A Low-Cost System for Monitoring Tower Crane Productivity Cycles Combining Inertial Measurement Units, Load Cells and Lora Networks

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Abstract

Tower cranes are one of the most expensive assets inside construction projects and they lead the timing of the planned activities. For this reason, assuring the efficient use of this equipment is essential for the productivity of the project. This work presents a monitoring system for tower crane productivity cycles. It uses an Inertial Measurement Unit (IMU) to calculate jib angles in real time which allows the evaluation of the crane position. In addition, a load cell system measures the lifted load by the tower crane. Data is transmitted via Long Range (LoRa) network. Data is tagged from the origin and sent to the brain, which uploads the information to the cloud. Results show that the system can be used for real time monitoring of the tower crane operation by measuring productivity cycles, average lifted load, and operation hours. This information is organized and displayed in a time series platform that generates inactivity and load alerts to construction managers within the projects.

Keywords

Tower crane • Productivity cycles • Monitoring system • Inertial measuring units • Load cells • LoRa networks

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81.1 Introduction

According to the World Economic Forum the population of urban areas is growing at a rate of 200,000 people per day [1]. Services as housing, transportation and infrastructure are required for communities to carry out their daily activities. Thus, the importance of innovating to optimize time and costs in the Construction sector. While other industries have experienced considerable technology changes, represented in financial and operational benefits, this sector has adopted the changes with lower pace and this situation has affected its productivity [1].

The theory of constraints (TOC), introduced by Goldratt in the 1980s [2], describes the importance of identifying bottlenecks in order to control and measure the flow of materials to increase the productivity of processes. Identifying and optimizing these constraints can be a source for increasing productivity. The main challenge of a construction project is its highly dynamic environment. Thus, programming a construction project involves challenges related to the use of resources. For example, in a building construction project, the structure execution is part of the critical path and the tower crane is a high-cost resource that defines project performance since it allows the transportation and installation of most materials and equipment.

In the past, some systems have been developed to monitor tower crane operation. Most of them aim at improving safety conditions in the construction site, generating alarm signals under hazardous conditions by measuring mechanical and electrical variables, loads, wind speed, among others. These systems use technologies such as RFID, wireless video, black box model, broadband and Building Information Modeling (BIM) [3–7]. Other systems allow measuring variables related to productivity and crane operation. For example, [8] presents a system composed by data acquisition, control, communication and alarm subsystems. The acquisition subsystem consists of four mechanical variables related to crane operation and one for wind speed. The work presented by [9] uses CAN bus and ZigBee technologies to supervise the operating status and tower crane position. In [10] a detailed description of a safety system used for the operation of tower crane groups is provided. Their system uses a sensor that sends information via GPRS or 3G to the terminals. Also, the scheme presented by [11] allows the acquisition, integration, management and control of the data required at a construction site using several communication systems based on ZegBee, 3G and an IoT sensor network connected via a CAN bus, which performs data management through an integrated cloud platform. However, only in a few cases results of the field deployment of the proposed systems are presented. On a commercial perspective, there are crane monitoring systems that provide information of the operational conditions but their high cost is restrictive for its implementation in a larger number of cranes. In addition, they do not provide productivity indicators directly on dashboards and in some cases they are only compatible with cranes from the same manufacturer, loosing flexibility.

This work presents a low-cost, flexible system for monitoring tower crane productivity cycles combining inertial measurement units (IMU), load cells and Long Range (LoRa) Networks. This system allows making informed decisions in real time as well as gathering information for future projects.

81.2 Methodology

A tower crane monitoring and control system was developed and implemented in three types of construction projects:

- An institutional building, developed with a column-beam and slab frame system, with 8 stories and 4 basement and located in Medellin, Colombia.
- A hotel in Bogotá, Colombia with 17 stories, 414 rooms and 2 basements. The construction system consists of column-beam and precast slab frames.
- A 26-story housing project in Itagüí, Colombia built with a traditional beam-column frame system.

81.2.1 System Technical Description

This work presents a system for tower crane productivity cycles monitoring. It uses an Inertial Measurement Unit (IMU) to calculate jib angles in real time. This allows to evaluate the position of the crane at any time. In addition, a load cell system measures the lifted load by the tower crane. This technology offers advantages in terms of power consumption, coverage and

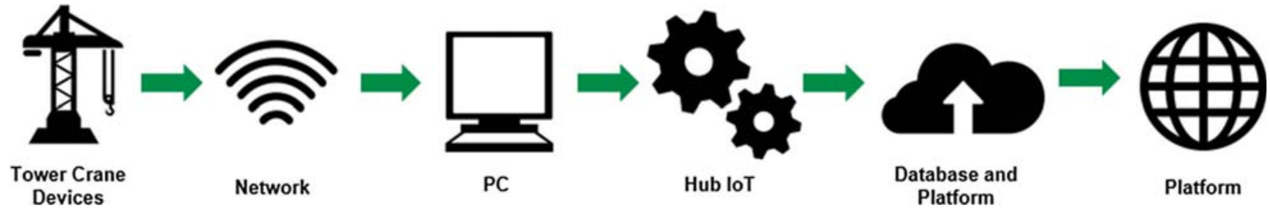


Fig. 81.1 Network overview

Table 81.1 Variables measured by the system

Variable	Units	Description
Jib slewing	Degrees	Generated from 9 variables that are the result of the measurements in the three axes of a magnetometer, gyroscope and accelerometer. Angle is measured in *x, y* and *z* axes
Lifted load	Kg	Indicates the load carried by the crane hook
Jib distance	m	Distance between the mast and the crane carriage

interference response [12], it has an estimated range of 12 km and supports the connection of 255 devices to the brain. Data is tagged from the origin and sent to the brain, which uploads the information to the cloud. The network overview is presented in Fig. 81.1. The coordinator receives the system's information through the LoRa network. Then it is redirected to the cloud platform, where it is processed and stored. The coordinator sends the information to the IoT hub. The load cell is powered by a solar panel that is located on the crane hook and guarantees the autonomy of the system. The system also includes a platform in which dashboards with the indicators are displayed. It also includes security and productivity alerts. The system was implemented in different cities, with different weather conditions, thus, allowing us to prove its energy autonomy due to the operation of the solar panel. Internet access and the quality of the WIFI connection also differ according to the project's resources and its location.

The developed system measures the jib slewing, the lifted load and the jib distance as presented in Table 81.1. Using this information, eight productivity indicators were generated, including cycle times, hook position, load capacity efficiency and percentage of use. Time cycle, hitch time, average time cycle and disengage time are used to analyze production based on the crane's operating cycles. The position of the hook is required to determine the material transported and the impacted activity. The percentage of use and the average daily load are required to analyze the overall performance of the crane over a time period defined by the user.

81.2.2 System Calibration

Laboratory and field tests were conducted in order to validate the system performance under controlled and real conditions.

81.2.2.1 Calibration of the Sensors at the Laboratory

Slewing angle error test: The rotation angle was measured combining the results of a magnetometer, an accelerometer and a gyroscope in the *x*, *y* and *z* axes. For this purpose, the IMU device was coupled to a calibration platform based on a robotic arm which was programmed to make turns at certain test angles. A servomotor rotates in the last degree of freedom of the platform and has a resolution of 0.29°. The IMU calibration procedure is described by [13]. The IMU sensors were individually calibrated, the information was used to find the bias and scale factor of the magnetometer and the accelerometer for each axis using the robotic arm position as ground truth. After making the calibration adjustments, the alignment between the axes was verified and the angle estimation was checked for an error of less than $\pm 1°$.

Load Cell Calibration: A universal testing machine was used to perform this calibration. The tests consisted on applying five different force values to the load cell, which were equally spaced in a range between 1000–5000 N. Each value was applied for 30 s. The test was repeated twice. The load values of the machine's force sensor were plotted against the ADC converter data of the load pin, getting a linear expression to determine the values of the load pin installed at the tower crane over the entire working range.

81.2.2.2 Field Tests

Load cell power supply using solar energy: A solar charging system was designed and implemented. The charging system allows the load cell to be autonomous. The system was tested over several consecutive days with the purpose of monitoring the actual radiation conditions and its internal energy losses. Battery charging efficiency was also tested using an SOC (State Of Charge) circuit.

Transmission range test: Information is transmitted from the tower crane to the central node (Fig. 81.1), which performs the data uploading. Communication distance tests between these components were performed. The central node was left in the project offices while crane devices were moved to different areas of the construction site. This test was made to determine the performance of the communication in the actual interference conditions. The communication between components was considered to meet the requirements of the system when it is transmitted at a distance of 5 km or less. This distance was defined considering the extension of building projects.

Validation of load linearization value on field: Based on the results obtained from the linearization of the load cell in the laboratory, a field validation was performed by comparing the value received by the system and the actual value of the lifted load. Linearization was considered to meet system requirements if it has an error rate of maximum 3%.

Trolley-operator's cab distance tests: Distance between the trolley and the mast was measured according to the power received by a LoRa sensor node located in the cab from a Bluetooth Low Energy (BLE) device located on the trolley. Power obtained by the cabin system is tested every 10 m. The average power for each control distance was estimated with ten movements of the crane carriage.

81.3 Results and Discussion

Results showed that the system could be used for real time monitoring of the tower crane operation. This information was organized and displayed in the platform as a time series. Figure 81.2 shows the percentage of use, average cycle time and number of cycles per hour for a labor day.

Due to the data uploading method required for the platform, sets of 20 data were sent every two seconds. The dataset transmission rate between towers and the LoRa central node was not constant to avoid collisions between data sent from different devices. Although the amount of data usage per day was just 1.2 MB, the Internet access had to be guaranteed, therefore the coordinator was connected to the access point both by Wi-Fi and Ethernet connection. In general, internet speed for construction projects in Colombia is not homogeneous and the connection is not stable.

Fig. 81.2 Indicators visualized on the platform

81.3.1 Calibration and Testing

81.3.1.1 Sensors Calibration in Laboratory

Slewing angle error test: After making the calibration adjustments, the alignment between the axes was verified and the angle estimation was checked for an error of less than ±1 degree for the measurement of the obtained slewing angle. Figure 81.3 shows the calibration cycle for one of the magnetometers. Red dotted circles represent the values of the magnetometer while the IMU rotates on the z-axis in the opposite direction to gravity. Black dots indicate the cycle with the inverted z-axis. The upper cylinder represents the raw acquisition data, and the origin-centered cylinder represents the calibrated data.

Load cell calibration: Two plots are shown in Fig. 81.4. The one on the left shows the value read from the load pin through the analog-digital converter. The plot on the right shows the force on the load cell (data supplied by the force sensor). A direct scale relationship is observed between the machine's force data and the value provided by the load pin.

The linearization value was obtained to perform the scale conversion. The procedure is explained above and the resulting linearization equation is showed below (Eq. 81.1). The plot of the data obtained with the load cell and the plot of the function obtained with linearization are shown in the Fig. 81.5.

$$\begin{aligned} L &= 0.114 * A - 1.3e + 04 \\ \mathrm{RMSE} &= 1.321e - 12, \end{aligned} \tag{81.1}$$

where L stands for load, A refers to the ADC value of the load cell and the Root Mean Square Error (RMSE) is used to determine the error of the estimation.

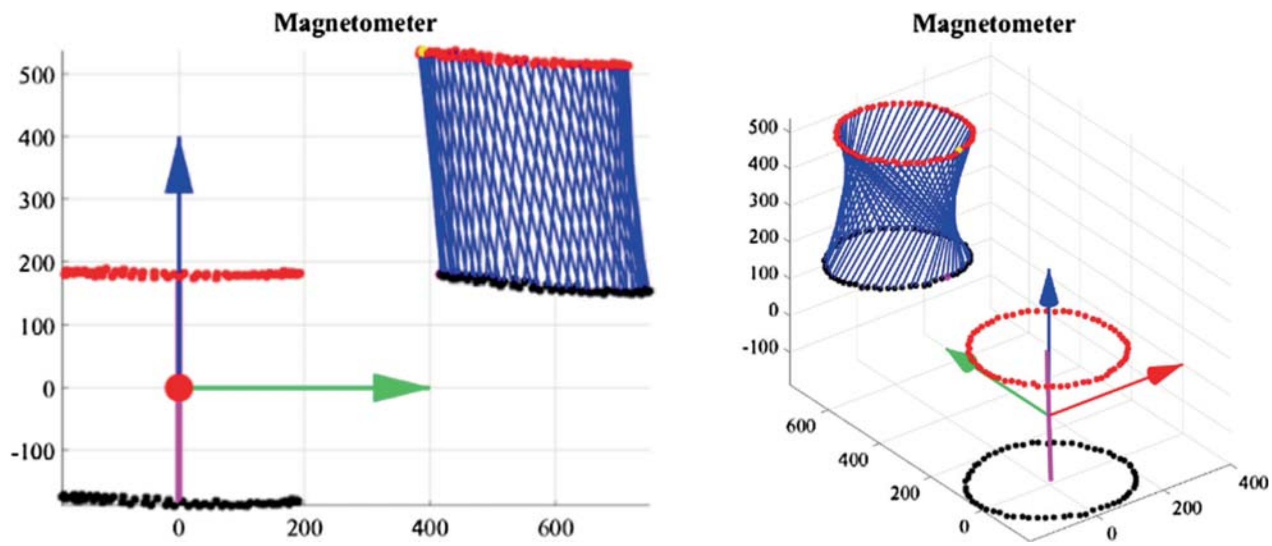


Fig. 81.3 Slewing angle error tests

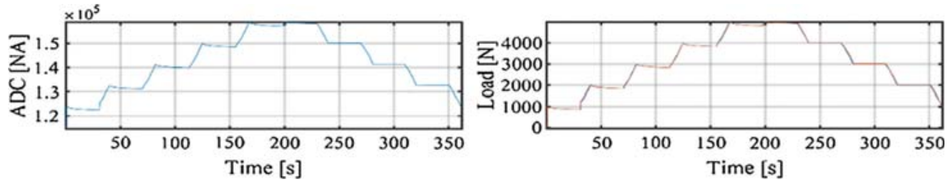


Fig. 81.4 Load cell calibration

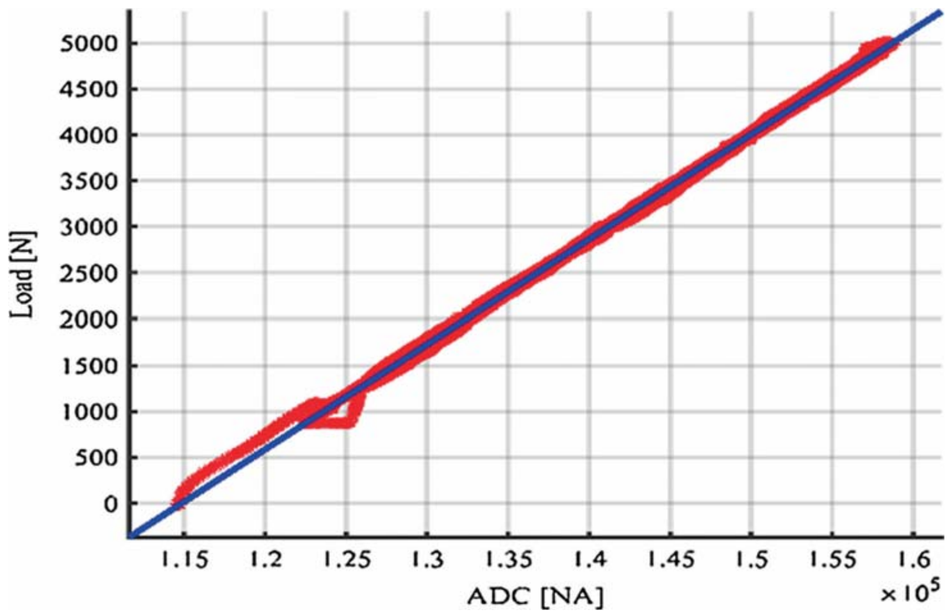
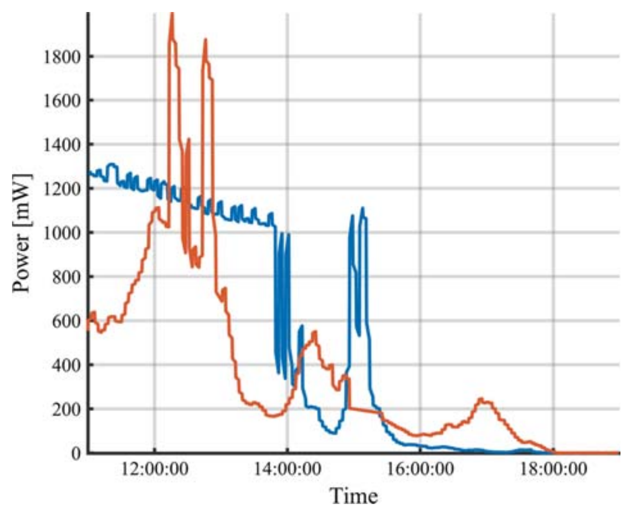


Fig. 81.5 Load cell linearization

Fig. 81.6 Power absorption profile



81.3.1.2 Field Tests

The Validation of the load linearization value on field showed an error of 1.29%.

Load cell power supply: The power profile generated by the solar cell over two consecutive days under actual conditions is shown in Fig. 81.6. The blue line is the profile of the first day, and the red one, the profile of the second day. This test shows that power is a random variable given the number of factors that affect it; however, a dimensioning was made in order to maintain the system functioning up to 5 days under adverse weather conditions.

The behavior of the solar panel during two days under real weather conditions is shown in Fig. 81.7. The blue line is the profile of the first day, and the red line is the profile of the second day. The difference between the state of charge of the battery for one-day to the next is approximately 20%.

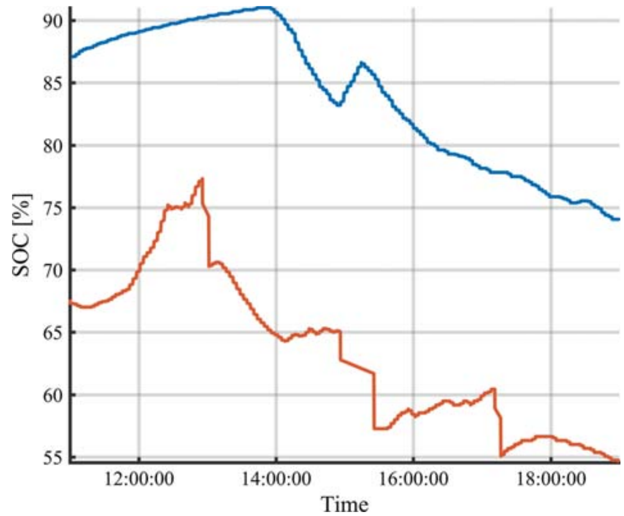


Fig. 81.7 State of chare of the battery for two different days

81.3.2 Comparison with Other Systems

After testing the system, several advantages were identified. The developed system can be implemented at one tenth of the cost compared to commercial systems. This is because the designed system was assembled in Colombia, developed with a local research group, and designed efficiently. Also, the developed system provides more flexibility than other systems, because it can be easily and quickly installed in tower cranes, regardless of their brand and specifications. Also, installation time is reduced about four times, compared to other commercial systems. This is because we use a pre-assembled system, which simplifies welding work, while the other systems need to be totally integrated to the tower crane. Finally, the commercial monitoring system allows the real-time visualization of data. These data must then be processed, which implies a considerable amount of time and work to translate the data into productivity indicators (Table 81.2) as opposed to the system developed in this project, which allows to obtain these indicators in real time directly from the platform that is an integral part of it. Table 81.3 shows a

Table 81.2 Productivity indicators delivered by the system

Indicators	Units
Cycle time	Minutes
Hook position	Meters
Hitch time	Minutes
Average cycle time (daily)	Minutes
Load capacity efficiency	Percentage
Disengage time	Minutes
Percentage of use	Percentage
Average daily load	Kilograms

Table 81.3 Comparison of the indicators measured and visualized by the developed system and by commercial systems

Indicator	Developed system	Other systems
Time cycle	Yes	No
Hook position	Yes	Yes
Hitch time	Yes	No
Average time cycle (daily)	Yes	No
Load capacity efficiency	Yes	Yes
Disengage time	Yes	No
Percentage of use	Yes	No
Average daily load	Yes	No

comparison between the indicators that are measured and displayed directly on the developed platform and the databases delivered by other commercial systems. The indicators are selected based on the productivity methodology implemented in the projects, in which our engineers rely to make decisions.

81.4 Conclusions

The visualization platform which displays real time productivity indicators, allows decision making regarding the actual use of the tower crane and its operation plans for future projects. The information delivered by the developed system is integrated into corporate methodologies which aim to improve productivity of projects. In addition, fewer man-hours are required in the productivity evaluation, thanks to the automation of the measurement and the overall processes.

This work presents a valuable tool for monitoring tower crane's work cycles, which allows improving productivity in construction processes, since this asset sets the rhythm of the project's structure construction phase. The developed system is easy to scale in a large number of tower cranes because it is 10 times cheaper compared to commercial systems. In addition, it is flexible, since it can be customized to the needs of the company and it allows to save time dedicated to information processing. Also, it can be adapted to different tower crane brands, weathers and types of projects. Furthermore, it does not depend on the specifications and type of crane assembly.

The LoRa network used in this project exceeds the initial operating parameters required for the system. The acceptance parameter for the network communication distance was defined with at least 5 km and the accomplished communication was 12 km in line of sight.

Additionally, it was possible to have an adequate data uploading rate (20 data package every 2 s) considering the usage levels of the crane and the need to detect all its movements. This fact makes the LoRa network a suitable cost and performance option for this application. Finally, given the obtained results with the implementation of the system, a second phase of the project is being evaluated. In this new phase the measurement of other relevant variables for monitoring the use of the tower crane, as well as the integration of the information obtained by the system with BIM (Building Information Modeling) is being considered.

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