A BIM- and sensor-based tower crane navigation system for blind lifts

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A R T I C L E   I N F O
Article history:
Accepted 3 May 2012
Available online xxx

Keywords:
Building information modeling (BIM)
Tower crane
Navigation system
Sensor

A B S T R A C T

Tower crane operators often operate a tower crane with blind spots. To solve this problem, video camera systems and anti-collision systems are often deployed. However, the current video camera systems do not provide accurate distance and understanding of the crane's surroundings. A collision-detection system provides location information only as numerical data. This study introduces a newly developed tower crane navigation system that provides three-dimensional information about the building and surroundings and the position of the lifted object in real time using various sensors and a building information modeling (BIM) model. The system quality was evaluated in terms of two aspects, "ease of use" and "usefulness," based on the Technology Acceptance Model (TAM) theory. The perceived ease of use of the system was improved from the initial 3.2 to 4.4 through an iterative design process. The tower crane navigation system was deployed on an actual construction site for 71 days, and the use patterns were video recorded. The results clearly indicated that the tower crane operators relied heavily on the tower crane navigation system during blind lifts (93.33%) compared to the text-based anti-collision system (6.67%).

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1. Introduction

The “blind driver challenge” [16] aims at developing interfaces that enable the blind to drive automobiles. The blind are not the only ones who need such interfaces. Tower crane operators often have to lift construction materials without actually being able to see the lifted materials because their sight is blocked by the building slab right below the tower crane's cabin. As buildings grow taller, the blind spots get larger, and, thus, operating a crane with blind spots gets more serious.

A video camera system [11] was developed and commercialized to solve this problem. The current video camera system displays only the top view of a lifted object from the video camera attached to the tower-crane trolley or hung at the tip of a luffing jib. This video system is ineffective for tall buildings because the lifted object from a distance looks too small to be seen by the operator. In addition, the vertical view of a lifted object does not give the crane operators a good sense of distance and their surroundings. This problem may be alleviated if additional video cameras are installed that can provide other views. However, finding the right locations for cameras is challenging because buildings grow and are consistently blocked by various objects. One possible, yet uneconomic, solution might be to install cameras at every second or third floor around the building and to relay the views. Another system often used to give the tower crane operators location information about the lifted object while they operate the crane with blind spots is the anti-collision system. Anti-collision systems usually show the slewing angle and the trolley's location, the maximum load, and sometimes the length of the unwound cable as numerical data (Fig. 1). The limitation of the video camera system and the anti-collision system is that they do not provide an overall view of the lifted object in the context of the constructed building and surroundings.

This study introduces a newly developed tower crane navigation system and evaluates user acceptance of the system. This system shows the location of a lifted object in the context of a constructed building and surroundings similar to a car navigation system showing the location of an automobile in the context of roads and landmark buildings. The tower crane navigation system deploys three-dimensional building information modeling (BIM) and sensor technologies. It visualizes the location information of the lifted object and a tower crane, acquired from the laser sensor and the encoder sensors installed at the tower crane, and the surroundings of a building in real time using the BIM model.

This study evaluates user acceptance of the tower crane navigation system from two perspectives, “perceived ease of use” and “perceived usefulness,” based on the Fred Davis’s (1989) Technology Acceptance Model (TAM), which is also known as the system quality assessment model.

This paper is organized as follows. Section 2 reviews previous studies related to automation of cranes and technologies used in the
2. Previous studies

Previous studies related to the tower crane navigation system can be categorized as location tracking technologies for construction equipment using various sensors such as the global positioning system (GPS), laser, and encoder sensors and solutions currently adopted when operating tower cranes with blind spots. Lu et al.’s study is a good example of the studies on the technologies for tracking the location of construction equipment. Lu et al. [13] used GPS and “beacons” to position and track construction vehicles in very dense areas like Hong Kong. The beacons, which are similar to the active radio frequency identifier (RFID) tag operating on Bluetooth, were used to calibrate the positioning errors in the GPS. The reliability of the system was tested by tracking the ready mixed concrete delivery process for about 12 months. Another study using GPS in tracking construction work was conducted by our team [27,28]. We developed a real-time lifting path tracking system for a tower crane using two GPS sensors and radio frequency (RF) MODEMs. Two GPS sensors were used to calibrate to the position errors. One GPS sensor was installed at the cabin, and the other one was installed at the hook block. The RF MODEM, an active RFID tag that could transmit a signal around 1 km away, was developed to signal and record the beginning and ending points of the lifting work in the real-time construction progress management server. The RF MODEM was adopted by the real-time progress management system of the tower crane navigation system in recording the start and end points of lifting operations. However, the GPS sensors were not. The positioning error using two GPS sensors was still very large, and an improved algorithm for minimizing the positioning error is being developed.

Encoder sensors are another popular sensor type deployed in tracking construction equipment and work. Commercial anti-collision systems for tower cranes often use encoder sensors to detect the horizontal angle of a tower crane by counting the number of spins or the vertical location of a hook block (i.e., a lifted object) by measuring the length of the released cable. However, because of the cables’ slippage, the encoder-based positioning system is not accurate, and errors accumulate.

To overcome this problem, Lytle et al. [15] deployed a three-dimensional (3D) laser scanner in acquiring the position and orientation information of a RoboCrane, a 6-degree-of-freedom cable-based crane developed by NIST. The potential of the 3D laser scanning system was successfully demonstrated, but further development was required to automate the measurement process. Another example of using laser sensors is the real-time tower crane lifting path tracking system that we developed using an affordable laser sensor [10]. This study demonstrated a possible use of the laser sensor in tracking the lifting path of a tower crane and proposed an algorithm to filter missing or erroneous signals. This system is also used in acquiring lifting path information for the tower crane navigation system in this paper.

A solution that directly addressed the problem of blind spots around the tower crane is the video camera system with an RFID tag system developed for the T-type tower crane by Lee et al. [11]. For any video-based tracking systems for construction work as well as tower cranes, finding the right location to install the cameras is always challenging because camera views can be easily blocked by constructed walls, slabs, and others, and because a building continuously grows until the construction ends. Lee et al. installed the wireless video camera system on the trolley of a tower crane so that the system could continuously capture the top view of a lifted object. The system transmitted video images wirelessly to the display module installed in the tower crane cabin. The system was limited to the top view, and the lifted object sometimes looked too small. Still, it was better to have some visual information than nothing. Lee et al. observed a 52.7% decrease in communication between the tower crane operator and the signaler when operating a crane with blind spots using the video camera system. This system was modified and commercialized later. Shapiro and his team [24] also developed a wireless-video-camera system similar to Lee et al.’s and conducted field tests. Shapiro et al.’s findings conformed to Lee et al.’s earlier findings. The wireless video camera module was partially integrated into the second version of our tower crane navigation system. Another system commonly used to support operating a tower crane with blind spots is the anti-collision system. Initially anti-collision systems were developed to signal tower crane operators when a tower crane moved beyond the preset boundaries (angles) to prevent collisions with adjacent buildings and tower cranes. Anti-collision systems also provide horizontal and vertical location information about a lifted object as numeric numbers (Fig. 1). Sacks et al. [21,22] used the tower crane operation data collected from the anti-collision system to monitor and analyze the productivity of lifting activities. In practice, anti-collision systems, which provide only textual data, are often used with the video camera system to overcome the shortcoming of the video camera system not being able to provide specific location information.

Many other studies related to crane automation and sensor-based safety monitoring have been conducted [3–9,12,14,19,20,23–26,29]. However, the studies have little to do with tower cranes’ blind lifts or other issues in our study.

This study proposes a tower crane navigation system, which displays the location of a lifted object in the context of a constructed building using sensors and a 3D BIM model as well as a video image. A good analogy that can help readers easily understand the difference between this system and previous systems is the car navigation system and the car’s front

Fig. 1. Monitor for an anti-collision system.
and rear view cameras. The video camera system is like a car’s front and the rear view cameras, which do not give drivers location information in terms of roads and buildings. The anti-collision system is like the GPS navigation system without a graphic user interface. The tower crane navigation system is like a car navigation system with an integrated video camera system, which allows users to selectively display the front and rear views or the navigation view as a nested view or as a main view. The next section describes the system functions and configuration of the new system in more detail.

3. Tower crane navigation system

The tower crane navigation was developed as part of a large governmental initiative to develop a robotic tower crane-based automated construction factory for steel construction funded by Korea’s Ministry of Land Transport and Maritime (MLTM) Affairs and begun in 2006. Fig. 2 shows an overview of the tower crane navigation system. Fig. 3 shows pictures of Items 1 to 4 in Fig. 2. The tower crane navigation system operated in accordance with other construction robots and equipment, and was monitored from the master control room in the field trailer (Item 4 in Figs. 2 and 3). When an emergency situation occurs, the main system can be stopped by pressing a large emergency button.

The system presented in this paper was developed for the luffing crane as shown in Fig. 2; however, application is not limited to the luffing crane. The system is composed of sensors for acquiring boom angle, slewing angle, and cable length information, a video camera for capturing a vertical view of a lifted object (Items 1 and 2 in Figs. 2 and 3), and the tower-crane navigation server that collects and displays the location information of the lifted object in a BIM model in real time. The navigation server and the monitor are installed in the tower crane cabin (Item 3 in Figs. 2, 3 and 8). The location information in the navigation server is also transmitted to the master server in the master control center in real time (Item 4 in Figs. 2, 3 and 9).

The vertical location of a lifted object is measured using two sensors: a laser sensor and an encoder sensor. The cable-length sensor in Fig. 4 uses the encoder sensor. As mentioned earlier, the encoder-based vertical distance measurement system is theoretically less accurate than the laser-based system because the encoder-based measurement system detects the position of a lifted object by measuring the length of the released cable rather than the actual distance between the tip of the boom and the hook block. However, the laser-based system is less reliable than the encoder-based system. The laser-sensor, installed at the tip of the luffing boom, measures the vertical distance of a lifted object using a laser beam reflected from the reflection board installed on the hook block (Item 1 in Figs. 2 and 3). The laser-based system sometimes misses the reflection board when the hook block swings hard and returns the distance from the ground to the boom tip instead of the distance from the hook block to the boom tip. The erroneous data are filtered out considering the speed and the moving direction of the hook block. An algorithm for filtering out erroneous data and other details on the laser-based system is described in Lee et al. [10]. A series of experiments to analyze the accuracy and reliability of the encoder-, laser-, and GPS-based measurement systems is being undertaken. Our early study showed that the errors of an encoder-based system accumulated as the lifting height increases [18]. However, follow-up studies showed that error ranges could be minimized when the encoder-based vertical distance measurement system was calibrated adequately by adjusting the settings provided by the manufacturer. Comparative analysis for choosing the optimal sensor for the vertical distance measurement continues. For the time being, the laser-based system was designed to be used as the primary measurement system, and the encoder-based system (the cable length sensor in Fig. 4) is used as a backup.

Fig. 4 shows the configuration of the tower crane navigation system. The “+” symbol in the circle between the laser sensor and the cable length sensor denotes “exclusive or (XOR),” which indicates that the system chooses either the data gained from the laser sensor or those from the encoder-based cable length sensor for the vertical location of the hook block. The location information including the vertical location information collected from various sensors and the video camera images is sent to the navigation server placed in the tower crane cabin. The navigation server is a database that stores all the location information. The location information and the video images are also sent to the real-time construction progress management system (the project server in Fig. 4 and Item 4 in Figs. 2 and 3) installed in the master control room. A BIM model of the constructed building is installed in the navigation server and the project server. The tower crane navigation

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**Fig. 2.** Overview of the tower crane navigation system.
system was developed through a series of mock-up tests, and a prototype system was deployed for 71 days on an actual steel construction project to build a seven-story building at a university in Seoul, Korea.

4. Evaluation of user acceptance

Some technologies are accepted by users, and some are not. A number of factors may influence users’ decisions. The Technology Acceptance Model (TAM) proposed by Fred Davis (1989) defines “perceived ease of use” and “perceived usefulness” as the main factors for determining whether to accept or reject information technologies. Perceived ease of use is “the degree to which a person believes that using a particular system would be free of effort.” Perceived usefulness is “the degree to which a person believes that using a particular system would enhance his or her job performance.”

This study analyzes user acceptance of the developed tower crane navigation system based on TAM. The perceived ease of use and the perceived usefulness of the system were analyzed through a series of user experiments. Since no standardized form exists for testing the perceived ease of use and usefulness of a system, a set of experiments customized for this system was developed.

The experiments were conducted on the actual construction site of a research building on a university campus. The construction costs were partially funded by our research project. The building was a seven-story steel-framed building. A single tower crane was deployed, and the site was fenced. The following sections describe

**Fig. 3. Components of the tower crane navigation system.**

**Fig. 4. System configuration.**
the user experiments for perceived ease of use and then perceived usefulness.

5. Perceived ease of use

The first usability experiment to evaluate the perceived ease of use was conducted with six tower crane operators with several years' experience using the very first prototype. The first experiment was conducted with six operators first, because it was difficult to recruit many experienced tower crane operators, and according to Nielsen's theoretical and empirical studies on the effective number of users for usability tests, "5 users is enough to find most (85% of the) usability problems" [17].

The first prototype system (Fig. 5a) was fully functional but was not connected to the location-detecting sensors. It was developed using Open GL and Visual C++. The navigation system was installed on an Ultra-Mobile Personal Computer (UMPC) with a 7-inch touch screen (Fig. 5b). It showed a 3D BIM model of the constructed building and surrounding buildings imported from a BIM authoring tool and a parametrically defined tower crane model (Fig. 5a). Users could switch between various view modes such as 3D view, front view, right view, left view, top view, and others and could rotate the view.

The experiment was composed of qualitative and quantitative evaluations regarding the ease of use. The experiment was conducted in the following steps:

1) The main functions of the navigation system were explained.
2) Each subject had some time to get accustomed to the system.
3) Each subject was asked to conduct a list of four simple tasks prepared in advance. The four tasks were “Rotate the view to get the view in the given picture,” “Change the view mode to the front view,” “Change the view mode to the side view,” and “Zoom in and out to show the lifted object.”
4) A qualitative survey and a one-on-one interview were conducted with tower crane operators using the preset survey questions (Fig. 5d).

The interview sheet was composed of three sections: tasks with images, interview (qualitative analysis) questions, and quantitative survey questions for evaluating the “ease of use.” The interview questions and the survey questions were basically the same. The main difference was that the quantitative survey asked users to evaluate ease of use using a 5-point Likert scale, with 5 as “very easy to use.” The questions were composed of a software aspect and a hardware aspect. The navigation system had only two functions: the information display function and the view change function. The software aspect was categorized into the information display function and the view change function. The hardware aspect was categorized into display device issues and control device issues. The following is a list of questions. The actual interview sheet is in a structured format with images and detailed descriptions of the tasks and the survey questions:

- **Software aspect**
  - Information display: Did the system functions provide enough information to operate the tower crane? Was it easy to understand the meaning of the icons? Were the colors of the objects easy to identify? Was the icon easy to understand? Was the icon too small? Were the icons easy to find? Was the level of detail about the model enough?
  - View change: Was it easy to conduct the tasks? (Was it easy to switch between views and zoom in and zoom out?) If not, which task was difficult to perform?

- **Hardware aspect**
  - Display device: How was the screen size (7 in.)? Where do you think is the best location to install the navigation system without blocking your view?
  - Control device: Was the touch screen method easy to use?
For the display device, we prepared mockups of display devices with 9-, 13-, 15-, and 17-inch screens (Fig. 5c). A mockup of a display larger than 17 in was not prepared because it was too big to fit in the cabin. Mockup tests had to be conducted for the screen size and the display location because the tower crane cabins are usually very compact. A large display can show more information than a small display but will block views and make operating a tower crane dangerous. (Imagine a 17-inch navigation system installed on the dashboard of your car.) In the future, a head-up display might be a good alternative to the LCD display, but the technology was too expensive when the study was conducted.

The first user experiment was conducted from February 3rd to February 5th, 2010, with six tower crane operators. The first experiment and interviews identified several drawbacks of the first prototype and enhancement items. All the six operators felt that the view rotation function was the most difficult from both hardware and software perspectives. The operators felt that the touch-screen-based interface was difficult to use to accurately control the view. Because their hands were mostly occupied with two levers to control the tower crane, the operators needed a simpler control method. In addition, the touch screen did not immediately react to touch. This was because a heavy 3D model was run on a UMPC, which had lower performance than personal desktop computers.

Another interesting finding was that the tower crane operators preferred 2D representations of a building to the 3D representation because they felt that it was much easier to understand the accurate location of a lifted object in 2D. Additionally, an operator suggested adding a video camera view in the view so that the actual view could be also shown with the computer model view.

Regarding the representation of the location information and user interface, the operators wanted to see numeric information for the vertical and horizontal locations of the lifted object.

Regarding the monitor size, five out of six felt that a 13-inch screen was appropriate. For the location of the monitor, the operators preferred either left or right of the operator's chair close to the levers so that the operator could quickly switch between the lever and the navigation system.

This feedback was incorporated into the second version of the tower crane navigation system. The screen was split into three views: the top view, the side view, and the video camera view. To simplify the control, other view modes were eliminated. Among these three, one selected view was displayed as the main view, and the other views were displayed as the secondary views. The display control method was also changed from a touch screen to a 19-key mini-keypad. To make the input system simple, only three keys on the mini-keypad were used. Pressing Enter changed the view from one view to another (Fig. 6). Pressing Control and F toggled between the full screen view and the divided views (Fig. 7). Instead of a 19-key mini-keypad, a simple control device with two buttons can be developed and used if the tower crane navigation system is commercialized.

An interesting finding regarding the representation of the side view was that, during the development of the second version of the tower crane navigation system, we showed the system under development to a tower crane operator and the operator asked us to rotate the building instead of rotating a tower crane in the side view when a tower crane rotated. The reason was that, if a tower crane rotated in the side view, sometimes it became very confusing to tell whether the luffing jib of a tower crane was folding up or a tower crane was rotating because of the narrowed angle of the luffing jib from the side view.

To reduce the response time, the UMPC was replaced with a high-performance personal computer (navigation server) connected to the Internet. In addition, instead of using OpenGL as the CAD engine, the navigation system was rebuilt from scratch using a commercial CAD engine called Eyeshot Pro and Visual C#. The tower crane model was composed of a boom, a cabin, a cable, a hook block, and a mast. The position and length of each component were parametrically adjustable. The position of each component was updated using new location information collected from sensors. While installing the system, determining the boom's hinge point was most challenging because the hinge point in the actual tower crane was different from that in a computer model. The location of the boom hinge in the model was determined through several iterations of measuring and adjusting the hinge point in the model. The building model was designed to be automatically updated by receiving construction progress data from a central database. However, since this automated update function (generally known as a 4D function) was implemented only after the user experiments were conducted, the building model was updated manually during the experiments by periodically replacing an old model with an updated one. Although a 4D function for automatically updating a building model in real time, as an individual steel member is installed in a building, might be essential for a commercial product, no major impact of the lack of a 4D function on the experiments was observed during the experiments because a construction project generally progresses slowly from a visualization perspective. The tower crane navigation information was displayed on a custom-developed 13-inch screen display system with an adjustable arm (Fig. 8).

The lifting location data was also sent to the master control room in the field office. The transmitted lifting location information and the camera view with other construction progress information were also displayed on the navigation system installed in the master control room (the two screens at the right bottom of Fig. 9). The field engineers in the master control room felt that the building displayed in 3D gave them a better understanding of overall activities. Thus, the navigation system in the master control center displayed the building in 3D. The BIM model was linked to the real-time construction progress management system (the screen at the right upper corner of Fig. 9).

The second user experiment was conducted to evaluate the perceived ease of use by deploying the system in the actual steel construction work of a seven-story building in Seoul, Korea, for 71 days with three tower crane operators using the second prototype system. One of them participated in the first experiment and the other two did not. The same steps were taken as the first experiment. Fig. 10 shows a comparison of the quantitative survey results of the first and second experiments. Overall, the crane operators felt that the second system was much easier to use, and the average score of the system interface went up from 3.2 to 4.4 out of 5.0. Especially the evaluation scores for the view control, the visibility of information, text sizes, and text locations received the highest.

![Fig. 6. Switch between views.](image-url)
The second prototype of the system with a 13-inch screen and an adjustable arm.

Fig. 7. Switch from a split view to a single view.

score. During one-on-one interviews, all three crane operators expressed their excitement about the system. One comment regarding the information content was that they would like to see the current load information displayed on the anti-collision system on the navigation system.

6. Perceived usefulness

The perceived usefulness was tested by video-recording and comparing the frequency of using the tower crane navigation system (Fig. 11 right side) and the anti-collision system (Fig. 11 left side) in actual steel construction work. The anti-collision system is commonly used today when operating a crane with blind spots. If the crane operator looked at (relied on) the navigation system during a lifting task, then the crane operator perceived that the navigation system was more useful for the task than the anti-collision system and vice versa.

The usefulness experiment was conducted as part of the usability analysis of the second system. Use of the anti-collision system (Fig. 1) and our tower crane navigation system by the same three crane operators who had participated in the second ease-of-use test was video-recorded for 71 days from behind the tower crane operators using a webcam (Fig. 11) and analyzed. The videos were analyzed on the task level. One lifting cycle was counted as one task. Each lifting task took about 2 to 5 min. A total of 345 tasks were observed. The tasks were categorized into six groups: 1) only the anti-collision system was used during the task, 2) only the navigation system was used, 3) the anti-collision system was used longer, 4) the navigation system was used longer, 5) the anti-collision system and the navigation system were almost equally used, and 6) none was used. In the analysis, actual use of the devices was distinguished from crane operators’ non-meaningful behaviors such as turning their heads from one side to the other out of habit or just as an action to relax their neck. Based on our experience and observation, it took at least 2 s to perceive the location information from a lifting supportive device (the navigation system or the anti-collision system). The event durations were included in the total amount of time spent using a lifting supportive device only when the crane operators looked at either the anti-collision system or the navigation system for more than 2 s.

Table 1 and Fig. 12 summarize the analysis results. The analysis results show that, for 90 tasks (26.09%) out of 345, the tower crane operators used neither the navigation system nor the anti-collision system, because a tower crane operator sometimes can see and lift an object without a blind spot in the case of low-rise buildings (a seven-story building in our experiment). However, for most cases (255 tasks out of 345), the tower crane operators used either the tower crane navigation system or the anti-collision system. When the tower crane operators used either the tower crane navigation system or the anti-collision system, they relied heavily on the tower crane navigation system during the lift tasks (99.33%). The crane operators used the anti-collision system only for the other 17 cases (6.67%). Out of 255 tasks that used either the tower crane navigation system or the anti-collision system, 197 tasks (77.23%) were conducted solely using the tower crane navigation system, and in 41 tasks (16.08%), the crane operators used the tower crane navigation system longer than the anti-collision system. No case was observed where the tower crane navigation system and the anti-collision system were used equally. Although the number of test subjects in this experiment was small, the test results clearly indicate that the tower crane operators perceived the new tower crane navigation system as more useful than the existing anti-collision system during blind lifts.

7. Conclusions

This paper presented a hardware system and a software system of a tower crane navigation system developed by the authors through five years of effort, and reported the user experiment test results. This system was developed to assist operation of a tower crane during blind lifts. The developed system showed the location of a lifted object in the context of a building and the surroundings using an imported BIM model and data collected through sensors and a video camera. The system showed the location of a lifted object from the top and side points of views of a 3D BIM model and the actual camera view from the top of the lifted object.

Even if a good technology is invented, if the technology is not accepted by users, the technology will be abandoned. Potential user acceptance of the tower crane navigation system was tested from two perspectives, “perceived ease of use” and “perceived usefulness” based on Fred Davis’s Technology Acceptance Model (TAM) theory [2].

The perceived ease of use was tested through the usability tests of the hardware and the software aspects of the system. Both the interview and the quantitative analysis showed that the perceived ease of use of the tower crane operators increased after they used the second version of the system. The first prototype of the system was tested with six tower crane operators. An interesting finding was that the operators felt that the location of a lifted object was easier to understand in 2D representations (i.e., the top view and the side view).
than in a 3D representation. The initial system was controlled using a touch screen. However, the touch screen technology was inaccurate and slow in controlling the views of a 3D model while the operators’ hands were mostly occupied with two levers to control the tower crane. In a mockup test, the crane operators felt that the 13-inch screen was the most appropriate of the 7-, 9-, 13-, and 17-inch screens and wanted to have the system as close as possible to them. The display system was custom-made using a 13-inch screen and a 19-key mini-keypad. To allow the navigation system to be located as close as possible to the tower crane operator, an adjustable arm was installed. In addition, the navigation system was rebuilt from scratch. The new system had three split views, the top view, the side view, and the camera view. The operators could switch between these three views and set up one view as the main view by simply pressing the Enter key (the largest key) in the mini-keypad. This second version of the system was deployed on an actual construction site for 71 days and tested with three tower crane operators. The quantitative analysis results showed that the perceived ease of use went up from the initial 3.2 to 4.4 points out of 5 after using the second version of the system.

The perceived usefulness was tested by video-recording and analyzing the duration of use of the navigation system against the anti-collision system, a commonly used supportive system for conducting lifting tasks in blind spots. The video analysis showed that tower crane operators used either the tower crane navigation system or the anti-collision system for 255 lifting tasks out of 345. For 197 tasks (77.25%) out of the 255, the operators relied solely on the navigation system, and for 41 tasks (16.08%), the operators lifted an object using the navigation system more than the anti-collision system. The anti-collision system was used for only 17 tasks (6.67%) out of 255. The video analysis and the interview clearly indicated that all the tower crane operators perceived that the tower crane navigation system was very useful in conducting lifting tasks in blind spots. The overall analysis results show that the developed navigation system has very high potential for successful adoption by crane operators.

However, this study has several limitations. In general, field tests of newly developed construction methods and equipment are challenging especially when they involve safety-sensitive tasks such as lifting tasks using a tower crane. Our tower crane navigation system
was not an exception. The number of subjects is too small to draw a statistically meaningful conclusion although the test results reveal a clear contrast in comparison of usefulness of the tower crane navigation system and the anti-collision system during blind lifts.

Second, the current study was conducted at a construction site of a relatively low-rise building (a seven-story building). High-rise buildings generally have more blind lifts than low-rise buildings, and the use of tower crane systems in high-rise buildings may expose the benefits and problems of the tower crane navigation system in different dimensions. Third, a function to automatically update a building model (i.e., a 4D function) was implemented only after the experiments were conducted. The BIM model was linked to a real-time progress monitoring system and designed to update the building model according to the construction progress and to check the status by simulating the construction progress in 4D according to a planned schedule and the actual schedule. The system uses a BIM model of a constructed building, which is connected to the real-time construction progress (schedule) management (RTTPM) system. The building model grows according to the actual progress of the construction. Due to the lack of this 4D function, the building model was updated manually by replacing a building model with a new one during the experiments. Because building construction progresses slowly, no major impact of the manual update on the use of the tower crane navigation system was observed during the tests. However, it would have been ideal if the 4D function was available during the tests.

Fourth, the navigation system can visualize motions of multiple tower cranes and possibly other moving obstacles such as trucks or workers. However, this system has not been tested on a site where multiple tower cranes are operating. And detecting moving objects on a construction site is challenging and will require a significant amount of research to make the technology reach a practical level. These are a few of the many issues awaiting future study.

Acknowledgments

This work was supported mainly by the Korean Institute of Construction & Transportation Technology Evaluation and Planning (KICTEP) with the program number “06-Unified and Advanced Construction Technology Program-D01,” and also partially by the Ministry of Knowledge Economy, Korea, under the national HRD support program for convergence information technology supervised by the National IT Industry Promotion Agency (NIPA-2010-C6150-1001-0013).

References


Table 1

<table>
<thead>
<tr>
<th>Use</th>
<th># of tasks</th>
<th>Subtotal</th>
<th>Interpretation</th>
</tr>
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<tbody>
<tr>
<td>Only tower crane navigation system used</td>
<td>197</td>
<td>238</td>
<td>Relied on the tower crane navigation system</td>
</tr>
<tr>
<td>Tower crane navigation system used longer</td>
<td>41</td>
<td>16 (6.08%)</td>
<td>Used equally</td>
</tr>
<tr>
<td>Systems used equally</td>
<td>0</td>
<td>0</td>
<td>Used equally</td>
</tr>
<tr>
<td>Only anti-collision system used</td>
<td>16</td>
<td>17</td>
<td>Relied on the anti-collision system</td>
</tr>
<tr>
<td>Anti-collision system used longer</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtotal</td>
<td>255</td>
<td>255</td>
<td></td>
</tr>
<tr>
<td>None was used</td>
<td>90</td>
<td>100.00%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>345</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 12. Comparison of navigation and anti-collision system use.

