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# Remote Physical Control for Upgrading Heavy Construction Equipment

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**Abstract**

**The construction industry heavily uses many different categories of heavy equipment on a daily basis. Generally, such equipment is used extensively and lasts a long time with limited to no possibility of updating or enhancing. Especially, with the current advancements of technology, there is a need to modernize such mechanical equipment. With regard to equipment control, most equipment requires users to stay close to or directly control the equipment. In this paper, the authors propose an upgrading system that allows the remote operation of heavy equipment through push and pull mechanism. By utilizing a single-board computer such as Raspberry Pi with linear actuators, the system can allow the users to control the heavy equipment remotely. The proposed system is successfully demonstrated by upgrading an indoor tower crane in the D. Dorsey Moss Construction Lab at Purdue University. This type of upgrade could support other heavy equipment in the construction field through integrating various sensors and actuators for digital enhancement.**

**Keywords –**

**Heavy Equipment Upgrading; IoTs; Construction 4.0; Actuators; Construction Automation**

## 1 Introduction

Construction 4.0 concepts lead to more adoption of various advanced digital technologies into the construction industry, including Building Information Modelling (BIM), Internet of Things (IoTs), Robotics, Automation, etc. [1]. Such integration spurs the need for more digitalization and automation, which results in increased productivity, safety and efficiency in the construction sector. With a focus on IoTs and Robotic Automation, the heavy equipment systems in construction need to be upgraded from traditional control (hands-on) to remote control, and eventually to fully autonomous systems.

While new construction equipment is built with certain smart capacities, there are still many problems with traditional heavy equipment in the sector. This equipment needs upgrades to fit the IoTs and Robotic application contexts of the future. In the work of Khan et al., a lot of emerging technologies have been equipped with heavy construction equipment such as Radio Frequency Identification (RFID), Geographic Information System (GIS), Onboard Instrumentation System (OBIS), Artificial Intelligence (AI), Digital Twin (DT), Internets of Things (IoTs), Cyber Physical Systems (CPSs), Computer Vision (CV), Telematics, and so on [2]. Their study showed how those add-on technologies improved the performance of construction equipment. For example, Hera et al. successfully experimented with fully autonomous forestry machine by equipping the AORO platform with GNSS, UEISIM RTW target and I/O computer, Jetson Xavier and Router, Stereo camera, and so on [3]. Zhang et al., with the purpose of guiding and improving the quality of dynamic compaction for geotechnical improvement process, developed a control system with mounting various supported devices such as AT311 antenna, Hydraulic sensors, Code the sensor, CB71108 car tablets and MC100 Beidou smart host on a mobile crane [4].

While many studies focus on the use of those technologies and their integrated benefit, there are not many that address the upgrade of existing physical systems. In case of an attached innovative physical system, Chen et al. developed a Proportional-Integral-Derivative (PID) based Rotation-control device which

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was used to attach at the end of a construction crane's hoist and effectively control suspended item with precise rotation through wireless remote control [5]. Yusof et al. developed a new tele-operated electro-hydraulic actuator which was attached with mini excavator to achieve a full tele-operation of the machinery [6].

While equipment has control buttons for hands-on operations, the ability to control these buttons from a distance is one of the key features for upgrading the system to an IoT with remote control access. Therefore, this paper focuses on developing a plug and play system with a push and pull mechanism, which can be used to allow the remote and/or algorithmic operation of heavy equipment in the construction industry. The proposed system aims to illustrate the potential integration with remote control of a construction crane as a case study.

## 2 Literature Review

Seeing the significance of automation and robotics in construction, especially the need to upgrade machinery to align with the construction 4.0 concepts, enabling the remote operation of construction tools and equipment is the first step to get them connected. The development of tele-operated electro-hydraulic actuators by Yusof et al. [6] could be seen as a key example of the mechanical attachment to the existing machinery for remote operations. In their work, electro-hydraulic actuators are developed specifically to attach to the mini excavator's various driving shifts through a push-pull mechanism. While the design showed case the possible use of the electro-hydraulic actuator with mechanical levers, the system was quite powerful and too complicated for smaller control hardware such as button press or reduced force lever. For smart control actuators, they were seen the most in IoT applications for smart home control and monitoring [7,8]. In the home IoT applications development, control and monitoring devices' "IoT brains", connectivity protocol, user interface, sensors, actuators, and others are the key components to successfully develop an IoT system [9]. With the purpose of developing a low-cost smart automation system, Eleyan and Fallon [8] developed a system that used Phidget Module to control a Servo with actuator that was used for locking the door. The system was designed to communicate with android phone's application through Message Queuing Telemetry Transport (MQTT) communication protocol [8]. In the development of smart home security system by Islam [10], the microcontroller, Yun Arduino, was used while the MQTT was selected due to its light weight connecting protocol to connect with Android application (from phone) and Arduino board. Rubies et al., while emphasizing the non-contact and non-intrusive device which enable users to control elevator button remotely (from phone), proposed an IoT system using servo motor (actuators) for pushing the button, Esp32 microcontroller, web-based interface, and Wi-Fi as communication protocol [11]. Laluma et al. implemented the IoT in the water treatment plant with the purpose of creating a control automation process through Adafruit.io server. Laluma et al. proposed a control system which uses Raspberry Pi, MQTT protocol, and servo motor (actuator) to control the waterflow [12].

Through the literature review, MQTT protocol is identified as a lightweight message protocol commonly used for IoT applications. And for the brain of the IoT, there are many boards available with different capabilities. Raspberry Pi was seen as a capable Single Board Computer (SBC) which can be used with MQTT protocol and can be configured for various control systems.

## 3 Methodology

In many IoTs projects that include the remote-control operation, single board computer/micro control is becoming more and more affordable and has sufficient capability in supporting system control development. While the system was purposefully developed for controlling any push-pull mechanism such as button- or lever-based control remotely, our proposed plug and play system in this paper makes use of single board computer, electrically motorized actuators, and control algorithm with MQTT communication protocol. The smart control module/components can be easily customized and attached to the existing control components/buttons of an existing machinery. The potential of the proposed system is demonstrated through lab testing of a tower crane control system.

Figure 1 illustrates the proposed system architecture, which contains two main sub-systems: (1) the user interface which can be run on any computer, and (2) the control system.

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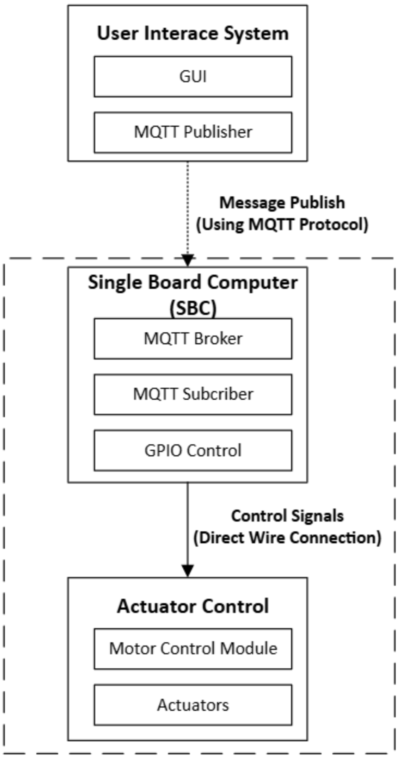


Figure 1. System architecture.

## 3.1 User Interface (UI)

The User Interface (UI) is implemented as a runnable .exe file which is customized to fit the requirement of the control system. Figure 2 shows the interface which is used in the crane control case study in Section 4.

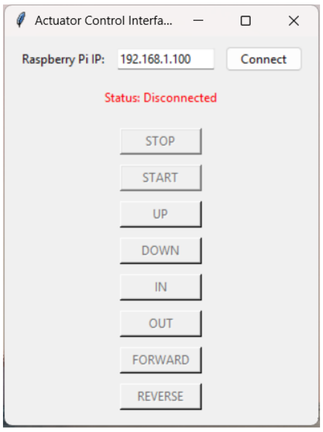


Figure 2. Custom user interface for crane control.

The UI algorithm is developed with TKinter python library with MQTT communication protocol. MQTT is a publish-subscribe and machine to machine (M2M) communication protocol which is widely used for IoTs connectivity [13]. The UI used MQTT as the communication backbone and acted as a client which connected to the MQTT Broker running on the SBC. The MQTT Publisher in the UI allows the user to publish the message from those control actions to the control system (Section 3.2) which will further act accordingly.

## 3.2 Control System

The control system is a key hardware circuit which contains three main components: SBC, motor control driver, and actuator. The system can be divided into 2 parts which are control and communication unit (referred to SBC) and actuator control (motor control driver and actuator).

The SBC, while running the developed control algorithm (Figure 1), triggered the MQTT broker (a central hub for all message exchange between the clients) with a specific IP address. At the same time, the SBC also acted as clients. From the UI, when IP address was provided, and the system was connected. It means that through MQTT, the clients (UI) were connected to server. When the message was published from UI, the client on the SBC (MQTT subscriber through server) received the published message. The message through direct General-Purpose Input/Out (GPIO) pins were connected to the actuator control system. In the control algorithm, there is also an error handling part that triggers the emergency stop condition or reset the control when the SBC loses communication with the server.

The actuator control unit is the circuit which makes use of the motor control driver to run the motorized actuators. The selection of the motor control driver allows the control of different states of the motor in the actuator.

The circuit of the control system which uses raspberry pi 4B as SBC, L298N as motor drive controller, and Actuonix pq-12-30-12-P as actuator is shown in Figure 3.

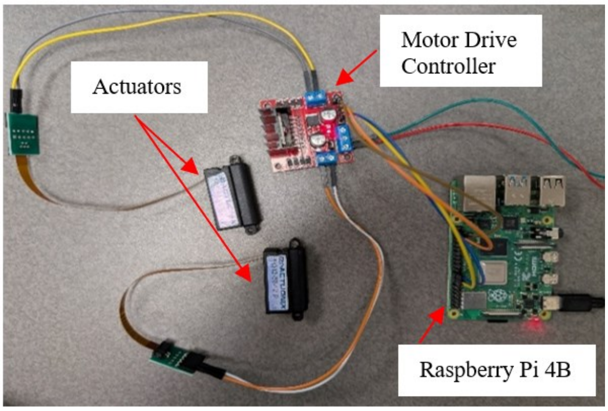


Figure 3. Control system circuit.

## 4 Application and Discussion

### 4.1 Hardware Setup

The system was customized as a plug and play instrument to control a crane controller for an indoor tower crane located in the D. Dorsey Moss Construction Lab in the KNOY building at Purdue University. The crane is operated by direct wire controller as shown in Figure 4.

Figure 4. Default crane control.

The default controller has 8 buttons with 8 different operational functions including START, STOP, UP, DOWN, LEFT (IN), RIGHT (OUT), FORWARD (clockwise), and REVERSE (counterclockwise). While the START and STOP are latching buttons, the others are momentary buttons. They are only activated when being pressed.

To attach the control system to the controller, a mount for the actuator was designed and 3D printed, as shown in Figure 5. The mount contains two parts: the upper part supports the actuator, and the lower part secures the entire structure on the crane's controller. The shape and size can be customized and modularized based on various types of crane controllers. This method can replace manual operation while achieving high speed and accuracy for remote button control.

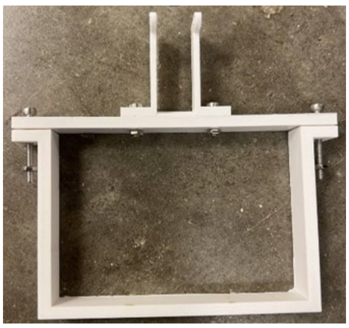

Figure 5. 3-D printed customized mount for the actuator.

As shown in Figure 3, two actuators can be connected to a motor drive controller and connected to Raspberry Pi. To control the 8 buttons of the crane's controller, 8 actuators are connected to 4 motor drive controllers and connected to Raspberry Pi through 16 GPIO pins. For this case, GPIO in and out for STOP, START, UP, DOWN, IN, OUT, FORWARD, and REVERSE are (23;24), (25;8), (26;16), (20;21), (2;3), (17;27), (5;6), and (22;13) respectively. The configuration of the mount with actuators on to the crane's controller is shown in Figure 6. Figure 7 shows the complete set up and testing of the system on the lab's crane.

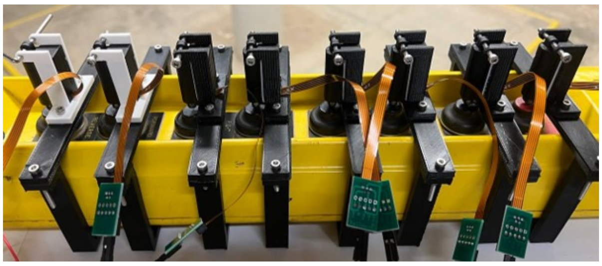

Figure 6. Crane remote control with mounts and actuators.

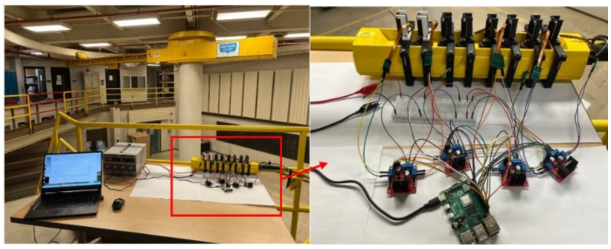

Figure 7. System setup for remote access crane.

The system setup for this crane controller needs two sources of power: (1) 12V power was needed for all the motor driver controllers which supplied to the actuators, (2) the Raspberry Pi ran on 3.3V power supply.

### 4.2 Crane Control User Interface

The development of the crane control UI (shown in Figure 2) resembles the crane controller. The interface required input from: (1) the IP address of the control system (raspberry pi as sever), and (2) status information whether the system is connected to the control system or not. As shown in Figure 8, the UI has 8 buttons as the controller which are divided into two different groups. Group 1 controls latching buttons for which a button is pushed to lock in place and the actuator can be used to push the button again to release it back. Figure 9 shows the algorithm which, when applied, allows the actuator to travel 0.3 seconds and push the latching button, then retreat to the original location.

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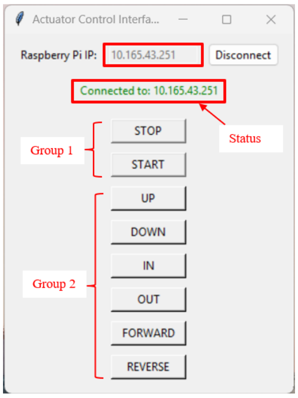


Figure 8. Crane remote control GUI.

```python
def extend_and_retract(pin_in, pin_out):
    GPIO.output(pin_in, GPIO.HIGH)
    GPIO.output(pin_out, GPIO.LOW)
    time.sleep(0.3)
    GPIO.output(pin_in, GPIO.LOW)
    GPIO.output(pin_out, GPIO.HIGH)
    time.sleep(0.3)
    GPIO.output(pin_in, GPIO.LOW)
    GPIO.output(pin_out, GPIO.LOW)
```

Figure 9. Control function algorithm for latching button.

The group 2 buttons are of the momentary type, for which continuing pressing is required to activate the corresponding function. For the interface and activation, when pressing, the state of the button of group 2 (as shown in Figure 10) changes its state in the interface when informing the user that the button is being pressed. When the user clicks on the button one more time, the button state will change to normal, and the actuator retreats to its initial state. The governing function of extending the actuator while being pressed and retreating it when being re-clicked are shown in Figure 11.

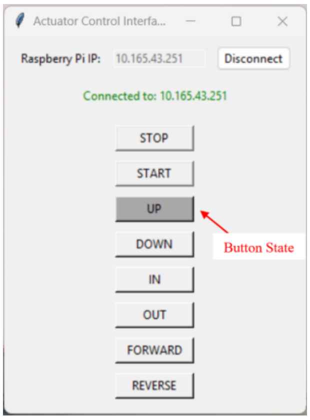


Figure 10. Button state change.

```python
def extending(pin_in, pin_out):
    GPIO.output(pin_in, GPIO.HIGH)
    GPIO.output(pin_out, GPIO.LOW)
    time.sleep(0.3)
    GPIO.output(pin_in, GPIO.LOW)
    GPIO.output(pin_out, GPIO.LOW)

def retracting(pin_in, pin_out):
    GPIO.output(pin_in, GPIO.LOW)
    GPIO.output(pin_out, GPIO.HIGH)
    time.sleep(0.3)
    GPIO.output(pin_in, GPIO.LOW)
    GPIO.output(pin_out, GPIO.LOW)
```

Figure 11. Control function algorithm for extending or retracting the button.

As shown in Figures 9 and 11, the *time.sleep* function of the algorithm allows the actuator to travel (extend or retreat) for 0.3 seconds. It is a trial-and-error value which can make sure the length of travel distance is long enough to press the core of the button firmly. The duration can be varied based on the design of the mount.

### 4.3 Crane Control

After the setting up as shown in Figure 7 and power on the raspberry pi, the autorun of the system triggers the algorithm and allows the MQTT broker to operate. In computer, after launching the crane remote control application (Figure 2), with knowledge of IP address of the Raspberry PI, the App was successfully connected to the PI. While remotely running the system, the proposed mounted platform allowed the user to remotely control all the functions of the crane's controller successfully. This demonstrates that the proposed system with push and pull mechanism can be integrated with various human-hand-friendly control mechanisms by simply altering the 3D printed mount design or mounting mechanism. For example, the system can be integrated to push or release buttons in a tower crane's cab or to shift operating levers and sticks inside an excavator or forklift.

## 5 Conclusion

The construction industry relies heavily on the use of heavy equipment which needs an upgrade to align with the digitalization trend of the construction 4.0 concept. Remote control of those equipment such as excavator, crane, and other mechanical machinery which usually requires hand-on operation are the first steps toward a fully autonomous machine operation. However, to retrofit those components requires significant time and budgets. To address that, this paper illustrates a plug and play system with simple and effective solutions for upgrading existing equipment with button- or lever-based control. This is achieved through a push and pull mechanism to control the existing controller. With the MQTT communication protocol, the remote control of the system can be achieved. The completed remote-control system was tested with a construction tower crane

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in the lab environment. The result showed that it allows the user to successfully control the crane wirelessly. It is proof of concept that can be used for all different devices with button- or lever-based control mechanism.

Despite the successful demonstration of the system, the following limitations of the system are acknowledged: (1) the 3D printed mounting mechanism is required to be modelled and designed based on the retrofitting purpose and existing control hardware, (2) the control system is mainly based one type of the single board computer (Raspberry Pi 4) and communication protocol (MQTT), and (3) only one selected type of actuator was used. Despite those limitations, the case study demonstrates capability and good potential of the system. Future research is recommended to investigate the full tele operation of the crane, linking the physical system with the digital system for digital twin applications, and the development of autonomous operations.

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