports multiple monitoring viewpoints, the owner was willing to install one monitoring viewpoint per site only. His rationales were that the area of both sites are not large (4,386 and 3,950 square meters respectively) and he wanted to minimize the disruption and discomfort to the site workers, as they may feel that they are being monitored. There is no major revision for the draft design but the installation location of the monitoring viewpoints and their housings had to be confirmed according to the status of the two testing sites. The following sections introduce the two testing sites and the configurations of the viewpoints.

5.1 Design Justifications for Test Site A

The first test site, Site A, is an ideal location for testing the system. It is because the works has just started and the owner owns a completed building, Property P next to Site A. It is ideal because we do not need to install the devices inside the construction site. Figure 10 shows the plan of site A and the Property P. Site A has a construction area of 4,386 square meters and the longest side of it is opposite to P. Since the building of A will be shorter than that of P, it is feasible to install the monitoring viewpoint on the roof of P and point it to A and the owner was pleased to approve this configuration. Indeed, by doing so, a long-range wireless connection may not be necessary because the monitoring viewpoint could use the broadband service inside P. However, in order to test the performance, it was decided to implement the original design (i.e., signal from the roof of P propagates to the site office of A).

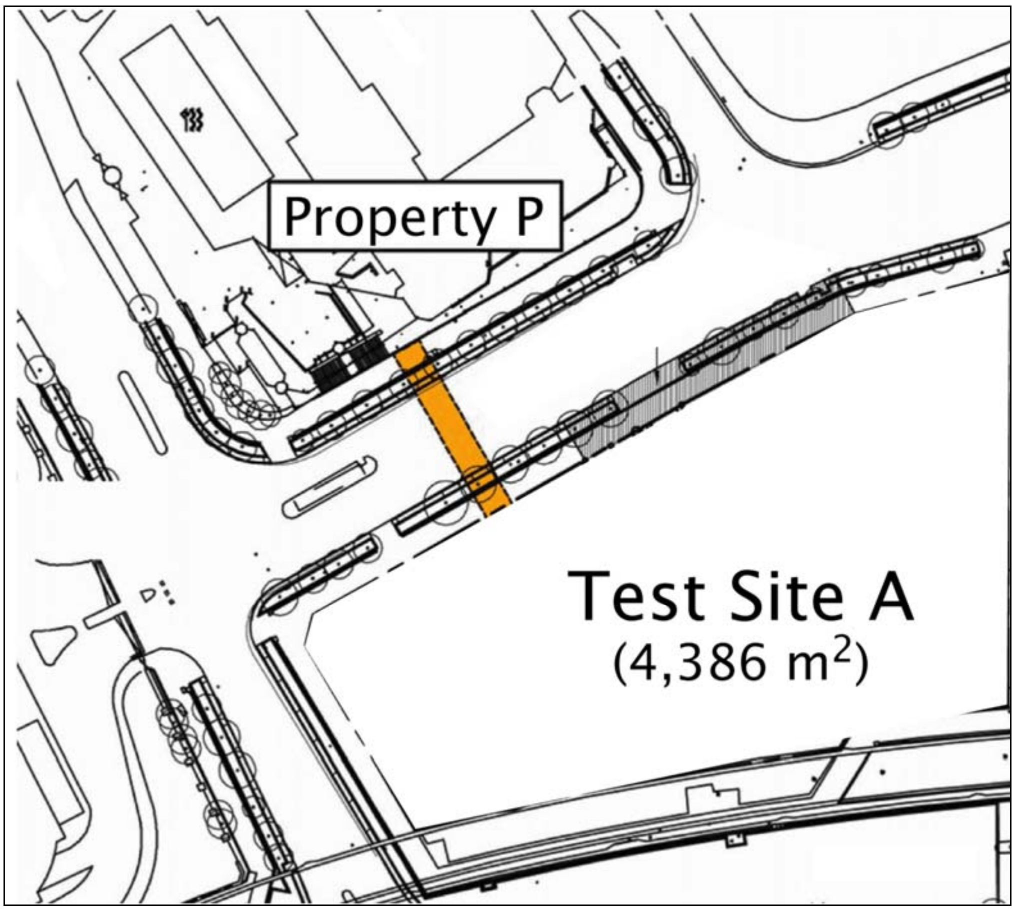

Figure 10. Plan of Test Site A

For the housing of the monitoring viewpoint, two metal cabinets with rubber weatherproof sealing were used to protect the network camera and wireless router respectively (Figure 11). Basically the two cabinets have the same design but one side of the cabinet that covers the network camera is partially cut and replaced by a hardened acrylic glass for camera viewing. Since the captured image quality may be affected by dust and dirt on the acrylic glass, it is suggested that the camera is set to focus to infinity. By doing so, dust and dirt would not actually make much difference in image quality under most circumstances since dust and dirt are far enough from the focusing point (Guy, 2006). As the camera and the router are fixed inside their cabinets that are in cuboids shape, it is not difficult to fix them in a horizontal surface such as on the parapet wall on the roof of a building. Further, it is convenient in reconfiguring their location without the hassle of damaging them. Lastly, as the equipment is fixed off site, it is less prone to be damaged or vandalized.

Figure 11. Metal cabinet with rubber weatherproof sealing

5.2 Design Justifications for Test Site B

Another test site, Test Site B (Figure 12), has a smaller in site area (3,950 square meters) and it was more challenging to implement the proposed system. The onsite activities started a few months before the owner agreed to install the proposed system. Therefore, there is no more suitable location other than the tower crane located in the center of the site.

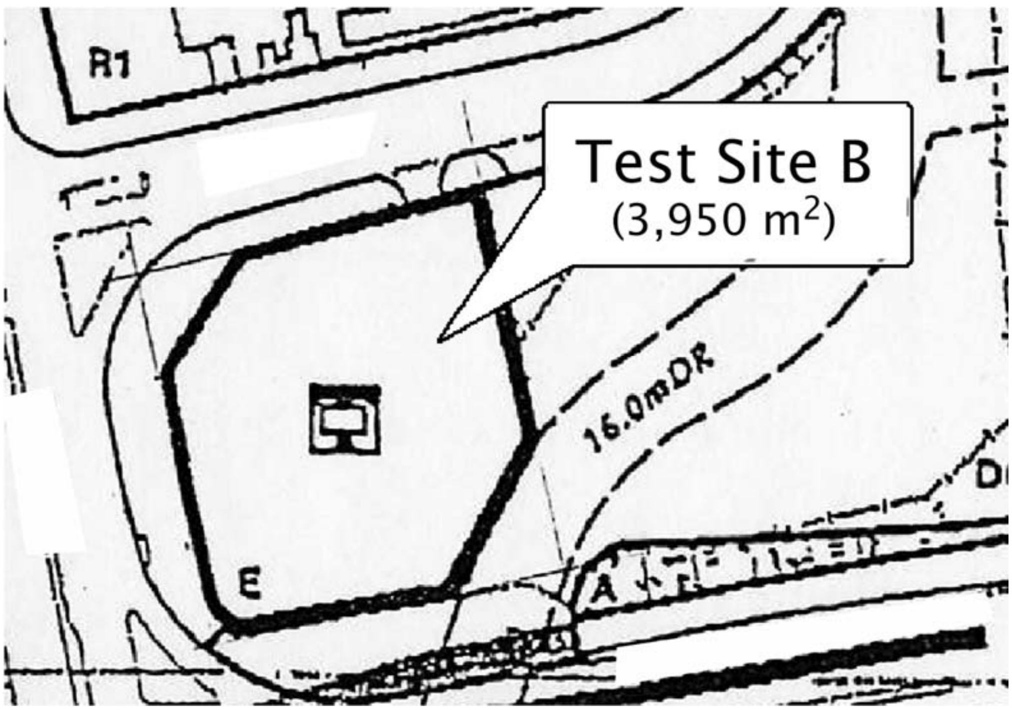

Figure 12. Plan of Test Site B

The monitoring viewpoint was designed to hoist near the operator's cabinet of the tower crane. Since there is only one viewpoint allowed to be installed and the installation location is roughly on the centre of the site, the camera in it must have a 360-degree of view, without the blockage of the housing sheltering it. If the cuboids cabinet of Site A on site B is used, most angles of view would be blocked. Although it is possible to use a transparent cabinet that is made of strengthened acrylic glass, the corner of it seriously distort the captured images. Therefore, a weatherproof dome housing case was used to protect the network camera. As shown in Figure 13, it offers a 360-degree of viewing angle for the camera when it is inversely hoisted. The convenience of hoisting the equipment there is that power supply is readily available (as the tower crane is driven by electricity). For the router of the viewing point, the housing configuration is the same as the one of Site A.

Figure 13. Network camera inside a dome housing

Chapter 6

Prototyping

While all components of the system were confirmed, there was still a need to make a prototype for it. Otherwise, it may be costly to find an optimal position of the monitoring viewpoint by trial and error. Moreover, up to this stage, all the proposed designs just theoretically work, and no concrete object was made. In fact, prototyping could be used for study, training, or testing and to determine if the apparatus can be manufactured easily and economically (Morris, 1992). In recent years there have been attempts to apply virtual prototyping (VP) to various sectors of the construction industry because of the low cost of this mature technology in terms of hardware and software. VP was used in this project to find an optimal setting, such as the best mounting position of the viewpoints and the pointing angle of the unidirectional antenna, as well as analyzing the impact of the environment, such as the lens flare caused by the sun.

6.1 Virtual Prototyping

VP is a computer-aided design (CAD) process using realistic three-dimensional (3D) graphical simulation that addresses the broad issues of physical layout, operational concept, functional specifications, etc. under various operation environments. Huang et al. (2007) categorize and summarize some IT tools such as layout planning, 4D, and virtual reality that are useful to implement VP in the industry. Recently, a freeware called “Google SketchUp” has started to arouse interest among the academic field (Bilasco et al., 2007). It is actually a trimmed-down, freely downloadable version of

“SketchUp”, a 3D modeling program designed for professional architects, civil engineers, and other users like filmmakers and game developers. Different from other 3D CAD programs, Google SketchUp is marketed as an easy-to-use conceptual tool with a simple interface but offering powerful tools for creating, viewing, and modifying 3D ideas quickly. The most beautiful feature of it is the online 3D warehouse. Users could upload and contributes the 3D models they built and download any models from the warehouse. Because most common objects in the real world are available to download, users can save enormous time for prototyping. In the warehouse, many construction-related models are available, including tower cranes, bulldozers, wheelbarrows, and even construction workers. Figure 14 shows the 3D warehouse interface. This project made use of this useful tool to visualize the two test sites installed with the monitoring system. The models were built in one to one scale so the stakeholders might spot some hidden problem before the implementation process.

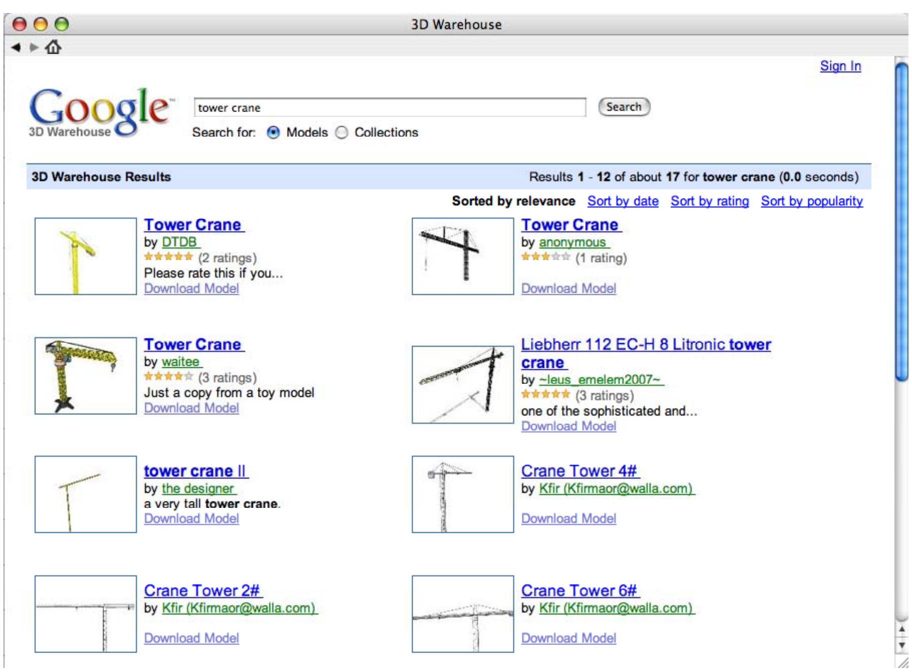

Figure 14. Tower crane models in the 3D warehouse

6.2 Virtual Prototype for Test Site A

For Site A, the monitoring viewpoint was installed on the roof of the building (P) next to it, where cuboids cabinets protect the gears of the viewpoint. Figure 15A illustrates the overview of the VP of Site A, while Figure 15B and C show a closer view of the monitoring viewpoint and the site office, respectively. One critical test is to investigate if there was any obstacle, including the cabinet, blocking the view of the camera. The VP simulates the pan, tilt, and zoom movements of the camera, by moving horizontally along the roof of P in order to find the largest viewable area. Figure 16 shows the leftmost and rightmost views of what the camera can "see" when the viewpoint is placed in the optimal position. Although a small amount view was blocked by the cabinet, the view of the camera covered over 80 percent of Site A. It is also valuable to note that the software is able to simulate the direction of sunlight and the position of shadows for all months and times, which is useful to test if there is a chance for direct sunlight to pass through the camera lens causing lens flare. Coincidentally the testing result showed that lens flare was not a concern, as the shadows of the buildings surround Site A blocked the direct sunlight.

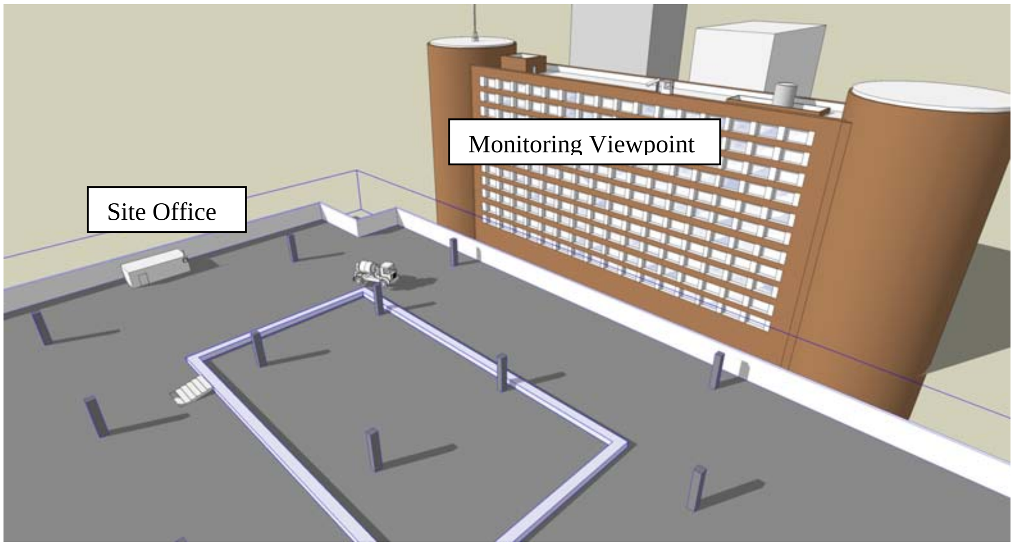

Figure 15A. Overview of the virtual prototype of Site A

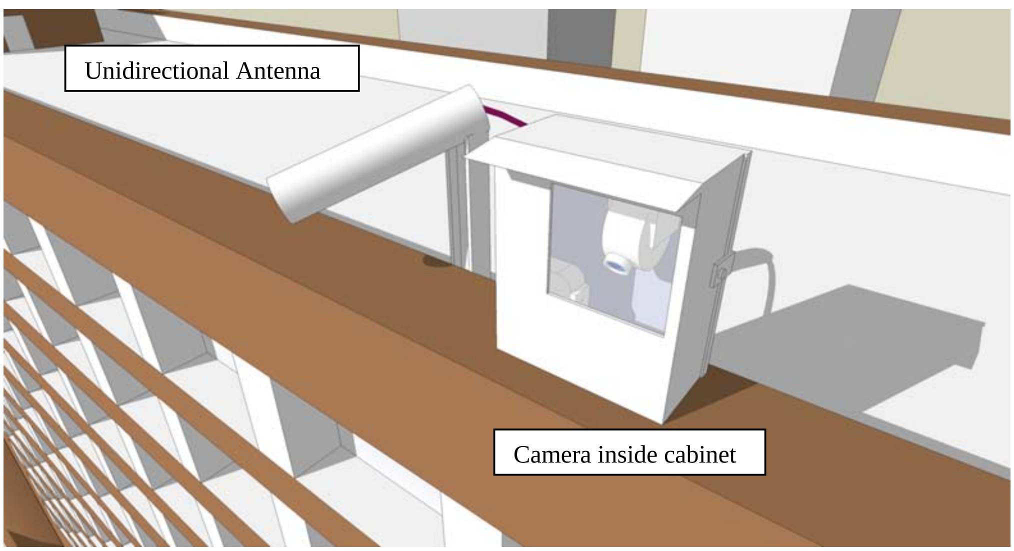

Figure 15B. Monitoring viewpoint of Site A

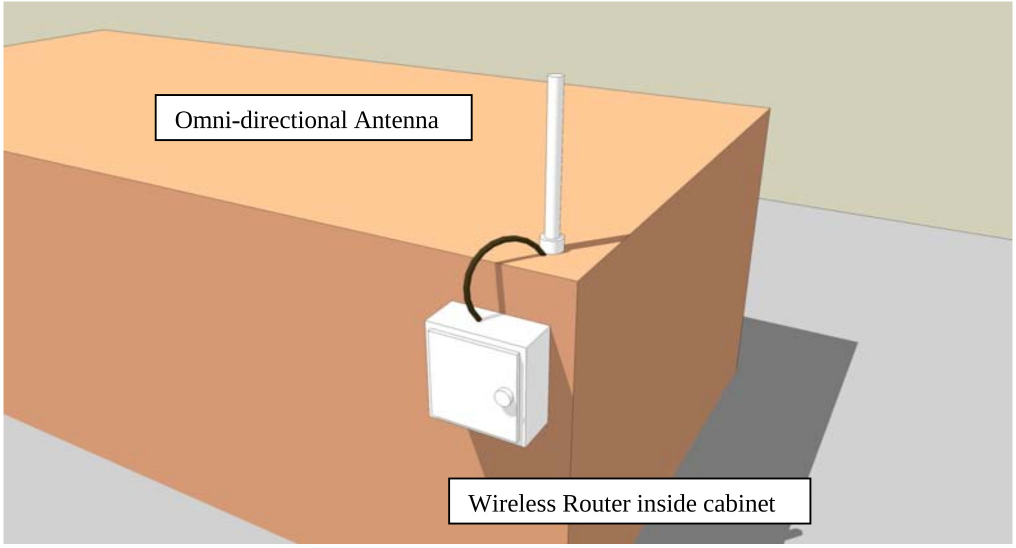

Figure 15C. Site office in Site A

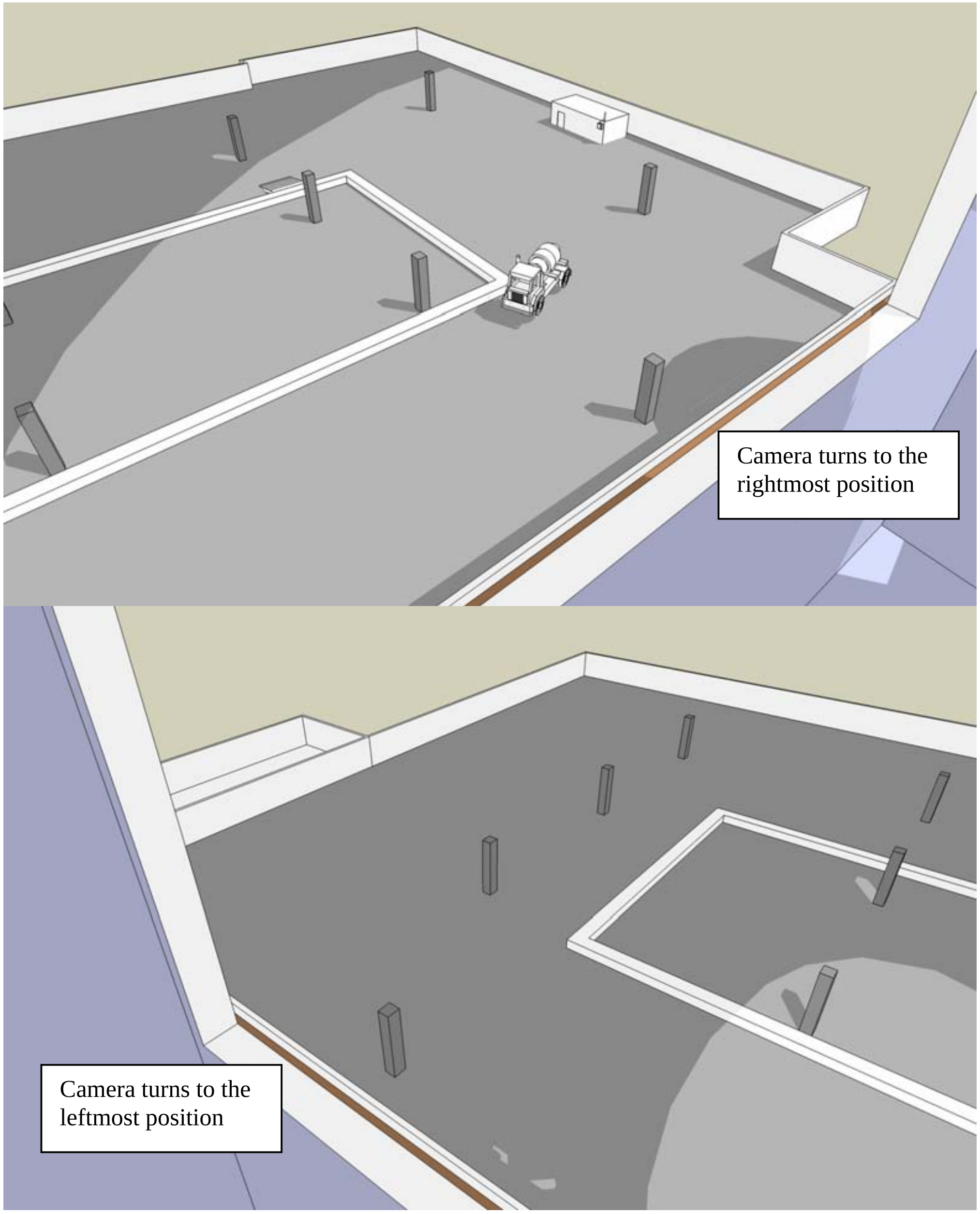

Figure 16. Simulated view of the camera inside the cabinet

6.3 Virtual Prototype for Test Site B

Comparing with Site A, the main difference of implementing the system in Site B is that the monitoring viewpoint was hoisted on the tower crane. As shown in Figure 17A and

B, the dome housing not only provided a 360-degree of viewing angle, but also protected the camera from the damages caused by bad weather and flying particles. The key concern for this site is the variation of the pointing direction of the unidirectional antenna. As the tower crane rises with the progress of the site, the pointing direction of the unidirectional antenna needs to be adjusted on a regular basis so that it is always pointing to the omni-directional antenna at the site office. As the restricted azimuth of the unidirectional antenna is around 12 to 75 degrees, the VP simulated different heights of the tower crane and adjusted the pointing direction in order to test if the signal could always propagate within the restricted azimuth range.

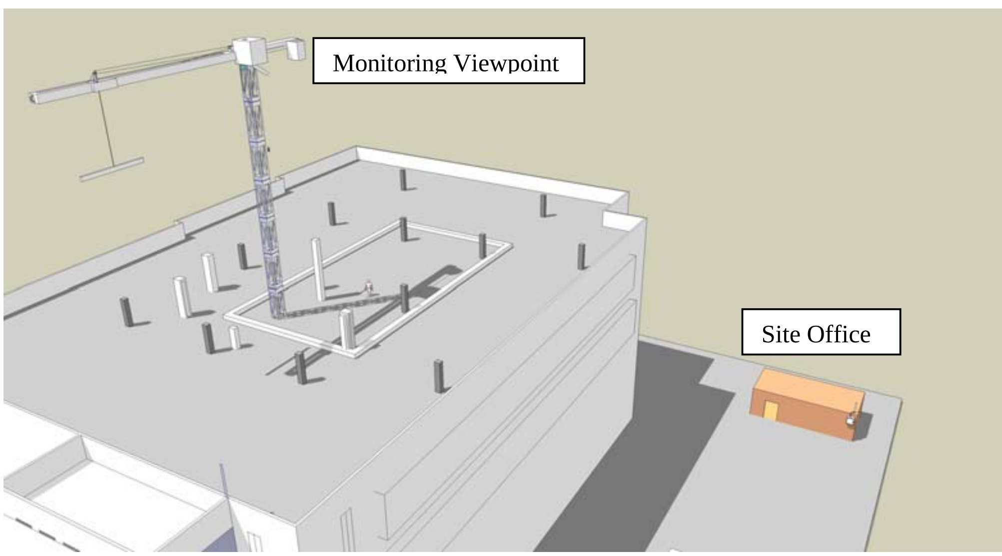

Figure 17A. Overview of the virtual prototype of Site B

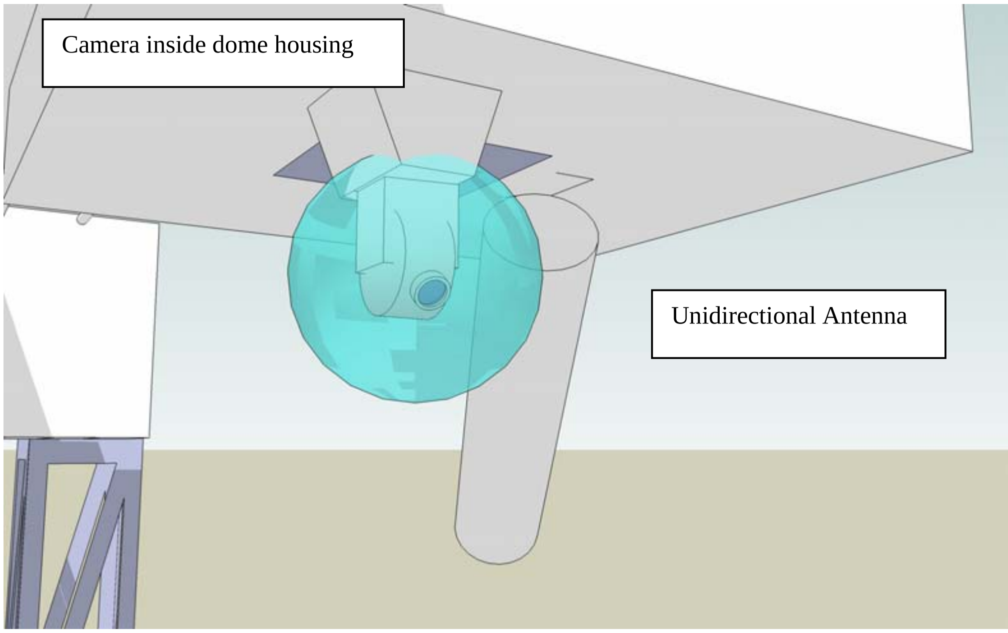

Figure 17B. Monitoring viewpoint of Site B

Chapter 7

Implementation and Testing

The core process of the system is to capture images using a network camera in a construction site, to send them to authenticated devices through a wireless network that cooperates with outdoor antennas and via the Internet. Since some researchers have already studied the performance of wireless network in construction areas (Ward et al., 2004; Meissner et al., 2001), the test mainly focused on the quality of the captured images, the reliability of the system and the visibility in dark environment. The system was installed in the two construction test sites, Site A and Site B in Hong Kong for over fifteen and ten months respectively. This chapter presents the implementation processes as well as the testing results.

7.1 Implementation on the Test Sites

For Site A, the actual installation settings of the monitoring viewpoint are shown in Figure 18. The two cabinets protect all electrical devices such as the network camera, wireless router, power adaptors, and the electricity sockets. The cables that were used to link between the cabinets and the antenna were also wrapped by flexible corrugated steel tubes for higher durability. Lightning rod was not required because there are taller objects nearby. As presented in Figure 19, the electrical gears of the reception point were also sheltered by a weatherproof cabinet. It is noted that both antennas were not required being enclosed because they are already weatherproof products.

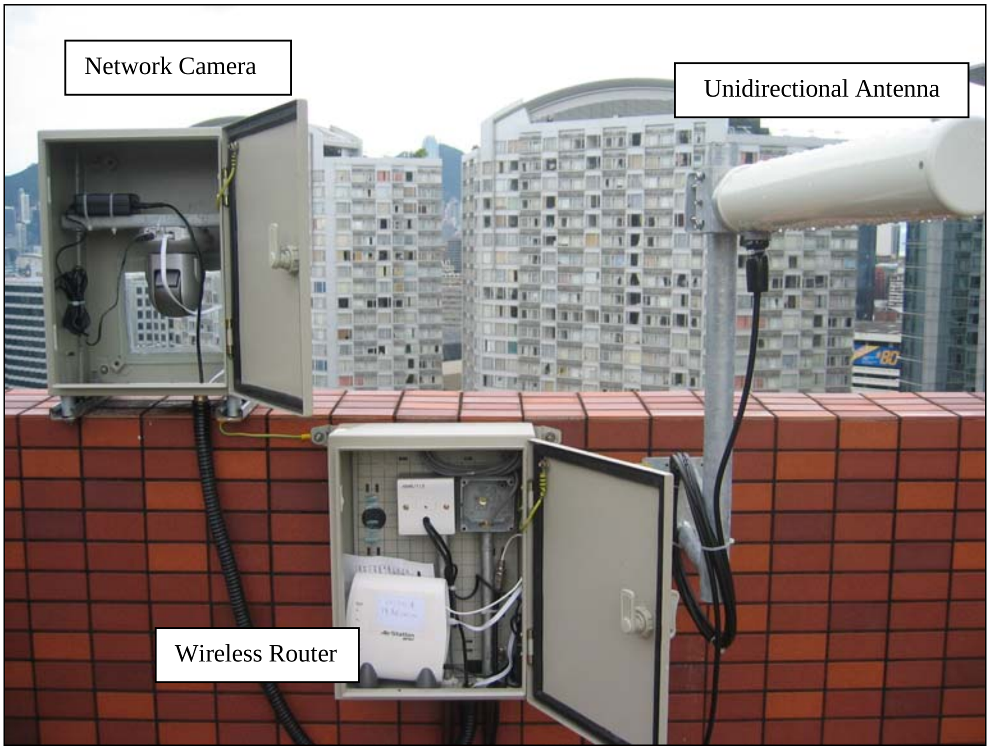

Figure 18. Installation setting of the monitoring viewpoint (Site A)

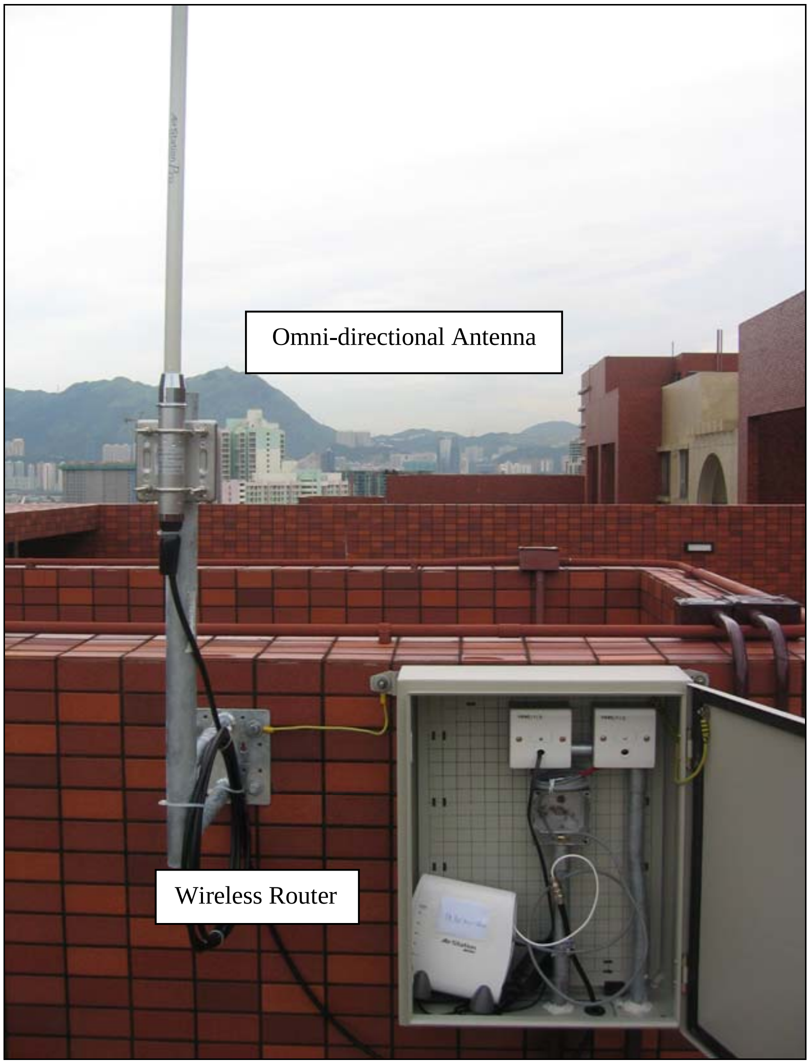

Figure 19. An omni-directional antenna and a wireless router connected to the Internet

In order to implement the system in Site B, more efforts were needed. Since the monitoring viewpoint was installed on the tower crane, the installation task was completed by the site workers of Site B. As the workers were not very familiar with the components, it took much time in briefing the purpose of the research and the related process. The VP of Site B was useful again: visualization was better than a thousand words. They might not be very clear about the research background but they got the idea about the allocations of the components very quickly after seeing the VP. During the installation of the unidirectional antenna, walkie-talkie communication was used to fine adjusting the pointing direction. Figure 20 depicts the installed monitoring viewpoint.

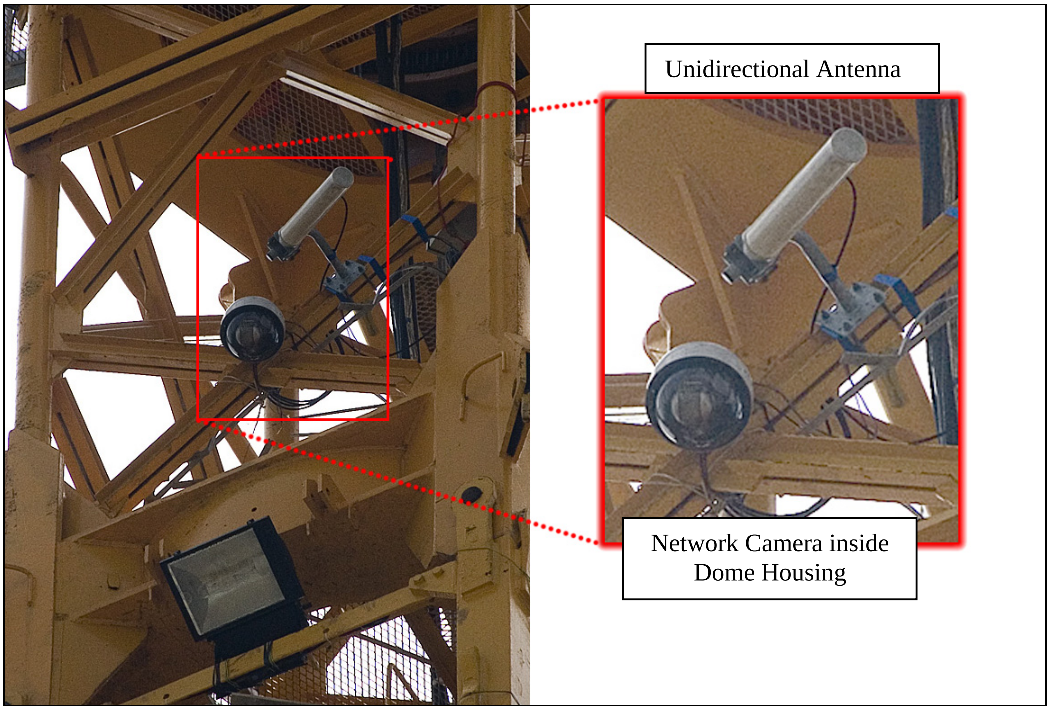

Figure 20. Monitoring viewpoint on the tower crane

7.2 Image Quality

For image quality, two major factors were used: fluency of real-time motion and clarity of images. The perceived motion fluency is subjective. To be more scientific, we have to measure the actual frame rate displayed on the computer screen instead of telling it is fluent or not. Although the manufacturer of the network camera claims that it is able to capture 30 frames per second (fps) under the resolution of 320 x 240 pixels, due to contention for a wireless environment, the actual throughput of the camera is substantially lower than when it is connected to a wired LAN. In fact, it has been tested that the speed of a WLAN is always below the maximum data rate of the standard (Wijesinha et al., 2005). In addition, due to signal attenuation of a long-range wireless transmission, degradation in frame rate is expected. However, it is almost impossible to count the frame rate manually, especially for a fluent motion with high frame rate. Therefore, an experiment was designed with the following steps:

1. place a digital clock with millisecond digit in front of the network camera read the display of the clock with an authenticated device (a PC in this case);

2. use Microsoft Media Encoder (a screen capture software) to capture the screen of the PC at 30 frames per second for five minutes and save it as a windows media video (wmv) file;

3. watch the wmv file in slow motion and count the number of distinct time digits captured;

4. divide the total number of distinct time digits by 300 (5 minutes) to get the frame rate;

For both sites, the experiment was repeated several times and similar results were obtained. When a computer is connected directly to the router of the site office, the frame rate is about 25fps at 320 x 240 pixels and 21 fps at 640x480 pixels. The result is considered good as the frame rate does not deviate too much from the specified performance of 30fps. When a computer is connected through the Internet, however, the frame rate drops to 16fps and 12fps at 320 x 240 pixels and 640 x 480 respectively.

The network camera transfers snapshots in JPEG format, therefore one of the factors influencing the clarity of the image is the compression ratio (Wallace, 1991). The standard size of snapshots taken by the camera is 640x480pixels and occupies about 40 kilobytes, which translates to a compression ratio of about 1:23. This is clear enough for monitoring purpose, bearing in mind that the compression ratio of images for medical screening is 1:20 (Basu et al., 2003). Another factor that affects the image clarity is dust and dirt. The casing of the camera in both sites has never been cleaned since they were installed. In site A, dust and dirt do affect the image quality but the effect is minor because they are not within the focusing plan of the camera (Figure 21). For site B, we have yet to observe serious effect of dust and dirt.

Figure 21. Image clarity is still good after fifteen months

7.3 Reliability

The systems on both sites have been running 7x24 (i.e. non stop) for over fifteen and ten months respectively. They still function perfectly and no maintenance call was received so far. They behave stably even during the typhoon season (June to September in Hong Kong) or under inclement weather conditions. The functioning of the systems is particularly important during inclement weather condition as it serves as a surveillance of the construction site in case the temporary works becomes unstable or poses danger to the public. Last but not least, in site B, the movement of the tower crane may result in flickering images but the impact is considered insignificant because the motions of workers and equipment are normally not very fast.

7.4 Visibility at dark environment

Basically the network camera gives a relatively blur image in low light environment. As shown in Figure 22, there is no light source directly shining site B, only little illumination produced by the facilities nearby. Under such situation, the camera gives an image with large amount of noise but users can still roughly recognize the outline and contour of the objects within the monitoring area. For example, it is possible to see someone walking inside the site but we may not know whether the person is a security guard or an intruder. Therefore it is suggested that if users use the system at night, a light source pointing to the target area is required.

Figure 22. Image captured at June, 8:30p.m.

Chapter 8

Conclusions

Conventionally most of the monitoring processes in the construction industry are conducted manually. For instance, a site foreman ensures the workers are compliant with the regulations, a safety officer are concerned with the safety and health of persons, and so on. The system introduced in this thesis automates part of the manual processes so that the workload of the involved team members could be reduced and therefore they may be more focused on decisional and managerial issues. Most importantly, although the proposed system is named as a “monitoring” system, indeed it also assists stakeholders in collaboration and decision-makings. It is because the system provides a real-time virtual meeting and interactive environment for users to analyze and comment on the monitored results anytime and anywhere with Internet connectivity.

The endeavor of this thesis focuses on designing and implementing a monitoring system to provide a cost-effective solution on quality assurance for construction projects therefore this thesis is more technical orientated. The system integrates long-range wireless network technologies, network cameras, and collaborative systems to form a comprehensive monitoring and meeting environment for project team members. The system has been tested in actual construction sites and the results of image quality and reliability are more than satisfactory so far. Up to the moment of writing this thesis, no other literature is found to be using similar configuration for construction site monitoring purpose. Therefore this thesis could be act as a guideline for parties who are interested on implementing not only electronic site monitoring, but also any wireless information and communication applications for construction projects.

Nevertheless there is one potential research limitation. Although the proposed system is point-to-multipoint ready, no test was conducted to test this feature in a construction site. When several viewpoints operate simultaneously, interferences may exist and data bandwidth provided by the proposed wireless network technology may not be sufficient resulting in degradation in system performance. The degradations perhaps include dropping of frame rate (i.e., fluency of motion of video is decreased) and increase of recoverable data transmission errors (affects the clarity of images). Fortunately there is a new wireless network standard, named “802.11n”, which will be introduced in year 2009 (http://www.ieee802.org/). The new standard is now in draft stage but its transmission speed is expected to be about five times of the current standard and the transmission range is also doubled. Therefore, theoretically it may be feasible to implement the monitoring system on a small construction site without using the long-range antennas. Further test is required to confirm this prediction and it may be regarded as part of future research.

Although this thesis focuses on design and implementation of an ICT application in the construction domain, some human factors like the decision on accepting and adopting new technologies should not be neglected. It is doubtless that the appropriate use of ICT does more good than harm to a construction project, and therefore many researchers and developers have been trying their best to investigate innovative and effective ICT solutions for the industry, and some of them are described in this thesis. Unfortunately, practitioners’ intention of adopting new ICT in construction project is still rare. It is found that the penetration rate of ICT within the core processes of the construction industry is still relatively poor when comparing with other industries (Nikas et al., 2007). Rather than technical and financial issues, researchers have been trying to figure out some factors to explain this phenomenon. For instance, the stakeholders are often satisfied with their conventional business method so that they are reluctant to change (Samuelson, 2002), culture and psychological factors may be barriers to widespread adoption of ICT (Backblom et al., 2003; Bjork, 2003), and so on. Although the study of this rather pessimistic phenomenon is not the theme of this thesis, it is hoped that more resources could be spent on advertising the R&D results to the business domain. The mission could not be accomplished by just the efforts of research teams, attitude and policy of the Government is the most critical success factor.

Further Research

By enlarging the scale of this project and the adoption of the said new wireless transmission standard, more applications could be implemented. While this project only focuses on building construction sites, by using the long-range and point-to-multipoint communication capability, larger civil engineering projects such as railway and highway construction could adopt the solution to implement inspection and quality control. As described in Section 4.2.3, in theory, it is possible to record videos by upgrading the proposed server to a video streaming server, but the cost is too high for pilot studying purpose and therefore only still images are stored in the server (note: observers could see fluid real-time monitoring motions, but the pictures not continuous stored in frame-by-frame fashion). If the proposed system is mainly used for surveillance purposes, the capability of archiving videos may be an essential feature. When a video streaming server is adopted, it is recommended to focus more on server maintenance because the server has to deal with large data traffic, and those 7 x 24 non-stop video files are thirsty for hard disk space. Therefore more effort has to be spent in "monitoring the monitoring system".

Being a pilot study using real life construction projects, this thesis confirms the technological feasibility of the proposed system. However, it is also valuable to further investigate the system from different angles such as managerial perception, workers' acceptability (e.g. any behavioral changes), legal issues, system adoption criteria, the impact on project planning, and so on. Although the monitoring system is beneficial to the managerial stakeholders and the owner, the perceptions of the construction workers who are monitored should not be neglected. With the growth of the adoption of information and communication technology in construction projects, it could be anticipated that more construction firms will attempt to equip with electronic gears and gadgets for site monitoring or surveillance purposes in the future. As the construction workers may be the major group of project team members being monitored, ethically it is essential to investigate their level of acceptance on the monitoring systems.

Appendix

Interview with stakeholders of the construction industry

Interviewees:

1. Owner
2. Contractor
3. Engineer

Questions:

Supposed there is a monitor system that could be able to let you see the activities in construction sites through a computing device.

1. What activities you are interested to be monitored through the device?
   你希望透過這個裝置可以監控到甚麼？
2. When do you use it? (Do you need to monitor the site at late night time?)
   你會在甚麼時候使用？(有需要在深夜使用嗎？)
3. Which part of the site do you want to monitor? How details? E.g. do you need to recognize the faces? (powerful zoom feature)
   你希望監控地盆內哪一部份？要多細緻？例如需要見到樣貌嗎？
4. Is there a need to archive the images? If so, keep how many days? For how long?
   有需要儲存那些影像嗎？要多少日，存放多久？
5. Who should be able to use the system?
   哪些人會用這系統？
6. How much do you wish to spend on the system?
   你會願意花多少錢？
7. Have you used any surveillance system before? If so, what is your comments?
   你之前有用過任何監察系統嗎？如有，有甚麼意見？
8. Do you have any concerns on placing the monitoring system in a construction site?
   你對在地盆放置一個監察系統，有沒有擔心或任何掛慮？

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