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An automated crane operation and construction material supply strategy

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Abstract: Traditional construction methods pose unique challenges, such as lack of skilled workers, long construction time and difficulties in quality control. To solve the limitations of traditional construction methods, modular construction has been widely investigated and applied. With the development of robotic technologies and control algorithms, robotic construction, which can further enhance the advantages of modular construction, has attracted many researchers' attention. In this study, an automated crane operation framework, which considers the robotic kinematics analysis and a loop shaping control algorithm, is proposed to automate the construction process. The proposed automated crane operation framework was verified through a construction material supply experiment. To test the performance of the loop shaping controller, a constant reference signal and a sine wave signal are used. The constant reference signal is used to assess whether the loop shaping controller can accurately control the crane to transport the construction material to the pre-defined target position. The reference sine signal is used to test the ability of continuous tracking of the loop shaping controller. Through construction supply experiments, the proposed automated crane operation framework can automate the mobile crane operation in a construction material supply task. This research indicates the potential of robotizing traditional mobile cranes by implementing robotic technologies and control algorithms for automated construction projects.

Keywords: automated crane operation; automated construction; robotic crane; robotic kinematics; loop shaping control

1. Introduction

Traditional construction approaches in the world have many limitations, including the lack of skilled workers, long construction time and poor quality control. In order to solve the issues faced in traditional construction, modular construction using prefabricated or precast components has gradually attracted research's and the construction industry's attention in both private and public sectors [1–6]. To further enhance the strength of modular construction, robotic technologies have been developed in recent years. Compared to the civil construction industry, automated robotic assembly has already been widely implemented in many manufacturing industries [7–9]. Hence, the investigation of using robotic assembly is urgent in the civil construction industry.

Recently, with the advancement of control algorithms and robotic technologies [10–16], the application of robots in robotic construction has been investigated. Leong *et al.* [17] constructed modular lattice structural panels using robotic arm 3D printing technologies. They developed a customized end effector and improved the printing path for the robotic arm to accelerate the construction process. Geno *et al.* [18] used a robotic arm to perform automated cutting for a reciprocal structure made from fourteen tree trunk elements. This research indicated the potential of accelerating the processes of automatic scanning and cutting of timber structures. Willmann *et al.* [19] proposed a novel robotic timber construction approach. The robotic arm was implemented to grasp, transport, and position structural components based on a digital blueprint. The research presented profound changes in the design and performance of architecture. Rogeau *et al.* [20] introduced a fully automated process for integrally attached timber plate structures using a 6-axis robotic arm. They achieved an automated construction by inserting a panel with two through-tenon joints. Currently, a great amount of research mainly focuses on the application of robotic arms. However, due to the size and physical properties of the robotic arms, they can only be used for the construction of small-scale structures or lightweight building materials. In civil construction, it is common to conduct lifting and construction tasks towards large-scale structures or heavy building materials. Therefore, research related to high-payload robots needs to be conducted.

Compared to the robotic arm, mobile crane is normally used for construction of large-scale structures or heavy building materials. Although the market for the robotic cranes involved in construction is still relatively small, the research towards crane control and operation has been conducted recently. The crane control methods mainly include two aspects, which are open-loop control and closed-loop control. Open-loop control methods implement the controllers that compute the input into a system using only the current system state and its model of the crane without the feedback from sensors or a feedback system. On the contrary, closed-loop control utilizes sensor feedback to regulate a crane and maintain a desired state without human interaction. Input shaping is one of the popular open-loop control methods that adopt feed-forward control to reduce the vibrations of crane systems [21–25]. They convolved a sequence of impulses, which are obtained according to natural frequencies and damping ratios of the cranes, to control the swing effects of cranes. However, these methods are not applicable to crane control with unknown parameters. Therefore, adaptive input shaping provides the solutions to tackle this problem. For example, Rehman *et al.* [26] proposed an adaptive input shaper for swing control of a tower crane. The proposed method can achieve good tracking performance under various parameters uncertainties. Open-loop control methods are easy to implement because no feedback is required, and the control law is straightforward. However, the performance of open-loop control methods is easily affected by external disturbances. Compared to open-loop control, closed-loop control methods are more robust and not easily influenced by external factors. One of the most popular closed-loop control methods is proportional-integral-derivative (PID) control. The control gain of the PID controller can be determined based on trial and error, root locus analysis and numerous computational intelligence methods [27–31]. Due to the robustness and ease of deployment of PID controller, it is widely used in various systems, such as shake table, crane systems and robotic arms. In addition to the PID controller, other closed-loop control methods were also investigated in recent years. For example, Kuo and Kang [32] proposed a simple vibration control method for fast crane operation. The proposed method used an open-loop control approach to reduce the swing angle of the hoist rope and high-speed crane operation. Thomas and Sawodny [33] proposed a model-predictive state-feedback control to avoid observation spillover effects for cranes. Their proposed method was tested through simulation and proved that it can dampen the pendulum motion and reduce the drive's acceleration. However, these control methods mainly considered the control of a crane system or a component on a crane. During a construction task, crane operation still required varying degrees of human intervention. More research on control methods that achieve full crane operation needs to be conducted. Research on crane erection plans and lifting path plans is also one of the popular topics. For instance, Kang and Miranda [34] used a virtual crane model to achieve an automated erection process in construction. Their proposed approach has the potential to be used in construction projects that require multiple closely spaced cranes working simultaneously. Kayhani *et al.* [35] proposed an automated lift path planning method for heavy crawler cranes. In this method, the crane was treated as a three-degree-of-freedom robot, and the crane capacity chart, tail-swing and boom clearances were modeled in the resolution-complete method. Zhu *et al.* [36] introduced an automated crane-lift path planning system for high-rise building construction. They verified their proposed metaheuristic path optimization algorithm in a simulation environment. Tian *et al.* [37] integrated building information modeling (BIM) and unmanned aerial vehicles (UAVs) to plan the lifting operation and monitor the construction process. However, the lifting path generated by these studies still required crane operators to execute. They didn't achieve a fully automated crane operation for construction tasks. Hence, more research on automated crane operation in civil construction tasks needs to be conducted.

To address the limitations mentioned above, an automated crane operation framework, which considers the robotic kinematics analysis and a loop shaping control (LS) algorithm, is proposed to automate the construction process. By arranging sensors on a mobile crane, implementing the robotic kinematics analysis and the developed LS control methods, the traditional mobile crane is robotized by our research team and a fully automated crane operation is achieved. The proposed automated crane operation framework was verified though a construction material supply experiment. The tests result proved that the proposed automated crane operation framework is able to automate the crane control and finish the construction material supply task automatically. This research indicates the potential of robotizing traditional mobile cranes by implementing robotic technologies and control algorithms for automated construction projects.

2. Methodology

2.1. Framework for automated crane operation

Traditionally, the mobile crane is controlled by a human operator through a remote controller (Figure 1). The crane motions in a construction task entirely depend on the operator's judgment. With the development of robotic technologies and control algorithms, automated crane operation has become possible. Figure 2 shows the approach that automates the crane operation during a construction task. To be specific, a target position (a 3D coordinate) will be determined first to define the location where the lifted construction material needs to be transported. This target position is determined based on the construction tasks. For the task of stacking building materials, this position can be a designated stacking point. For the construction task, this location can be the position on the structure where structural components need to be placed. Through robotic kinematics, the crane motions that can enable the crane to transport the lifted construction material to this target position will be analyzed. Then, several reference signals, that are calculated based on the generated motions, will be sent to a crane controller. After the crane controller receives the reference signal, corresponding control signals will be generated and sent to the robotic crane to execute. Finally, after the crane receives the control signal, the lifted construction material will be transported to the target position, and an automated construction process will be achieved.

Figure 1. Traditional crane control method.

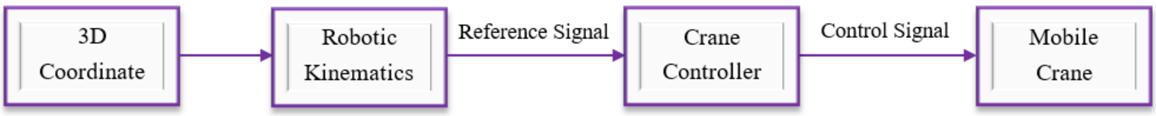

Figure 2. The framework of automated crane operation.

2.2. Robotic kinematics

When conducting robotic kinematics analysis, a mobile crane can normally be represented as a series of links, including a truck frame, turntable, inner boom, outer boom and telescopic booms (Figure 3). A joint is defined to represent the relative motions (rotational or translational movement) between two adjacent links. In this study, joint 1, joint 2 and joint 3 represent the rotation of the turntable, inner boom and outer boom respectively. Joint 4 represents the extension of the telescopic boom. To automate the operation of a traditional mobile crane, robotic kinematics needs to be analyzed including forward kinematics (FK) and inverse kinematics (IK). IK is to calculate the relative motions of all joints (translational or rotational movements) based on the known pose of the end effector link, while FK is to obtain the pose of the end effector link according to the relative motions of all joints.

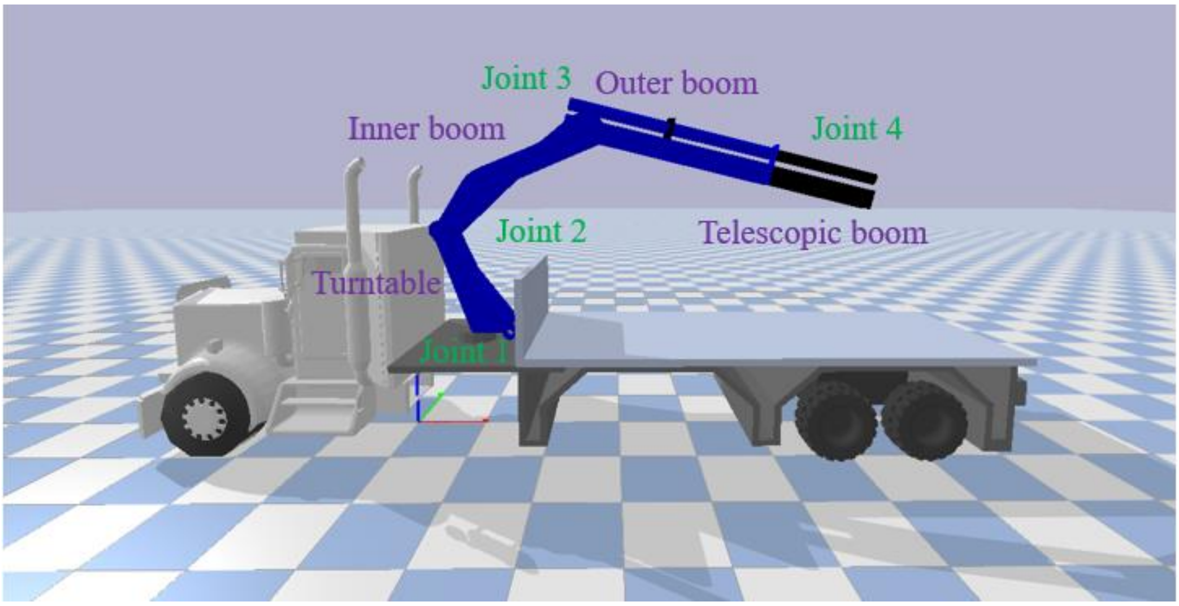

Figure 3. Components of mobile crane.

To analyze the robotic kinematics, a transformation matrix (T) describes the relative pose (including position and rotation) relation of two adjacent joints, which can be expressed as Equation (1):

$$T = \begin{bmatrix} \boldsymbol{R} & \boldsymbol{P} \\ \boldsymbol{0} & 1 \end{bmatrix} \tag{1}$$

where $\boldsymbol{P}$ is the position matrix defining the x, y and z coordinates of an origin of a child coordinate system under its parent coordinate system (Equation (2)). $\boldsymbol{R}$ is the rotation matrix. When the coordinate system rotates an angle (β) about its X, Y and Z axis, the rotation matrix ($\boldsymbol{R}$) can be expressed as Equations (3), (4) and (5) respectively.

$$\boldsymbol{P} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{2}$$

$$\boldsymbol{R_X}(\beta)=\begin{bmatrix}1 & 0 & 0\\ 0 & cos\beta & -sin\beta\\ 0 & sin\beta & cos\beta\end{bmatrix} \tag{3}$$

$$\boldsymbol{R_Y}(\beta)=\begin{bmatrix}cos\beta & 0 & sin\beta\\ 0 & 1 & 0\\ -sin\beta & 0 & cos\beta\end{bmatrix} \tag{4}$$

$$\boldsymbol{R_Z}(\beta)=\begin{bmatrix}cos\beta & -sin\beta & 0\\ sin\beta & cos\beta & 0\\ 0 & 0 & 1\end{bmatrix} \tag{5}$$

In this study, joint 1 to joint 3 are revolute joints. The transformation matrix can be expressed as:

$$T_i^{i-1}=\begin{bmatrix}\boldsymbol{R}(\beta) & \boldsymbol{0}\\ \boldsymbol{0} & 1\end{bmatrix} \tag{6}$$

where $\boldsymbol{R(\beta)}$ can be calculated using Equation (3) to Equation (5) based on which axis to rotate around.

In the case of a prismatic joint (joint 4 in this study), we replace $\boldsymbol{P}$ with the transformation matrix (T):

$$T_4^3=\begin{bmatrix}1 & 0 & 0 & \mathrm{x}\\ 0 & 1 & 0 & \mathrm{y}\\ 0 & 0 & 1 & \mathrm{z}\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{7}$$

The relative movements between the link 0 and the end effector link, which is also known as the FK analysis, can be expressed using Equation (8). When analyzing IK for robotic kinematics, the pose of the end effector link (T_4^0) is known. Therefore, by solving Equation (8) using the method provided by Klampt [38], the relative motions of all joints (including rotation of joints 1–3 and translation distance of joint 4) can be determined. These relative joint motions will be used as the reference signals for the crane controller.

$$T_4^0=T_1^0T_2^1T_3^2T_4^3 \tag{8}$$

2.3 Control algorithm

In this study, the loop shaping (LS) controller is adopted as the crane controller. Figure 4 shows the block diagram of the loop shaping control. Loop shaping control is a commonly used linear control design technique, which can be expressed in Equation (9). The reference signals generated by the robotic kinematics analysis will be sent to the LS controller to generate voltage control signals for the mobile crane. String pots are used to measure the rotation of turntable, and the actuator extended length for the inner boom and the outer boom. A laser sensor is used to measure the extension of the telescopic boom. The reference signals together with the sensor feedback will be sent to the LS controller to generate voltage control signal for the crane to execute the construction task. Through LS controller, the control signals sent to the crane will ensure that each part of the crane (including the turntable, inner boom, outer boom and telescopic booms) will reach the target position (reference signal).

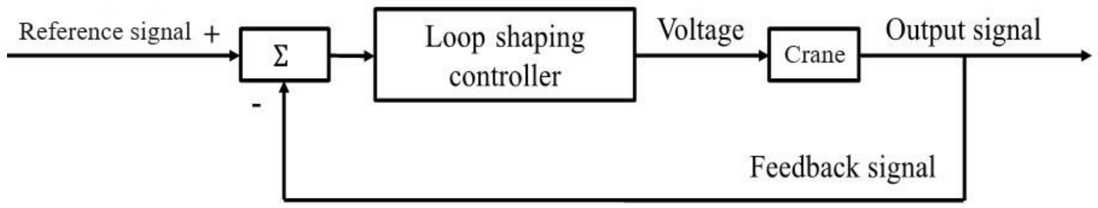

Figure 4. Block diagram of loop shaping control.

$$LS(s) = \frac{LF(s)}{TF_{Plant}(s)} \tag{9}$$

where $LF(s)$ is a loop response function and $TF_{Plant}(s)$ is the transfer function of the controlled system. s is a variable in complex form.

The loop shaping controller main includes the design of the loop function $LF(s)$ to satisfy control system requirements, such as bandwidth, gain and phase margins. In this study, the loop shaping controller is designed for the hydraulic actuator in the mobile crane and $LF(s)$ is designed as Equation (10), where ω_n is the desired crossover frequency. Figure 5 shows the bode diagram of the hydraulic actuator, which is obtained from system identification using a sine wave signal. The transfer function of the hydraulic actuator, representing the servo valve voltage to the actuator displacement, can be obtained based on the bode diagram using "tfest()" application programming interface (API) in MATLAB. After obtaining the transfer function, the loop shaping controller ($LS(s)$) can be calculated using Equation (9). The $LS(s)$ controller is presented in Equation (11), which is expressed in complex form.

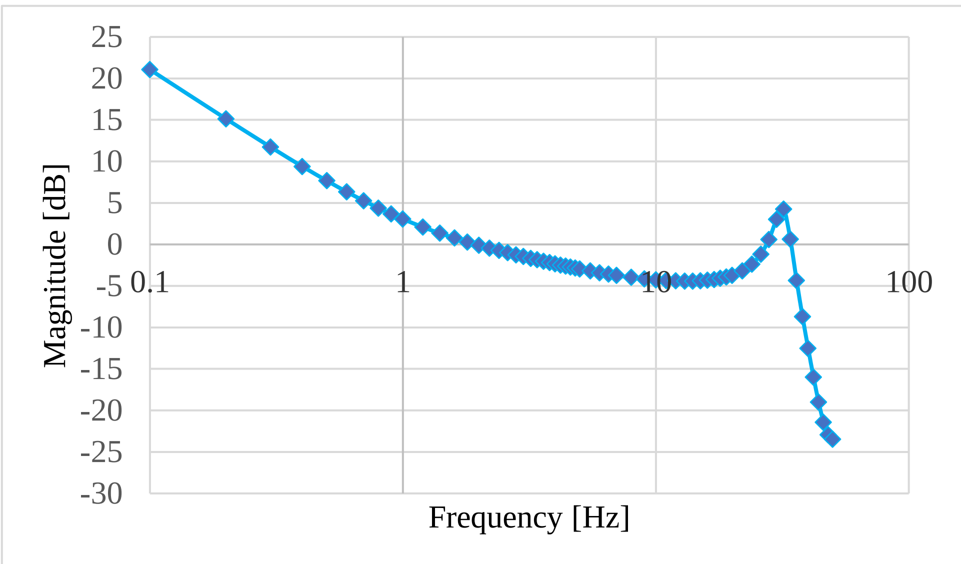

Figure 5. bode diagram of the hydraulic actuator.

$$LF(s) = \frac{\omega_n}{s} \tag{10}$$

$$LS(s) = \frac{39652s^3 + 6.2896e6s^2 + 1.791e9s + 2.1648e11}{s^4 + 4633.8s^3 + 3.8582e6s^2 + 5.4825e8s} \tag{11}$$

3. Experimental validation

3.1. Experimental setup

In this study, the mobile crane, which is robotized by our research team and used to achieve automated robotic operation for construction tasks, is shown in Figure 6. Figure 7 shows the experimental hardware that is used to achieve the automated crane operation. The Advanced Control Testing Systems (ACTS) is used to implement robotic kinematics and LS controller. The data acquisition system (DAQ) is used to send control signals to the control board on the robotic crane and receive control feedback signals from sensors. String pots are used to measure the rotation of the turntable, and the actuator extended length for the inner boom and the outer boom. A laser sensor is used to measure the extension of the telescopic boom.

Figure 6. Robotic mobile crane.

Figure 7. Experimental setup.

3.2. Experiments

In this section, the robotic crane is used to provide construction timber materials by implementing the proposed automated crane operation framework shown in Figure 2. To make sure that the robotic crane can undertake the task, the performance of the LS controller needs to be assessed first. Hence, a reference target position (a constant reference signal) and a reference sine wave signal were used to check the tracking performance of the LS controller without lifting the concrete block. The reference target position is used to assess whether the LS controller can accurately control the crane joint to move to the corresponding target position. The reference sine signal is used to test the ability of continuous tracking of the LS controller. During testing, no object is lifted by the robotic crane. The duration of each test is approximately 1–2 minutes. Take the telescopic boom as an example, the tracking performance results of the LS controller under the reference constant signal and the reference sine wave signal are presented in Figure 8 and Figure 9, respectively. According to the close-up view of the tracking performance, it is evident prove that LS controller has a good tracking performance when controlling the robotic crane.

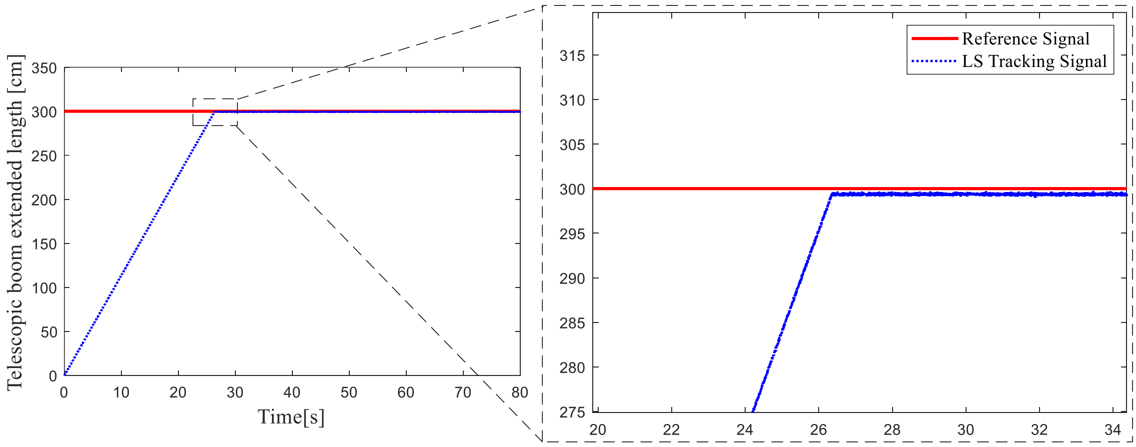

Figure 8. Tracking performance of the constant reference signal.

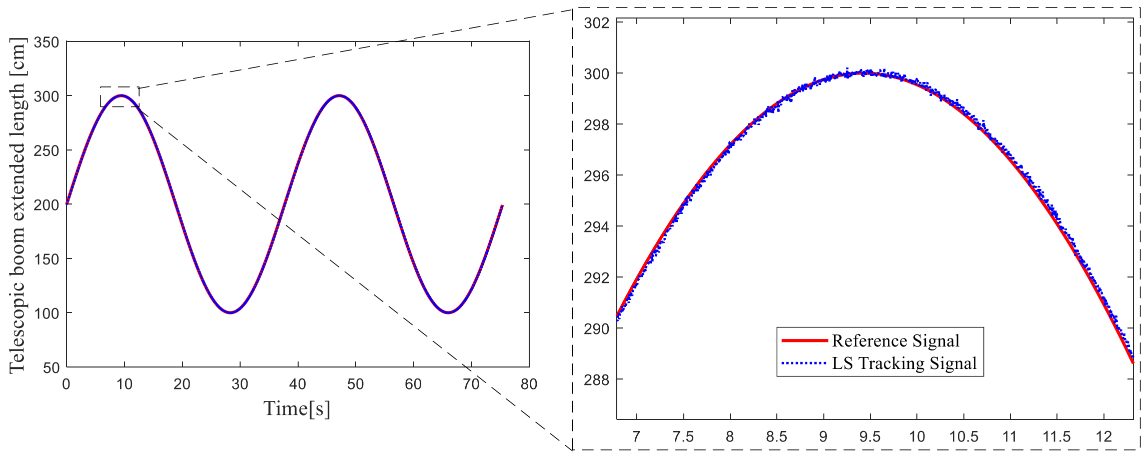

Figure 9. Tracking performance of the reference sine wave signal.

The root-mean-square-error (RMSE) method, shown in Equation (12), is adopted to quantify the performance of the proposed LS controller. Table 1 summarizes the RMSE of the LS controller for constant and sine wave reference signals. When the reference signal is constant, since the telescopic boom needs time to reach the reference position, the RMSE only considers the errors after the telescopic boom reaches the reference position. For the reference sine wave signal, all test data is used to calculate RMSE.

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}\left(S_{ref,i}\text{-}S_{tracking,i}\right)^{2}}{n}} \quad (12)$$

where n is the total number of data used to calculate RMSE. $S_{ref,i}$ and $S_{tracking,i}$ are the reference signal and tracking signal at the i^{th} data, respectively.

Table 1. RMSE of the LS controller for different reference signal.

Type of reference signal	Constant	Sine wave
RMSE	3.54	3.16

Figure 10. Process of automated construction material supply. **(a)** Lifting; **(b)** Transporting (reach TP1); **(c)** Placing (reach TP2).

Figure 10 shows the construction process using the automated framework shown in Figure 2. Two target positions are defined for the robotic crane. The first target position (TP1) is defined in the air where the timber material can be lifted up. The second target position

(TP2) is defined on the ground where is a stacking area for the timber materials. TP1 and TP2 will be used for robotic kinematics analysis to generate reference signal for the LS controller. Then, the LS controller will send the control voltage signal to the robotic crane using DAQ. After the crane receives the control voltage signal, the robotic crane can continuously work until the timber material is transported to the stacking area.

4. Conclusion

The current construction industry poses unique challenges, especially the significant shortage of skilled workers. This research proposed an automated crane operation framework to reduce skilled worker involvement during crane operations. The proposed framework utilized robotic kinematics and loop shaping control algorithms to achieve an autonomous crane operation process. This can reduce the investment in human resources and construction costs during a construction project. In this study, the proposed automated crane operation framework is used to automatically provide construction material on-site. The robotic kinematics was implemented to generate a reference signal for the crane controller and the LS controller is designed to control all the joints of the robotic crane. The tracking performance of the LS controller was assessed through on-site experiments using the mobile crane. A construction timber material supply task was performed to verify the feasibility of the proposed automated crane operation framework. The experiments prove that the proposed automated crane operation framework is able to automate the mobile crane operation in a construction material supply task. In addition, a number of limitations were observed in this research, which are summarized as follows:

(1) When lifting the heavy timber material, the tracking performance of the LS controller was affected. This is because the developed LS controller is a linear controller, and it cannot consider nonlinear effects and the influence on moment of inertia on joint rotation (especially joint 2 and joint 3) when lifting heavy objects. Hence, for those construction tasks that require high lifting accuracy, more advanced control algorithms that consider the effect of lifting heavy objects need to be developed.

(2) Obstacles were not considered in this study. In order to achieve obstacle avoidance, artificial intelligence (AI) algorithms, such as reinforcement learning and deep learning algorithms, need to be developed for the robotic crane.

(3) The experiment task performed in this study is simple and requires low accuracy of the crane controller. Hence, LS controller is capable of undertaking the construction material supply task. However, more complicated experiments, that require high lifting accuracy, need to be conducted to check the feasibility of the advanced control methods and AI algorithms.

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Conflicts of interests

The authors declare that they have no conflicts of interest in this paper.

Authors' contribution

Yifei Xiao: conceptualization; data curation; formal analysis; investigation; methodology; project administration; validation; writing – original draft; writing – editing. **T.Y. Yang:** funding acquisition; resources; supervision; project administration; writing – review.

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