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DESIGN OF PARALLEL PROCESSING VERTICAL CLIMBING ROBOT FOR AUTONOMOUS BOLT TIGHTENING OF STEEL STRUCTURE BOLTS

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Abstract: A design of a vertical climbing robot is proposed for steel structure application which specializes in bolt tightening. It utilizes 2 main components, the robot positioning and bolt tightening mechanisms. The robot positioning mechanism allows the robot to move vertically along the steel column; while, the bolt tightening mechanism executes the bolt tightening sequence. The robot should be able to climb up steel I-beam columns, detect location of snug-tightened bolts, map the position of each bolt, and tighten the bolts. The research begins with the design for each component and defining its function and validation is done through simulation of the control process in PICOSOFT 6. The mechanical design of the robot compared to the CFs consists less components which allow quick and flexible installation as it can adjust to different column specifications. The simulation is able to show and execute the sequence of tasks executed such as climbing, sensing of bolts, mapping, and bolt tightening. The vertical climbing robot can execute the bolt tightening task similar to CFs, however the robot is integrated with parallel processing allowing it to be autonomous and consume less time to execute bolt tightening tasks. It maps out the bolts through the CHT algorithm together with the CAM shift method to accurately locate the position of the bolt and tighten the bolts successively with minimal human interaction. Since the paper offers a simulation of the process, further studies such as physical experimentation can be applied to further validate the application of the robot in construction.

*Keywords:*Vertical Climbing Robot, Bolt Tightening, Construction, Parallel Processing, Steel Structure

I. INTRODUCTION

Industrial automation utilizing robots is one popular concept that is incorporated into the system process of various industries. The field of assembly and manufacturing, particularly in automobiles, benefit greatly from robotic systems; since, the application of the system significantly increases the process productivity, in terms of the output quantity and quality [1]. As robotics can greatly improve the process productivity, it however possesses a limited range of application since one requirement is that the robot must operate in an orderly or systematic environment.

A popular field of research for robotic applications is the construction field, due to the concerns it possesses. One important concern in the field of construction is safety. The method that is being practiced up to this day, though guided by safety regulations, still subjects the laborers to fall hazards. Laborers need to climb up high structures or ride man-lifts and bringing all the necessary equipment and materials; thus, this method subjects the laborers to fall hazards or subjects the laborers below to falling objects. The Occupational Safety and Health Administration [2] conducted a study and concluded that Fall hazard is one of the "Construction Fatal Four" and contributes around 39.2%, 381 deaths out of 971, mortality rates in construction. In addition to the mentioned concern, there has been a decrease in skilled or experienced workers due to low birth rate and larger ageing population which are incapable of handling high risk tasks [1]. This offers an opportunity for robot application in construction researches that will answer the mentioned concerns. Integrating automation in the work process will also increase the process productivity [3]. Previous researches in Japan and Korea utilizes a concept called Construction Factory (CF) system [4-13]. This system is similar to a mobile mini factory, equipped with robotic systems which allow some construction processes to be autonomous [1]. Some construction companies in Japan, together with Shimizu Construction developed the Advance Robotics Technology by Shimizu Manufacturing (SMART) in the early 1990s. The SMART system is a fully autonomous construction system and is designed for high rise buildings [3]. The SMART system, however, is limited to rectangular-shaped structures, weighs around 1200 tons, and it can take more than 2 months to assemble and install. Due to these limitations, companies were challenged to meet a breakeven return-of-investment [1]. Developments by Korea was done to answer this issue and designed their own CF and applied the robot-based construction automation (RCA) system. The RCA system, as compared to the SMART system, weighs only 200 tons and is specialized in steel beam assembly bolting and bolt tightening [1]. Construction companies have benefitted from the application of CF systems, but CF systems usually take time to assemble and install and rely on independent structures to be able to translate around to reach a desired position.

This paper proposes a vertical climbing robot specialized in steel structure bolt tightening application, which is capable of functioning independently from CF systems. The robot should be lighter and offers easier installation as there are less components compared to CFs. The robot is more flexible in its application since it only requires steel structure columns as its workspace and is not dependent on the shape of the whole structure. The objectives of the robot are the following: (1) climb up steel I-beam columns, (2) detect location of snug-tightened bolts, (3) map out the position of each bolts, and (4) tighten the bolts. The study offers a design concept of the robot together with the required components of the robots to accomplish the bolt tightening task; and will focus on tightening of bolts located on I-beam column splices.

II. DESIGN CONSIDERATIONS

The structure of the vertical climbing robot possesses 2 main components, namely the bolt tightening mechanism and the robot positioning/translation mechanism. The robot positioning device, equipped with a grasping mechanism, moves the robot vertically along the column whether it is along the flange or the web of the column. A vision camera installed on the robot detects whether bolts are available along its field of vision and maps the position of the bolts. The map is reflected to the GUI that interacts with the operator. The operator selects a path to tighten the bolt and the robot will proceed to tighten the selected bolt as specified with the bolt tightening device. The bolt tightening device is also equipped with a laser range finder to avoid overshooting of the mechanism as it approaches the bolt. After the tightening process, the robot undergoes a looping function until all bolts are tightened. After the whole process, the robot then proceeds to descend from the column back to the initial position it was installed. Figure 1 (*Flowchart of Tasks Executed by the Robot*) represents the flow of the work process and the decision-making considerations executed by the robot in the PLC. The robot will utilize an Allen-Bradley PLC as the controller for the system.

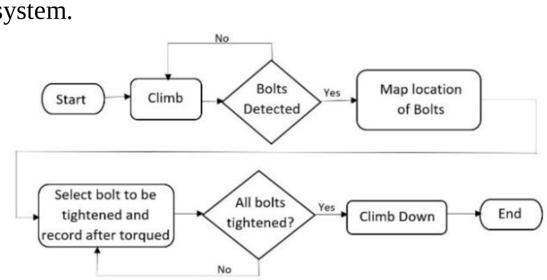

Figure 1. Flowchart of Tasks Executed by the Robot

A. Vertical Climbing Robot

The initial design of the Vertical Robot is shown in figure 2 (Vertical Climbing Robot for Bolt Tightening). The initial function of the robot is to ascend the steel column. As it ascends, the robot utilizes a camera to detect the presence of bolts, upon detecting the bolts, it starts to map the location of each bolt. The robot then proceeds to the bolt tightening phase where in a bolt holder equipped with a piezoelectric sensor, holds the bolt in place then the bolt tightening mechanism, equipped with a laser range finder, proceeds to tighten the bolt. The bolt tightening sequence is repeated until all bolts are tightened, then the robot disengages all the active bolt tightening functions and starts to descend. A proximity sensor is equipped below the robot to avoid clash as the robot descends to the maximum allowable point. Figure 3 (Vertical Climbing Robot Latched to Column) shows 2 positions how the vertical climbing robot can be installed on the column. Detailed explanations for each component are in the further sections.

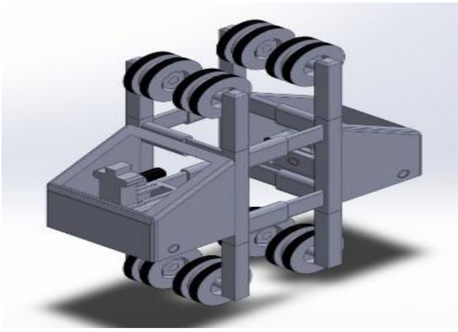

Figure 2: Vertical Climbing Robot

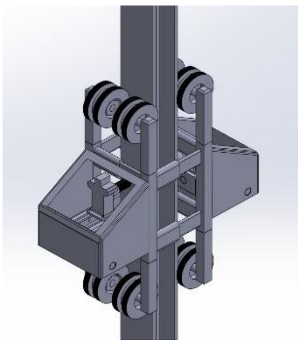

Figure 3(a). Climbing Robot Latched on Column Flange

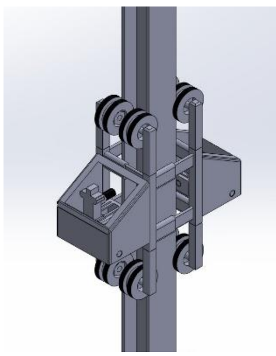

Figure 3(b). Climbing Robot Latched on Column Flange Edge

B. Translational Mechanism/ Robot Positioning Mechanism

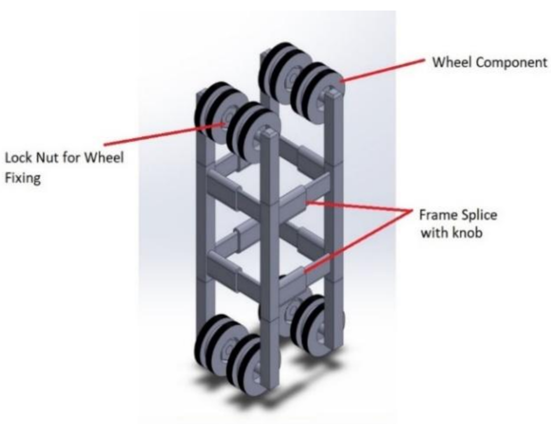

Figure 4: Translation Mechanism

The translational mechanism is composed of a combination of steel frames, wheels, and motors as shown in figure 4 (Translation Mechanism). Figure 5 (Motor Positions) shows the location of the motor that is coupled to a gear box located at the bolt tightening and bolt holding modules. It transfers the torque generated by 2 motors to the wheels which allows the ascending and descending movements of the robot. The 3rd motor rotates the threaded rod which is further explain in sections 2.1.2 and 2.1.3. Additionally, the frames can be adjusted and fixed along the splice by a knob; this allows the robot frame to be applicable to column beams that are 200mm x 200mm up to 300mm x 300mm. The wheels, as shown in figure 6 (Wheel Component) are designed in such a way it allows bolt tightening to be done on both the flange and web side of the steel column. The gap in the middle of the wheel would run along to the side of the flange to avoid slippage while accessing the web area. This design is used since there is a small working surface area on the flange edge. The main function of this mechanism is to position the robot vertically along the column.

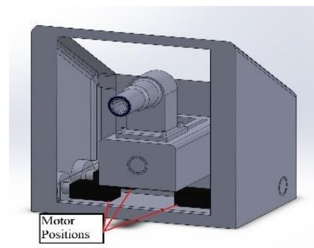

Figure 5(a). Motor Positions

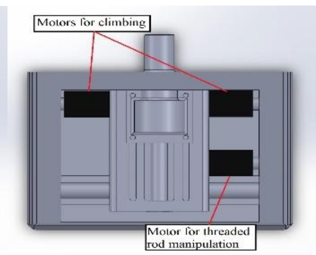

Figure 5(b). Top View

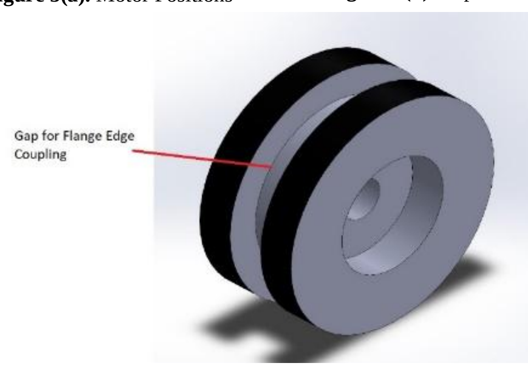

Figure 6: Wheel Component

C. *Bolt Tightening Mechanism*

The bolt tightening mechanism is located on a chamber at the front portion of the robot as shown in figure 7 (*Bolt Tightening Mechanism*). It is equipped with a camera and a laser range finder on top of each other. Table I shows the recommended specifications for vision systems including the laser range finder. The bolt tightening machine is mounted on a slider, actuated by a servo motor connected to a threaded rod, which moves the bolt tightening machine along the x-axis and the y-axis. Figures 7 and 8 shows the allowable positions of the mechanism. Figure 7 shows the mechanism is on the forward left position, while figure 8 (*Bolt Tightening Machine Moved to the Right and Back Position*) shows the mechanism is on the back-right position. A top view is also shown in figure 9 (*Top View of Bolt Tightening Mechanism*) to show the position of threaded rods which moves the mechanism to the desire position.

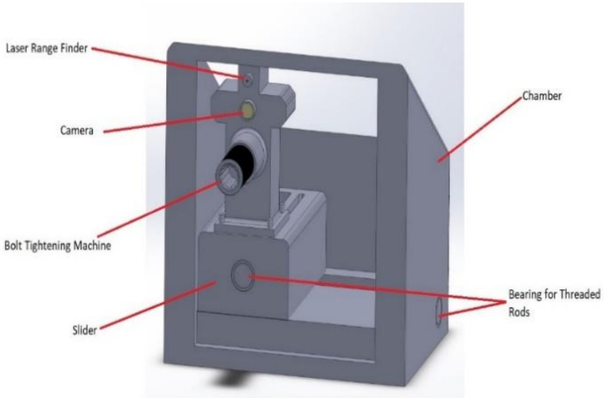

Figure 7: Bolt Tightening Mechanism

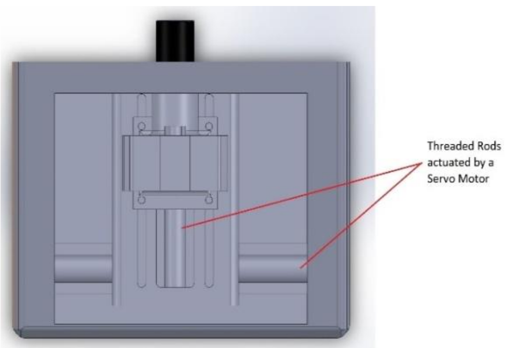

Figure 8: Top View of Bolt Tightening Mechanism

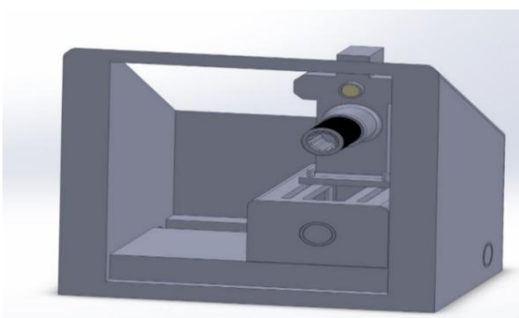

Figure 9: Bolt Tightening Machine Moved to the Right and Back Position

The bolt tightening machine approaches the bolt to be tightened, while the laser range finder will continually send a feedback loop to the PLC controller until the desired position is achieved. The bolt tightening machine will proceed to tighten the bolt with high torque, then disengages and proceeds to the next bolt to be tightened as mapped by the camera. The bolt tightening method utilized in this process is the turn-of-nut method.

D. Bolt Holder Mechanism

The bolt holder mechanism as shown in figure 10 (*Bolt Holder Mechanism*) is located opposite to the bolt tightening mechanism.

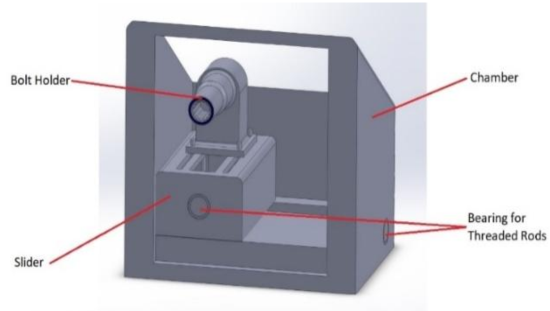

Figure 10: Bolt Holder Mechanism

It is mounted on a chamber with a slider which is also actuated by a servo motor connected to a threaded rod. The bolt holder mechanism holds the bolt head and fixes the bolt into a stationary position to restrict it from rotating together with the nut as it is being tightened. Figures 10 and 11 (*Bolt Holder Mechanism Moved to Right and Front Position*) also shows the allowable positions the bolt holder mechanism can achieve and figure 12 (*Top View of Bolt Holder Mechanism*) shows the top view of the mechanism and the location of the threaded rods which manipulates the position of the mechanism. The bolt holder mechanism is equipped with a piezoelectric sensor (the black colored ring in figure 10). This sensor acts as a contact sensor, as contact is made, the piezoelectric sensor returns a high signal to the PLC controller which stops the bolt head from moving and locksit in position. The bolt holding sequence is before the bolt tightening and is repeated until all bolts are tightened.

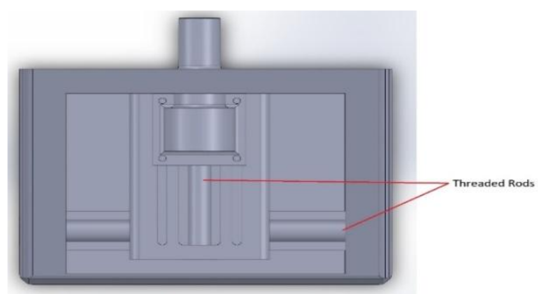

Figure 11: Top View of Bolt Holder Mechanism

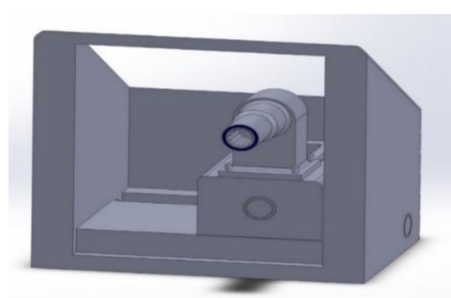

Figure 12: Bolt Holder Mechanism Moved to Right and Front Position

E. Camera

A vision camera is utilized to gather information and process them. Generally, any camera which meets the specifications stated in table I (*Specification for Camera and Laser Range-Finder*) can be utilized in the system. For this experiment, the Kinect v2 can be utilized as it meets the requirements and possesses flexible applications, which allows further developments.

Figure 13 (*Block Diagram of Image Processing*) shows the block diagram of the image processing done. Since bolts are generally circular, the circular Hough transform (CHT) algorithm is used to detect and process circular image as well as the center of the circle. This algorithm is applied to get the location and the center for each bolt present in the splice. The extracted information is then relayed to a feedback control for the image processing. Continuously Adaptive Mean Shift (CAMShift) method is coupled together with the CHT algorithm to continually track the location of the bolts for accuracy.

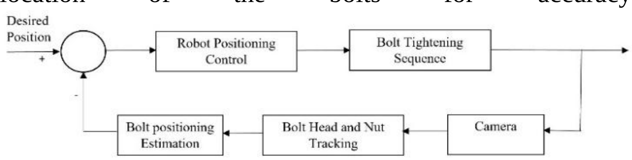

Figure 13. Block Diagram of Image Processing

Table I. Specification for Camera and Laser Range-Finder

Device	*Specifications*
Video camera	Resolution: 640×480×24 b, 30 fps
Laser range-finder	Measuring distance: 0–30 cm Measurement error: less than 0.1 mm
	Communication type: RS232

F. Circular Hough Transform

The circular Hough transform is one common method utilized for extracting circular patterns from an image. It follows the general equation of a circle [14].

$$(x-a)^2 + (y-b)^2 = r^2 \quad (1)$$

Where (a,b) represents the center of the circle and r as the radius of the circle. The algorithm continually calculates points along the circumference through the following governing equations.

$$x = a + r\cos\theta \quad (2)$$
$$y = b + r\sin\theta \quad (3)$$

With set increments for the angle (θ), the algorithm can gather information on the circular pattern. However, this method may take time due to high computing requirement. Since the bolt diameter is known and set in the algorithm, the mentioned limitation or disadvantage is addressed.

III. SIMULATION RESULTS

Simulation of the control system is done in a PLC programming software. This shows the process and decision making the robot applied upon meeting certain conditions. Switches will simulate conditions such as detection of bolts, mapping of bolt locations, bolt tightening sequence, and confirmation of accomplished task. This simulation will only validate the control system of the robot. Simulation is done on PICOSOFT 6 which shows all the process executed by the robot. The simulation will be executed in a ladder logic with a series of rung sequences. When the rung is highlighted with red, it denotes that the rung is active and is being executed in that point. Table II (*Program symbols and representations*) shows a list of the symbols used in the simulation program and their representations. Generally, 'I' would denote an input, 'TT' would denote a timer relay, 'Q' denotes an output, 'M' denotes a marker, and 'C' denotes a counter. The inputs represent the switches which require human interaction such as turning the machine on or off. Outputs represent the particular action done by the robot. Markers, counters, and timer relays serve as the internal decision-making system within the microcontroller.

Table II. Program symbols and representations

Symbol	*Representation*	*Function*
I01	Start button	Stars the robot
I02	Emergency stop button	Stops the robot
M01	Initiates robot ascend	Ascending signal
M02	Initiates bolt detection	Bolt detection signal
M03	Initiates counter 1	Bolt mapping counter signal
M04	N/a	System bug
M05	Initiates bolt holder	Bolt holding sequence signal
M06	Initiates bolt tightening	Bolt tightening sequence signal
M07	Initiates descent	Descending signal
T01	Ascending time	Ascending of robots until detection of bolts
T02	Bolt mapping	Bolt mapping duration
T03	Laser range finder	Bolt tightening machine approach up to desired distance
T04	Bolt holder approach	Bolt holder mechanism approach until desired

		piezoelectric voltage is achieved
T05	Bolt tightening duration	Bolt tightening duration
T06	Proximity sensor	Robot descends until a certain proximity
C01	Counter for bolt mapping	Symbolizes the mapping of 4 bolts
C02	Bolt tightening counter	Symbolizes the tightening of 4 bolts
Q01	Robot ascend function	Execute robot ascend
Q02	Bolt tightening sequence	Execute bolt tightening sequence
Q03	Robot descend function	Execute robot descend
Q04	End	End

The simulation operates under the assumption that 4 bolts need to be tightened in the splice. Figures 14 to 20 shows the ladder logic simulation done in PICOSOFT 6 and each sequence are labeled in a light-yellow highlight.

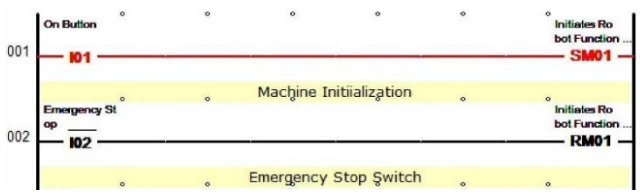

Figure 14: Initiation Phase

Figure 14 (*Initiation Phase*) shows the ladder logic rungs 1-2 which serves at the initiation phase. This switches the robot on and start climbing the vertical column. Line 1 turns the robot on while line 2 serves as an emergency stop button.

Rungs 3-4 as shown in figure 15 (*Climbing Phase*) initiate the robot to climb up and simultaneously detect the presence of bolts. A timer relay was used to simulate the detection of bolts.

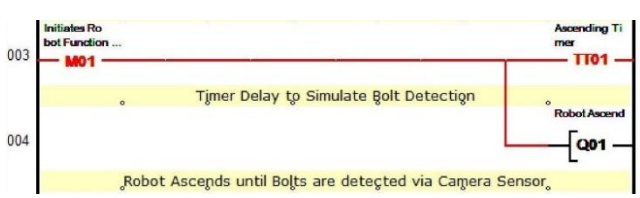

Figure 15 Climbing Phase

Figure 16 (*Bolt Mapping Sequence*) represents the executable set of tasks when bolts are detected. Rungs 5-8 execute the command to stop the robot from climbing further and initiate the bolt mapping phase wherein a timer relay is utilized to simulate the duration to locate and record a single bolt. In this sequence the robot will be actively using the camera to map the location of the bolts. Rungs 9-10 continue the bolt mapping sequence, and loop the function 4 times, as this simulation assumes there are 4 bolts to tighten and this assumption is configured to the counter relay.

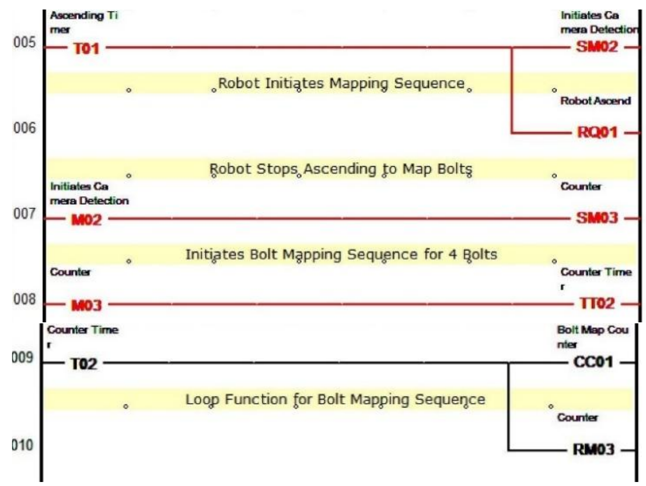

Figure 16: Bolt Mapping Sequence

Figure 17 (*Bolt Holding Phase*) Upon mapping 4 bolts, rungs 11-15 which serve as the bolt holding phase are initiated. Rungs 11-12 initiates the start of the bolt tightening sequence and halt the mapping sequence; while, rungs 13-15 execute the approach and fixing of the bolt holder together with the approach of bolt tightening machine to the bolt head.

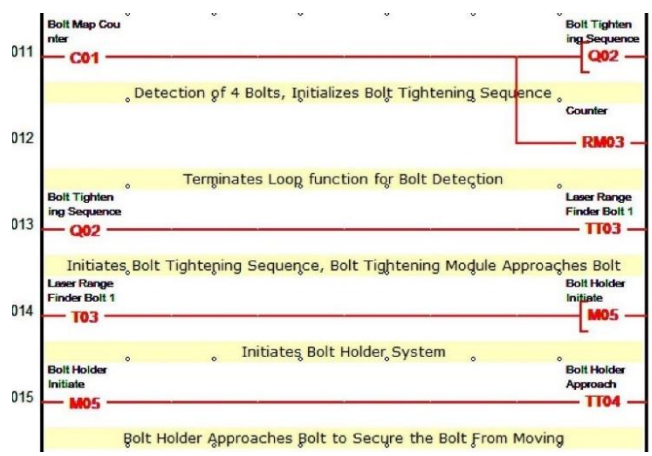

Figure 17: Bolt Holding Phase

Figure 18 (*Bolt Tightening Process*) shows the ladder logic responsible for the bolt tightening process. In rungs 16 the bolt holder fixes the bolt in place and the bolt tightening process is initiated. Rungs 17 – 18 represent the bolt tightening process and timers are used to simulate the duration of bolt tightening. Rung 19 loops the process 4 times for 4 bolts.

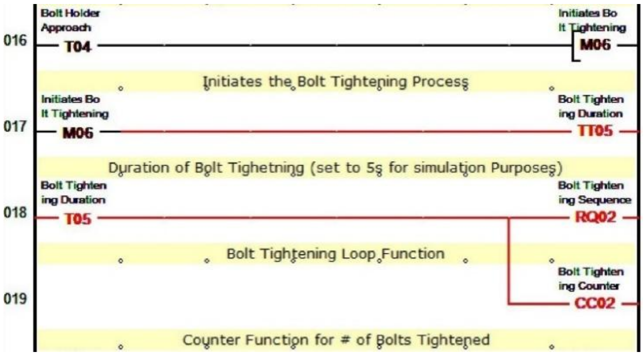

Figure 18: Bolt Tightening Process

Figure 19 (*End of Bolt Tightening Sequence*) shows the steps done upon completing 4 bolts. Rungs 20-21 terminate the bolt tightening sequence and initiate the descent of the robot.

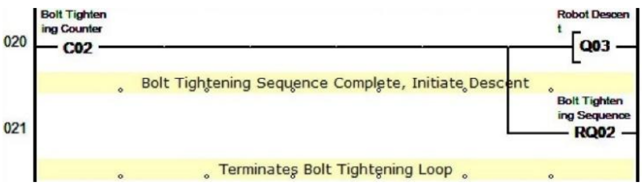

Figure 19: End of Bolt Tightening Sequence

Figure 20 (Descent Sequence) shows the final steps which are executed to conclude the task. Once the descent sequence is initiated, rungs 22 – 27 will disengage any active function and move the robot down. A proximity sensor, represented by a timer, allows the robot to go down until it meets an obstruction or reaches the desired position. Upon reaching the desired position, line 28 ends the robot function.

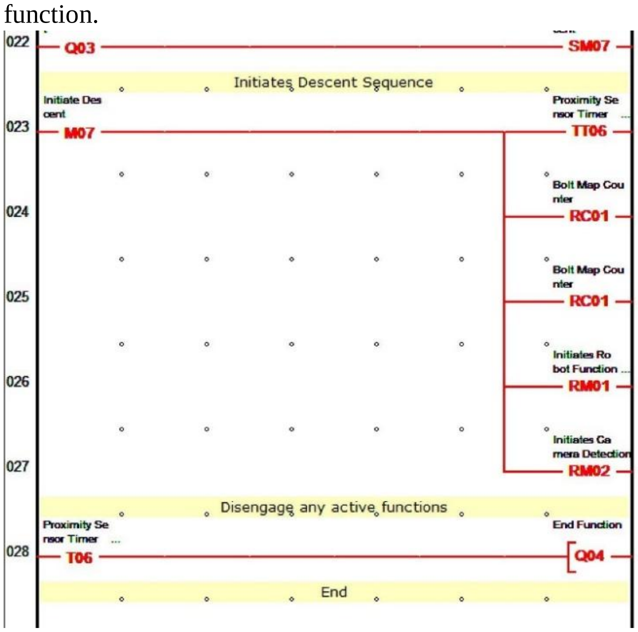

Figure 20: Descent Sequence

Parallel processing was applied to some critical tasks wherein they were executed simultaneously such as the ascend and bolt detection, bolt holder approach and bolt tightening machine approach sequences, mapping and recording of the bolt position. These processes are executed simultaneously to speed up the whole sequence of work. The constant feedback from the sensors and camera allows the work sequence to be autonomous. Human interaction is only required in the initialization phase, emergency stop, pattern setting for bolt tightening, and powering down phase. The simulation conducted in PICOSOFT6 was able to validate the work process of the robot, however timer relays were used to represent the sensors for simulation purposes. The ladder logic was able to autonomously conduct one full sequence of bolt tightening for 4 bolts. The emergency stop button breaks the commands and stops the sequence but freezes the robot in place.

IV. CONCLUSIONS

The paper presented an autonomous vertical robot system for bolt tightening which does not utilize CF systems, allowing it to be lighter and allows quick installation. The translation mechanism allows the robot to move up and down the beam and position accordingly along the z-axis. The bolt tightening mechanism and bolt holder mechanism execute the bolt tightening sequence which are looped until all bolts are tightened. After the bolt tightening sequence, the robot will descend, while a proximity sensor detects when the robot should stop descending. The robot utilizes an Allen-Bradley PLC controller to execute all the necessary processes. A simulation of the control system was done to validate the proposed design and the control system, however further studies can be done by fabrication of the components and physical experimentation of the robot in construction of steel structures to further validate the robot application.

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