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

Ghang Lee [a,*], Joonbeom Cho [a], Sungil Ham [a], Taekwan Lee [a], Gaang Lee [a], Seok-Heon Yun [b], Hyung-Jun Yang [a]

[a] Department of Architectural Engineering, Yonsei University, Seodaemun-Gu, Seoul 120-749, Republic of Korea
[b] School of Architecture, Gyeongsang National University, Gyeongnam, Republic of Korea

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ABSTRACT

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%).


## 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 through a wireless data transmitter. 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

* Corresponding author.
*E-mail address:* glee@yonsei.ac.kr (G. Lee).

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**Fig. 1.** Monitor for an anti-collision system.

tower crane navigation system. Section 3 describes the system configuration of the tower crane navigation. The system was developed and evaluated through two user experiments. The usability of the first prototype system was tested with tower crane operators. Then the second system, developed based on the comments and analysis results from the first experiment, was deployed at an actual construction site for 71 days during steel construction work. Sections 4 and 5 report the evaluation results of user acceptance from the "perceived ease of use" and the "perceived usefulness" points of view, respectively.

## 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.

Araya et al. [1] identified a similar problem of blind spots in operating a crawler crane (mobile crane). Crawler crane operators often had a hard time safely controlling a crane boom, which required simultaneous control of several raising, lowering, and hoisting actions, with two levers without visual observation when they had to lift or lower an object to very high or low invisible places. Using a microcomputer-based controller, various sensors, and an algorithm for leveling a boom, Araya and his team enabled crawler crane operators to keep suspended loads level during blind lifts.

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. Shapira and his team [24] also developed a wireless-video-camera system similar to Lee et al.'s and conducted field tests. Shapira 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