# Experimentation to Support Real-Time Monitoring of Mobile Crane Operations

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## Abstract

Monitoring mobile crane motion in real-time is the first step to identifying and mitigating potential mobile crane-related hazards on construction sites. Although standard motions of a mobile crane, such as hoisting, luffing, and slewing of the load can be captured by existing techniques, a reliable approach to accurately position the load and monitor the base motion remains elusive. This study seeks to address this problem by exploring an approach to monitor mobile crane motion comprehensively and consistently in real-time. Two types of sensors are adopted in this approach: 1) inertial measurement unit (IMU) for monitoring the crane load position and sway, and 2) proximity sensing system (iBeacon technology) for monitoring the base motion as well as locating the mobile crane with respect to items on the construction site. This proposed approach was tested in a controlled lab setting. Scenarios were developed to test 1) if the sensory data can be processed and converted to reconstruct the mobile crane motion in a virtual model, 2) if the crane motion can be continuously and accurately modelled in real-time, 3) if potential hazards associated with mobile crane operations can be well detected, and 4) if this approach effectively presents the crane operator with crane motion information and warns them of potential hazards. By enabling real-time monitoring of crane motions and pro-actively warning of the potential hazards, this approach will advance safety practices in mobile crane operations.

**Keywords:** Real-time monitoring, IMU, iBeacon, Mobile crane

# 1. Introduction

The construction industry has long been criticized for its poor safety records. Cranes as one of the central components applied widely in many construction projects, are associated with a large fraction of construction fatalities. According to Neitzel et al. (2001), crane-related fatalities account for one third of the total fatalities in the construction industry. As the two mostly used types of crane in the construction industry, tower cranes and mobile cranes have very distinct uses. While tower cranes sit at a fixed location and operate within a given workspace, mobile cranes have more mobility and flexibility in performing the lifting tasks. According to a study conducted by Kan et al. (2018a), from 2006 to 2016, mobile crane-related fatalities totaled 325 in the US construction industry, accounting for 56% of the crane-related fatalities.

Accidents caused by the operation of cranes are always associated with severe consequences such as occupational injuries and fatalities. Research was conducted to isolate the causes of crane-related accidents, and it was claimed that lack of visibility for crane operators was the principal contributing factor (Hinze and Teizer, 2011). While performing the lifting tasks, crane operators do not receive adequate information concerning the object being lifted and the surrounding conditions. As for mobile crane, the visibility is even more limited since the crane cabin in which the operator sits is attached to the crane base on the ground. The operator's visibility can be easily blocked by obstructions on site or the building under construction. Thus, monitoring mobile crane operations in real-time and providing visual feedback to the crane operator is the first step to identifying and mitigating potential mobile crane-related hazards on construction sites. Although standard motions of a mobile crane, such as hoisting, luffing, and slewing of the load can be captured by existing techniques, a reliable approach to accurately position the load and consistently monitor the base motion remains elusive.

With the aim of advancing mobile crane safety practices, this paper presents a multi-sensor-based approach to monitoring mobile crane motions comprehensively and consistently in real-time. Two types of sensors are adopted: 1) inertial measurement unit (IMU) for monitoring the crane load position and sway, and 2) proximity sensing system (iBeacon technology) for monitoring the base motion as well as locating the mobile crane with respect to items on the construction site. This proposed approach was tested in a controlled lab setting. Scenarios were developed to test 1) if the sensory data can be processed and converted to reconstruct the mobile crane motion in a virtual model, 2) if the crane motion can be continuously and accurately modelled in real-time, 3) if potential hazards associated with mobile crane operations can be well detected, and 4) if this approach effectively presents the crane operator with crane motion information and warns them of potential hazards. The remaining part of this paper is structured as follows: first, existing methods for monitoring crane operations are discussed. Then, the proposed sensor-based method being developed for real-time mobile crane operations monitoring is described. This method was tested in a controlled lab setting and the preliminary results are presented. The concluding part of this paper highlights the limitations of this approach and future steps in implementing the sensing system.

# 2. Related Work

The first known crane monitoring system was developed by Bernold et al. in 1999 and patented in 2002. This monitoring system incorporated a variety of sensors mounted to a crane and an on-board control unit. The control unit stored data collected by the sensors and processes these data to identify unsafe crane conditions, defined as alarm events. Each alarm event was time stamped, and data resulting from the time prior to the alarm event until the conclusion of the event were logged and stored in the control unit. The stored data can be accessed later on and analysis can be conducted against the operations which trigger the alarm event (Bernold et al., 2002). This crane monitoring system was not on a real-time basis, but it brought the crane safety issue to the forefront and represented a good start towards realizing real-time monitoring of crane operations.

Recent studies related to this issue are mostly sensor-based. Lee et al. (2009) introduced a laser-based real-time tower crane lifting path tracking system. In their study, the laser was installed at the tip of the boom, and a reflection board was installed on the hook block. The position information was acquired through the laser beam reflected from the reflection board. However, it was pointed out that this approach was more reliable in measuring the vertical distance between the lifted load and the boom. It failed to position the load three-dimensionally due to the load sway.

Zhang and Hammad (2012) employed a real-time location system (RTLS) using ultra-wideband (UWB) to collect location data of the objects on site and calculate crane poses. In this system, UWB tags were deployed on several spots of the crane boom, and all mobile objects such as workers were equipped with UWB readers when entering the monitored area. It was stated that by using the near real-time updated information, crane pose was estimated, and potential collisions could be detected and avoided. However, there were several practical problems. For instance, UWB works in certain frequency range. The emission of the signal experienced significant loss when falling out of range. In addition, the strength of the signal fluctuates easily due to the existence of interference sources on site. In view of this, the UWB-based approach failed to track the crane poses and load position continuously and stably.

Another major research stream is camera-based. For instance, Lee et al. (2006) deployed a video camera system on tower crane to improve the crane operator's visibility while lifting. A wireless video camera was mounted on the trolley of the tower crane to continuously capture the top view of the lifted load. Videos were transmitted through the wireless communication module to the central computer module and displayed on a monitor installed in the crane cabin. The system was tested in a project using multiple tower cranes and the system was only deployed on one of the tower cranes. It was claimed that considerable improvement could be seen in lifting productivity through the comparative experiment. Communication between the operator and the signal person was also more efficient using the camera system. The camera system provided the crane operator an alternative perspective for the lifting job, however, the vertical view of the lifted load did not provide the operator with enough sense of proximity to the surroundings. The estimation on the position of the load was still subject to the operator's own judgment. In addition, the video camera system was sensitive to the environmental conditions (such as light), and it was ineffective in high-rise building due to the increased distance between the camera and the lifted load.

In these previous attempts, the monitoring of load sway was not well addressed. The monitoring systems that have been developed failed to provide the operator with enough sense of proximity to the surroundings. In addition, existing research on real-time operation monitoring are mostly on tower cranes. Very limited number of researches has taken account of the mobility of the cranes on site. In this regard, an approach to accurately and consistently monitor the mobile crane operations is needed to address the persisting problems that previous research failed to address.

# 3. Methodology

In this section, the two types of sensors adopted in this study, IMU and iBeacon technology are introduced. The following sub-sections highlight the sensor's specific use cases, the mobile device used for visualization, and the communication network used for data transmission.

## 3.1 Mobile crane motion data capture -- IMU

An IMU is an electronic device assembled with a combination of accelerometers, gyroscopes, and sometimes magnetometers. It measures and reports a body's gravitational forces, angular orientation, and sometimes the magnetic field surrounding the body (Dissanayake et al., 2001). The IMU sensor estimates orientation by combining the data it gets from three types of sensors: 1) a gyroscope which measures angular motion, 2) an accelerometer which measures the acceleration due to gravity, as well as any other accelerations that occur, and 3) a magnetometer which measures magnetic direction. The readings from the compass and accelerometer are used together to form the absolute component of orientation, which is used to correct any short term changes the gyroscope makes (Dissanayake et al., 2001).

Generally, an IMU sensor has one accelerometer and one gyroscope for each of the three axes. When rigidly mounted to a point, the IMU sensor measures the linear and angular acceleration and automatically calculates the orientation of the object attached to this point (Zhang et al., 2005). With the ability to track position changes and report inertial measurements, IMU was chosen to capture the position of the crane load and monitor the load sway. Two IMUs were proposed for installation at the tip of the boom and on the hook block, as shown in Figure 1. The illustration here is a crawler lattice boom crane, but the uses are not limited this specific crane type.

Given the measured angular orientation of each axis, the estimated position of the boom and the hook can be calculated by converting the Euler angle measurements to Cartesian coordinates in the local coordinate system (Raab et al., 1979). The axes of the original frame are denoted as x, y, z and the axes of the rotated frame as X, Y, Z. φ represents a rotation around the z axis, θ represents a rotation around the y axis, ψ represents a rotation around the x axis, as shown in Figure 2.

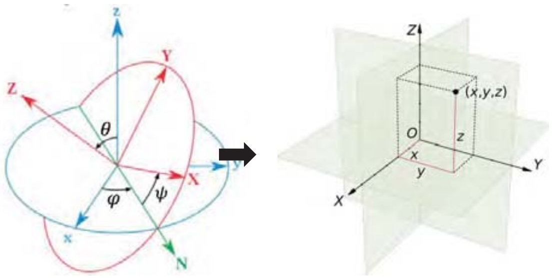


*Figure 1: IMUs' Location on a Mobile Crane (left)*
*Figure 2: Transforming the Angular Measurements to Absolute Positions (right)*

The orientation measurements of one single load can be decomposed into three axes. The individual rotation matrices for each axe are given in Equation (1), (2) and (3) (Raab et al., 1979).

$$M_z(\varphi) = \begin{bmatrix} cos\varphi & -sin\varphi & 0 \\ sin\varphi & cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \ldots(1) \qquad M_z(\theta) = \begin{bmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{bmatrix} \ldots(2) \qquad M_z(\psi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\psi & -sin\psi \\ 0 & sin\psi & cos\psi \end{bmatrix} \ldots(3)$$

Therefore, a single rotation matrix, as shown in Equation (4), can be formed by multiplying the rotation matrices for the three axes. The converted IMU data are used to reconstruct the location of the boom and hook/lifted load. These are then transmitted to a mobile device for the crane operator to visualize the crane motion.

$$M\,(\varphi,\theta,\psi) = M_z(\varphi) \times M_y(\theta) \times M_x(\psi) = \begin{bmatrix} cos\varphi \times cos\theta & cos\varphi \times sin\theta \times sin\psi - sin\varphi \times cos\psi & cos\varphi \times sin\theta \times cos\psi + sin\varphi \times sin\psi \\ sin\varphi \times cos\theta & sin\varphi \times sin\theta \times sin\psi + cos\varphi \times cos\psi & sin\varphi \times sin\theta \times cos\psi - cos\varphi \times sin\psi \\ -sin\theta & sin\theta \times cos\psi & cos\theta \times cos\psi \end{bmatrix} \quad (4)$$

## 3.2 Mobile crane motion data capture – iBeacon

As one of the primary crane motions, the proximal location of the crane is measured by the iBeacon. The iBeacon proximity sensing system is based on Bluetooth wireless sensing technology. The units adopted in this study are Estimote location beacons. The maximum communication range is up to 150 meters, and its frequency ranges from 2400 MHz to 2483.5 MHz. The output power is adjustable: from -20 dBm to +4 dBm in 4 dB steps, to take account for both short-range communication and long-range communication. The proximity sensing system incorporates Bluetooth signal transmitter (iBeacon) and crane operator's receiver (mobile device mounted in the crane cabin). This iBeacon-based proximity sensing system is leveraged to locate the mobile crane and to create a hazard detection area so that alerts will be sent to the crane operator when potential collisions are detected.

In the case of creating a hazard detection area, a three-level warning system is created, as shown in Table 1. The iBeacons which constantly transmit Bluetooth signal are to be placed on mobile objects on site, such as workers. The mobile device, possibly a tablet, which is able to scan for the Bluetooth signal is installed in the crane cabin. In this way, the distance between any objects on site and the mobile crane are monitored and warning messages displayed on the tablet once potential collision hazards are detected.

*Table 1: Collision Warning System*

| Collision Probability | Safety Threshold | Warning Message Triggered | Denoting Colour |
|---|---|---|---|
| Elevated | 15 feet | Danger ahead, need to decelerate | Yellow |
| High | 10 feet | Moderate danger ahead, decelerate immediately | Orange |
| Severe | 5 feet | Critical situation, stop immediately | Red |

The proximal location of the mobile crane is measured through the use of triangulation with three iBeacons (Liu et al., 2007). It is represented as (X, Y) in the coordinate system developed within Unity 3D. iBeacons a, b, and c are iBeacon sub-classes with pre-set X and Y values, where $(X_a, Y_a)$ represents the location of beacon a, $(X_b, Y_b)$ represents the location of beacon b, and $(X_c, Y_c)$ represents the location of beacon c. The proximal location of a mobile crane, (X, Y) can be calculated using Equation (5) and (6) shown as follows:

$$Y = ((T \times (X_b - X_c)) - (S \times (X_b - X_a))) / (((Y_a - Y_b) \times (X_b - X_c)) - ((Y_c - Y_b) \times (X_b - X_a))) \quad (5)$$

$$X = ((Y \times (Y_a - Y_b)) - T) / (X_b - X_a) \quad (6)$$

where $S = (X_c^2 - X_b^2 + Y_c^2 - Y_b^2 + D_b^2 - D_c^2) / 2$

$T = (X_a^2 - X_b^2 + Y_a^2 - Y_b^2 + D_b^2 - D_a^2) / 2$

$D = 10 (txPower - RSSI) / 20$

* RSSI stands for Received Signal Strength Indicator, and txPower stands for calibrated transmitter power.

* The txPower is denoted as the known measured signal strength in RSSI at 1 meter away. Both txPower and RSSI are provided by the iBeacon manufacturer.

An example of using triangulation to determine the location is shown in Figure 3. The three iBeacons are placed on the perimeter of a rectangle. The distances between these three are known so their locations in the coordinate system developed in Unity 3D are known as well. If one is manually set to (0, 0) for the ease of calculation, the locations of the other two can be denoted as (20, 20) and (40, 0). The mobile device, which is the tablet mounted in the crane cabin, is able to receive the Bluetooth signal that the three iBeacons transmitt, so that the RSSI and txPower for the three are known. In this regard, the location of a mobile crane (X, Y) can be calculated using Equation (5) and (6).

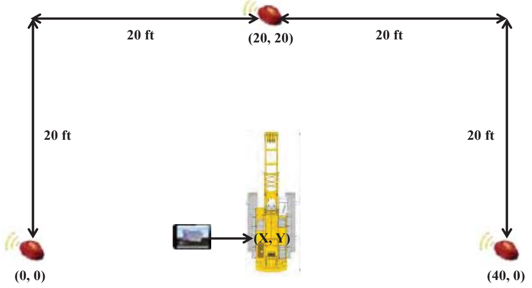


*Figure 3: Triangulation Example*

## 3.3 Mobile devices for visualization

Mobile devices adopted in this study are portable computing devices which have a screen for displaying information, such as tablet PC and Bluetooth enabled smart phones. The mobile device is installed in the crane cabin. It is intended to provide the operator with real-time mobile crane operational conditions as well as the surrounding site conditions, and any supplementary information such as warning messages triggered. Messages shown on the mobile device and auditory warnings are used in this study to indicate hazardous situations.

Figure 4 shows an example of visualizing the crane operational conditions. This virtual platform was developed in Unity 3D. More details concerning how the platform was built and what control algorithms were embedded within the platform can be obtained from Kan et al. (2018b).

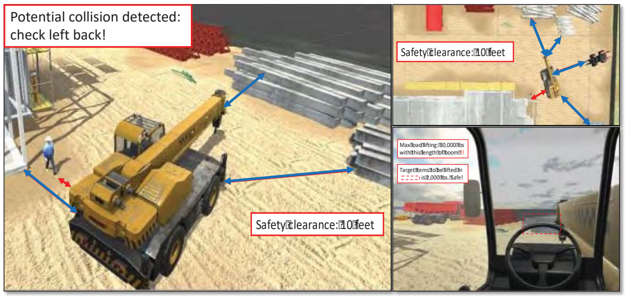


*Figure 4: Example Crane Operation Visualization Shown on a Mobile Device (Kan et al., 2018b)*

## 3.4 Communication network

The communication network enables communication and coordination between the virtual platform and the physical mobile crane on site by enabling sensory data exchange. The communication network adopted in this study includes the Internet and wireless fidelity (Wi-Fi) for IMU data transmission and Bluetooth for iBeacon data transmission. The sensory data are transferred through the communication network to the virtual platform on the central server, which is a local computer. With the mobile device connected wirelessly to the computer, the operational conditions of the mobile crane can be visualized by the crane operator.

# 4. Lab Test & Results

The following sub-sections present the tests performed on IMU and iBeacon respectively. Results are discussed at the end of each sub-section.

## 4.1 IMU

The objectives of the experiment include: 1) to test if the IMUs are capable of tracking the location of the boom and monitoring the load sway and 2) if the sensory data can be processed and converted to re-construct the mobile crane motion in the virtual platform.

To simulate the condition of crane load sway, firstly a tripod was equally spaced and firmly fixed on the ground to establish a stable levelled point. A round load with an IMU vertically attached was hung using a steel chain and securely mounted through the levelled point, as shown in Figures 5 (a) and (b). The IMU used in this study is a 2.4GHz wireless sensor from YostLabs. A direct sequence spread spectrum (DSSS) communication interface in conjunction with a rechargeable lithium-polymer battery are embedded into a single end-use-ready unit. The on-board gyroscope, accelerometer, and magnetometer in conjunction with the processing algorithms are capable of reporting the location relative to an absolute reference in real-time. A communication dongle unit is needed in order to transmit the data to the central computer, as shown in Figure 6. The data received by the computer are constantly written to a txt. file for further analysis, as shown in the bottom of the computer screen in Figure 6.

*Figure 5: Load Sway Simulation: (a) tripod setup and (b) IMU sensor (left)*

*Figure 6: Dongle Unit Connected to a Laptop (right)*

In order to test the capability of IMU in monitoring the crane load sway, a scenario was designed. The load hosting the IMU sensor was lifted 0.3 meters off its original resting position with the steel chain fully stretched and was released with a lateral force. Consequently, the load started to sway annularly. A total of 973 measurements were captured by the IMU in around 60 seconds, and then the load was stopped manually. The measurements recorded in the txt. file were exported into Excel for analysis. The conversion algorithm introduced in the previous section was applied and load sway trajectory was simulated. The results shown in Figure 7 (a), (b) and (c) are for XY, YZ and XZ plane respectively, with the dots denoting the exact measurements and lines mapping out the trajectory. It should be noted that the unit is in meters.

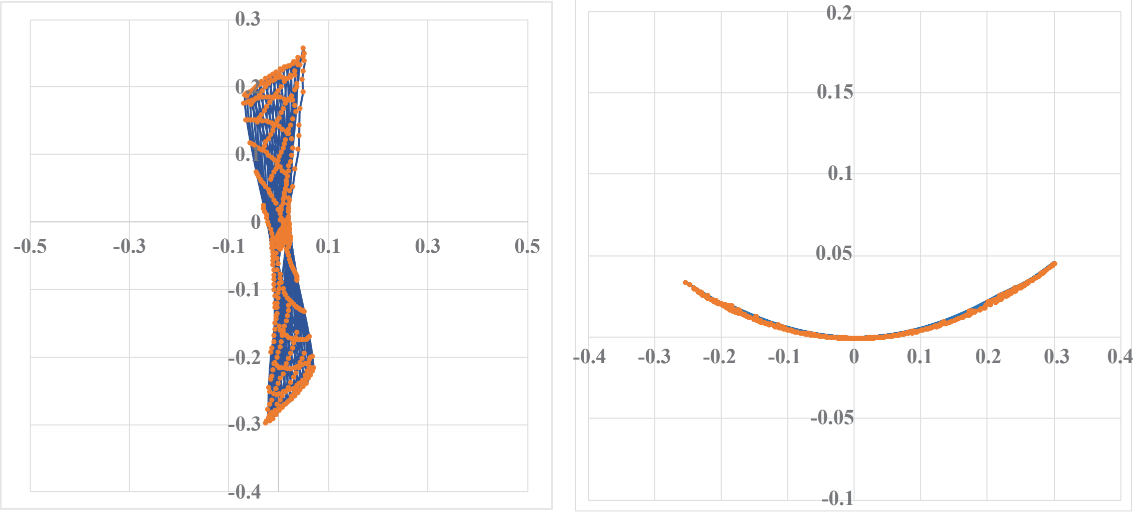
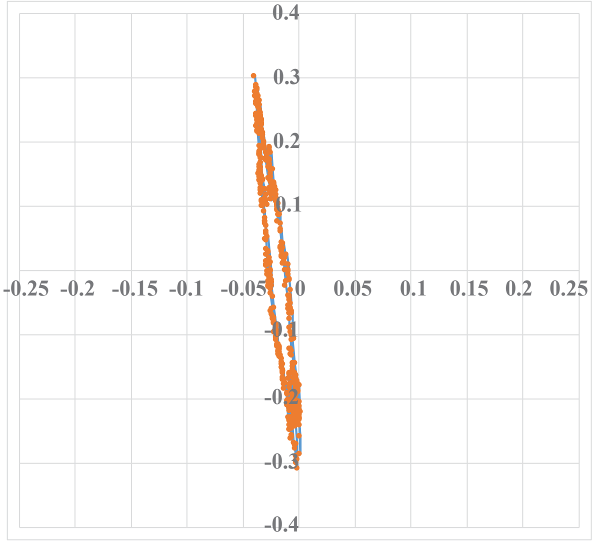


*Figure 7: (a) Sway trajectory in XY plane* *(b) Sway trajectory in YZ plane*



*(c) Sway trajectory in XZ plane*

As indicated by the results, the load sway is an evenly-displaced oval shape, which matches what was observed during the experiment. In this regard, the IMU is capable of tracking the load sway. In addition, the successful re-construction of the load position also indicates that the algorithm for transforming angular measurements to absolute positions works as expected. Thus, the proposed use of IMUs for monitoring and visualizing the positions of the crane boom and load can be further carried out on site for full-scale validation.

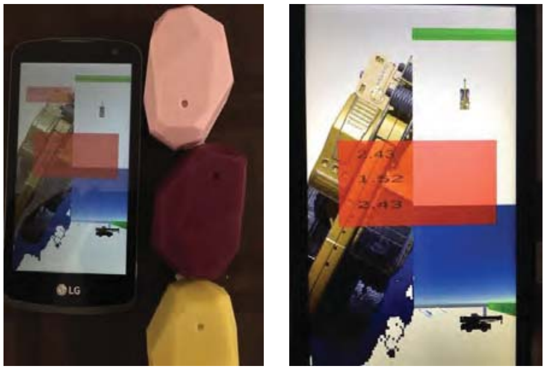
It should be noted that drift was observed during the lab experiments. The drift of the IMU plays a major role in causing some degree of precision loss in the velocity, attitude and position data provided by the unit. Moreover, the drift and precision rates tend to change each time the IMU unit is turned on. In this regard, the drift effect must be adequately considered in order for the IMU unit to capture the load and boom positions accurately in the long term. In future experiments, algorithms adapted from historical inertial data would be used to conduct IMU drift correction upon static positions. In addition, Kalman filter is also proposed to be used to estimate the drifts of the unit and to reduce the accumulated error of the IMU.

## 4.2 iBeacon

The iBeacon-based proximity sensing system was tested with two scenarios to establish 1) if the potential collision hazards could be well detected and 2) if this approach presents the crane operator with proximal crane location.

In order to test the first use case scenario with iBeacon, creating a hazard detection area around the mobile crane, a model with a sole function built-in, ‘reporting the distances between the iBeacons and the mobile device’ was developed in Unity 3D. For ease of reading, the distances between the iBeacons and the mobile device were set to be displayed in a red rectangle in the center, and any warning messages triggered were displayed in the top left corner of the screen, as shown in Figures 8 (a) and (b). In Figure 8 (a), the mobile device was placed in close proximity to the iBeacon, and the distance read in the red rectangle are on a 0.00 (meter) scale. When moving the device away from the iBeacon, the distance read increased, as shown in Figure 8 (b).

In order to further test the function of triggering warning messages, the three-level collision warning system stated in the previous section was added to the model. The function was tested by people with the iBeacons approaching the mobile device from different angles. Figure 9 shows an example of a ‘serve’ condition. One iBeacon were identified to be within 5 feet (1.43 feet) as shown on the top right corner of Figure 9, and a warning message was triggered and was displayed in red.




Critical situation
Stop immediately!

*Figure 8: The Distance Read on the Mobile Device:(a) iBeacons in close proximity and (b) increased distance between the mobile device and iBeacons (left)*
*Figure 9: Example Visualization of a Warning Message (right)*

The second scenario with iBeacon was to determine the proximal location of the crane using the triangulation method. The method was tested in a 16 x 16 ft room. As shown in Figure 10, the three iBeacons were placed on three sides of the room, while the mobile device was placed in between these three. The mobile device was carried and moved in the room, and the location changes for the device were tracked on the central computer.

The triangulation algorithm has been embedded into the virtual platform, with the locations of the three iBeacons manually set to (0, 0), (8 ft, 8 ft) and (16 ft, 0) in this specific case. The three numbers displayed in the top left corner of Figure 11 indicate the distances between the mobile device and the three iBeacons, and the location of the mobile device is represented as the intersection of the three circles. This simple 2D illustration was created in Unity 3D as a separate testing scene apart from the scene with the crane model, and it is only used to visualize the location changes more clearly.

*Figure 10: Lab Settings*

*Figure 11: Mobile Crane Location Determination*

The two test scenarios gave out very sensitive results, which comes from the nature of RSSI. In the first scenario, the distances between the iBeacons and the mobile device are calculated once a RSSI is returned by the iBeacon. The RSSI readings are not very stable and highly depend on the transmission power setting as well as environmental factors. The Bluetooth signals can suffer interference, be diffracted or absorbed. In this sense, the distance calculated is not very accurate. In the second scenario, the location of the mobile device is calculated based on the distances between the three iBeacons and the mobile device. The (X, Y) was set to be calculated once five RSSI readings are received, and the median of the five is used. It takes around two seconds for one calculation to be performed based on the transmission power setting. The problem within this setting is that, the time it takes for the system to receive 5 updates from each of the three iBeacons varies, so the calculations could not reflect the location changes on X and Y at the same time. In addition, the three distances calculated are not accurate on their own, so error accumulation occurs.

Issues that might also account for the error in the results were observed during the tests, and are summarized as follows:

- RSSI goes down if any obstruction is placed between the iBeacon and the mobile device. The reason for this is that, iBeacon signal is a series of radio waves that bounce off obstructions such as walls, ceilings, objects…etc. If a radio wave bounces off an obstruction, and then reaches the mobile device, its strength will be smaller than a radio wave that goes straight from an iBeacon to the mobile device.

- Placing the mobile device at different positions, such as carrying in the pocket, also affects the RSSI.
- The model of the mobile device affects the RSSI (Different antenna affecting the signal propagation… etc.).

Based on the lab test results, the iBeacon technology is not recommended to be used to locate the mobile crane. And in the case of creating a collision hazard detection area, additional algorithm can be added to remove the outliers in the data. If the positioning error can be reduced to an acceptable limit, iBeacons can be used to determine the relative distances between the crane and the mobile objects on site.

## 5. Conclusions

This paper has presented an approach to monitor mobile crane operations comprehensively and consistently in real-time. Two types of sensors were adopted for various purposes: 1) IMU for monitoring the crane boom position and load sway, and 2) iBeacon for determining the location of the mobile crane as well as locating the crane with respect to other mobile objects on the construction site. Tests were conducted for the two types of sensors respectively in a controlled lab setting. Scenarios were developed to test 1) if the sensory data can be processed and converted to re-construct the mobile crane motion in the virtual model, 2) if the crane motion can be continuously and accurately modelled in real-time, 3) if potential collision hazards can be well detected, and 4) if this approach effectively presents the crane motion information and any warning messages triggered. The results indicate that the IMU is capable of monitoring and visualizing the positions of the crane boom and load. Experiments should be carried out on construction sites for full-scale validation. As for iBeacon, it can be used to create a collision hazard detection area around the crane. Algorithms should be added to the existing model to filter out the irregular data, thus providing a more reliable result. iBeacon is not recommended to be used to locate the mobile crane unless better mechanisms/algorithms are found.

The next step of this research will focus on the validation of IMU and finding an alternative approach for locating the mobile crane. Field tests on a real construction site are planned to demonstrate the practical functionality of the system.

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## References

Bernold, L. E., Lorenc, S. J., Elliott, S. D., Cobb, M. S., & Green, A. R. (2002). Crane monitoring and data retrieval systems and method. United States Patent No. US6496766B1. Retrieved from https://patents.google.com/patent/US6496766B1/en

Dissanayake, G., Sukkarieh, S., Nebot, E., & Durrant-Whyte, H. (2001). The aiding of a low-cost strapdown inertial measurement unit using vehicle model constraints for land vehicle applications. IEEE Transactions on Robotics and Automation, 17(5), 731–747. https://doi.org/10.1109/70.964672

Hinze, J. W., & Teizer, J. (2011). Visibility-related fatalities related to construction equipment. Safety Science, 49(5), 709–718. https://doi.org/10.1016/j.ssci.2011.01.007

Kan, C., Zhang, P., Fang, Y., Anumba, C.J., & Messner, J.I. (2018a). A Taxonomic Analysis of Mobile Crane Fatalities for CPS-based Simulation. 17th International Conference on Computing in Civil and Building Engineering (Mela, K., Pajunen, S., & Raasakka, V. (eds.)), Tampere, Finland, June 5-7.

Kan, C., Anumba, C. J., & Messner, J. I. (2018b). A Framework for CPS-based Real-time Mobile Crane Operations. 35th CIB W78 2018 Conference: IT in Design, Construction, and Management (Mutis, I., & Hartmann, T. (eds.)). Advances in Informatics and Computing in Civil and Construction Engineering, Chicago, IL, USA, October 1-3. https://doi.org/10.1007/978-3-030-00220-6_78

Lee, U.-K., Kang, K.-I., Kim, G.-H., & Cho, H.-H. (2006). Improving Tower Crane Productivity Using Wireless Technology. Comp.-Aided Civil and Infrastruct. Engineering, 21, 594–604. https://doi.org/10.1111/j.1467-8667.2006.00459.x

Lee, G., Kim, H.-H., Lee, C.-J., Ham, S.-I., Yun, S.-H., Cho, H., … Kim, K. (2009). A laser-technology-based lifting-path tracking system for a robotic tower crane. Automation in Construction, 18(7), 865–874. https://doi.org/10.1016/j.autcon.2009.03.011

Liu, H., Darabi, H., Banerjee, P., & Liu, J. (2007). Survey of Wireless Indoor Positioning Techniques and Systems. IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), 37(6), 1067–1080. https://doi.org/10.1109/TSMCC.2007.905750

Neitzel, R. L., Seixas, N. S., & Ren, K. K. (2001). A review of crane safety in the construction industry. Applied Occupational and Environmental Hygiene, 16(12), 1106–1117.

Raab, F. H., Blood, E. B., Steiner, T. O., & Jones, H. R. (1979). Magnetic Position and Orientation Tracking System. IEEE Transactions on Aerospace and Electronic Systems, AES-15(5), 709–718. https://doi.org/10.1109/TAES.1979.308860

Zhang, P., Gu, J., Milios, E. E., & Huynh, P. (2005). Navigation with IMU/GPS/digital compass with unscented Kalman filter. IEEE International Conference Mechatronics and Automation, 2005, 3, 1497-1502 Vol. 3. https://doi.org/10.1109/ICMA.2005.1626777

Zhang, C., & Hammad, A. (2012). Multiagent Approach for Real-Time Collision Avoidance and Path Replanning for Cranes. Journal of Computing in Civil Engineering, 26(6), 782–794. http://doi.org/10.1061/(ASCE)CP.1943-5487.0000181