Coordinated Motion Planning for Multi-Degrees of Freedom Industrial Robots using Edge Computing Devices

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***Abstract*—Industrial robots are getting a lot of traction in various fields including manufacturing, transportation, healthcare, etc. The coordinated operation of such systems requires the use of multiple sensors, large-scale machine learning, and big data analysis. In this paper, three degrees of freedom (3DoF) pick and place robotic arm is presented, and its coordinated operation is proposed using edge computing devices and programmable logic controllers (PLCs) that execute a proximity sensing and coordination algorithm. The use of edge computing devices executing a sensing and coordination algorithm enables the synchronized operation within microseconds of delay, which could not be achieved using the programmable logic controllers. The results indicate that edge computing devices could significantly improve the safety and security of modern industrial systems.**

Keywords—Programmable Logic Controller (PLC); Raspberry Pi; Motion Planning; Coordination

I. Introduction

Industrial robotics arms are types of autonomous systems that can be used to perform tasks that could take a lot of time or energy if they had to be done manually. Such robots are also being used in safety-critical areas where a human being cannot execute tasks due to safety or security concerns. Robotic arms can be used to reduce the cost of industrial operations and increase the accuracy and precision of tasks if their operation is programmed and coordinated properly. An example of three degrees of freedom (3DoF) robotic arm can be seen in Figure 1, where there are three motors on the arm. The name three degrees of freedom is derived from the fact that the three motors can move independently of each other.

The independent motion of the robots on the arm creates a scenario where tasks can be performed in multiple ways, that involve only one, two, or all three motors at the same time. Considering the case of operating more than one of such motors in an industrial factory as an example, the degrees of freedom could grow with the number of robotic arms used. A 3DoF robot arm could assist an operator who can work on-site or remotely. This automation could allow the operator to execute multiple tasks and operations without concern about being present in person around the factory. Coordinated operation of multiple robots to pick and place items could help system operators who are often engaged in such tasks for long hours. This could save the industry or factory some time, money, and energy, making the process a lot more convenient for all entities involved.

However, there needs to be a mechanism to coordinate which of the tasks could be performed by which robot based on their current status and operating conditions. If there are tasks that are not completed or that have been done so with an error, they need to be corrected by co-ordinating two or more such robotic arms. This work addresses this problem by proposing a new coordination algorithm for motion planning that uses sensor signals from each motor.

II. Literature Review

Recent literature is being performed in the area of motion planning of multi-degrees of robots. Some literature is being developed in this area related to the interaction between mobile pervasive IoT devices [1], multi-robot routing for robots in vineyards [2], position error compensation [3], multi-sensor fusion platforms [4], and dual arm coordination [5], [6]. Algorithmic approaches such as multi-objective optimization and extended and unscented Kalman filters are also being explored for robot motion planning and obstacle avoidance [7], [8].

Literature on coordinated motion planning for industrial robots has focused on using wireless, Wi-Fi, and Bluetooth applications for remote control of the robots. A robot application via a wireless module, which is connected to an Arduino controller board with an ATmega2560 processor model, which has 75 I/O ports and four serial ports has been presented in [9]. In the literature, four stepper motors and one servo motor have been presented that serve as the actuators of the robotic arm, which can move in four different axes. In another literature, a robotic control method based on a closed-loop was proposed for the compliance control of dual-arm robots [10]. The approach used a torque sensor to adjust the robot positions. An interactive control system based on virtual technology has been presented using fuzzy logic for operating in harsh environments [11]. The results from the literature are useful to operate dual robots remotely. However, motion planning and coordination have not been addressed in an industrial setting which is prone to various types of objects and obstacles.

The research area of identifying the types of sensors and information that need to be communicated to coordinate the motion of industrial robots is still not fully explored especially considering complex tasks that involve the motion of various robotic arms and the presence of obstacles. This paper aims to shed some light on this area using a multi-sensor-based coordination algorithm that can be used to send relevant information between three degrees of freedom industrial robotic arms. The rest of the paper is organized as follows. Section III presents the materials and methods used in this research. Section IV presents the results of using a Siemens programmable logic controller (PLC) for coordinating the tasks of robotic arms. Section V presents the results of using edge computing devices for coordination. Section VI presents the conclusions and presents directions for future work.

III. Materials and Methods

The materials used in this project include a programmable logic controller, two types of edge computing devices, and ten different types of sensors. For the programmable logic controller, Siemens S7-1200 PLCs, Siemens Simatic, and PLC simulation software are used. For the edge computing devices, a Raspberry Pi edge computing device and an Arduino Uno device are used. Moreover, the ten types of sensors experimented with in this work include obstacle avoidance sensors, optical proximity sensors, passive infrared sensors, light detection and ranging (LiDAR) sensors, a Doppler-based short-range radar sensor, a microwave motion sensor, analog sound sensors, sonar-based rangefinders, ultrasonic sensors, and collision sensors. The implementation of the multi-sensing platform designed for coordinating the operation of 3DoF robots is shown in Figure 1.

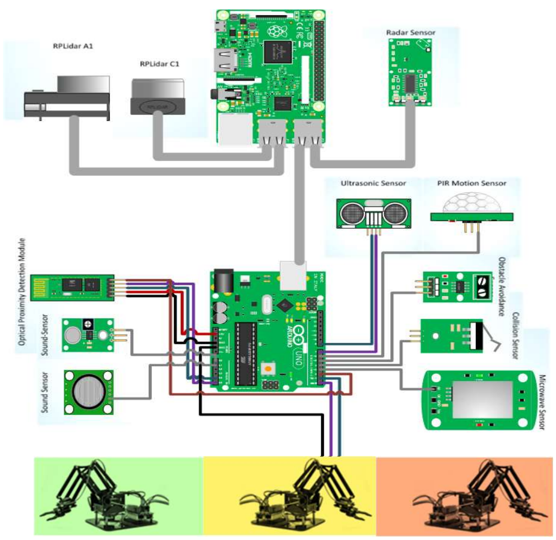

Figure 1: A three degrees of freedom (3DoF) Robot Arm interfaced with sensors connected to edge computing devices

An overview of the coordination method used for multi-sensor, multi-robot operation is shown in Figure 2, where each action is verified from the multi-sensor signals of each robot, and a decision on which robot to move for which task is determined based on the signals from each sensor attached to each 3DoF robot, and based on the task completion status. The details of the coordination are shown in Table 1, where each task has time and space requirements. Whenever a task i is assigned to a 3DoF robot j, there is an associated cost of c_{ij}. In addition, there cost to activate each 3DoF robot j that is represented with a_j. Moreover, the maximum number of tasks that could be handled by each 3DoF robot j is represented by *bj*. The task of coordinated motion planning is to identify a way of operating a group of 3DoF robots to accomplish time and space-constrained tasks efficiently.

For the PLC, a ladder logic diagram was designed to implement the coordination algorithm that engages the different types of sensors with the actuators and motors on the robotic arm. In the ladder logic program, timers are used to synchronize the operations of the motors on the different robotic arms, and the sensing platform is used to coordinate the operation completion status.

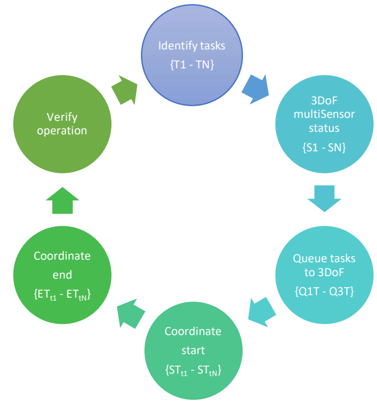

Figure 2: Overview of the coordination algorithm

Table 1: Coordination of the 3DoF robot j to perform task i

Task *i*	**1**	**2**	**3**	**4**	**5**		
Task *i* (*time*)	0.5s	0.2s	0.7s	0.1s	0.25s		
Task *i* (*space*)	0.01m	0.03m	0.01m	0.02m	0.01m		
3DoF *j*	c_{ij}	c_{ij}	c_{ij}	c_{ij}	c_{ij}	a_j	b_j
1	4	3	4	2	1	100	60
2	3	5	5	4	2	100	70
3	1	2	4	3	1	100	80

For the edge computing device, Raspberry Pi boards that implement a coordination algorithm written in Python were implemented to control the sensors and actuators on the robotic arms. The coordination algorithm defines appropriate general-purpose input-output pins, step ranges for the actuators, and step sequences for the motors. The sensing would indicate which of the robot tasks would need to be performed repeatedly to accomplish a given task. The hardware system consisted of sensors and actuators connected to a Raspberry Pi to create a physical representation of the industrial model. All the sensors and motors were connected to the GPIO board and interfaced with the robotic arm.

IV. Results of Using a PLC with Timer Coordination

Using a programmable logic controller, when an industrial tool is placed in the designated location, a proximity sensor is activated, which signals for the robot to begin the retrieval process. The robot moves horizontally for ten seconds and vertically for seven seconds. This is performed by the activation of two different motors and ultimately positioning itself directly above the desired destination. This process can be seen in Figure 3. Once the arm was above the tool that needed to be picked, a third motor, which controls a claw attached to the end of the arm, was activated. The arm paused above the tool for 3 seconds to make sure the item was picked properly, then returned to its original location. This process can be seen in Figure 4. Once a robot arm arrived at its original location, the items that were retrieved were dropped into a bin. Moreover, a one-second delay was added to make sure the items were placed in the appropriate bins.

The use of multiple sensors on the robot arm enabled the prevention of collisions between robotic arms while they operate. This avoided major risks to the safety of the operating environment. In addition, it is important to note that the duration of time each motor is running is coordinated. The operational times depended on the information that is communicated between the sensing platform and the individual robots. The timing of the current system can be seen in Figure 3 and Figure 4. The green lines show when a motor is running, and the blue lines show when it is not.

V. Results of Using Edge Computing Devices for Multi-Degrees of Freedom Robot Coordination

The edge computing device consisted of a Raspberry Pi and an Arduino Uno with Wi-Fi and Bluetooth functionality. The three motors of the robotic arm were programmed to run on a loop, mimicking the forward and backward movements of the arm. These motors were activated to run in loops within 10 seconds of cycles. However, if any of the sensors were activated on the multi-sensing platform, the system would verify the signals with the remaining sensors. This was created to prevent the robot from continuing to run if there was an obstacle in the way. Also, the LED would light up when the motors were in use and turn off when there was an obstacle activating the collision sensor. The signals from the multi-sensors from the three degrees of robots are shown in Figures 6 to 10, where a Doppler radar sensor, an ultrasonic sensor, a microwave sensor, and LiDAR were used to verify sensing from one or more points of reference. The results are interesting in that they show that no one sensor outperforms other sensors in quality of measurement, however, a consensus can be generated.

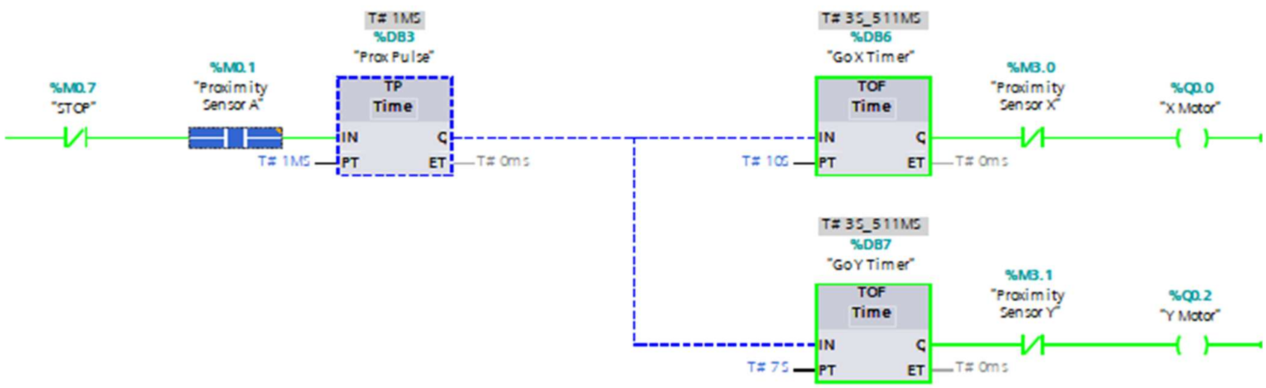

Figure 3: Motion control of three degrees of freedom robot arms to move a tool to a specified X and Y location

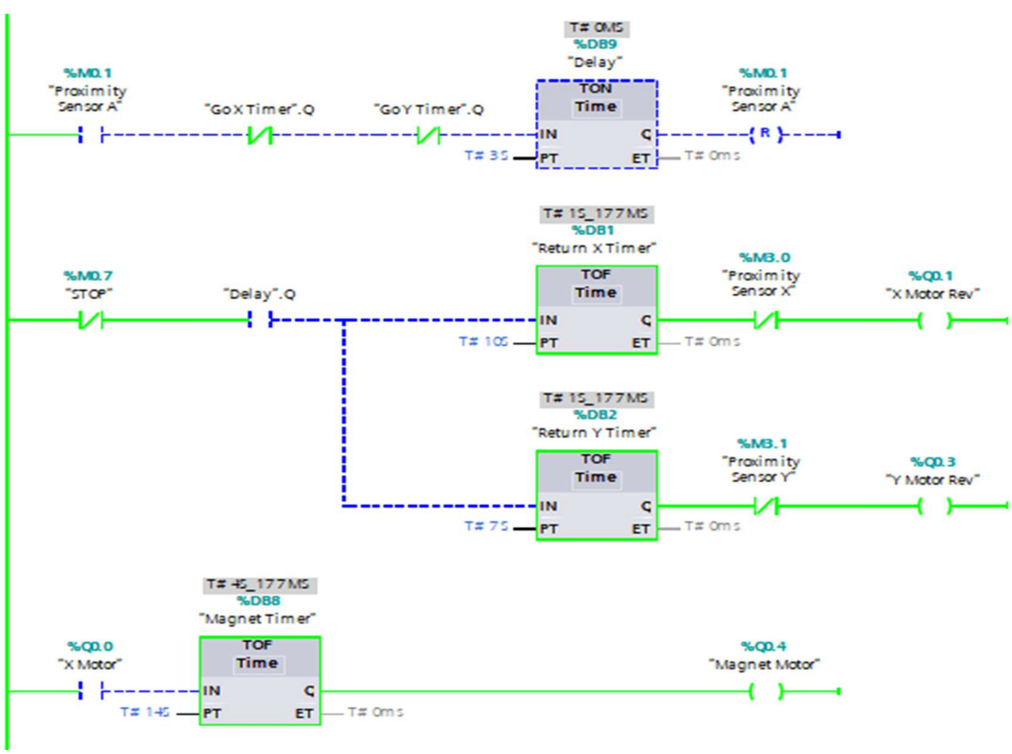

Figure 4: Mechanism of checking that the required tools are retrieved

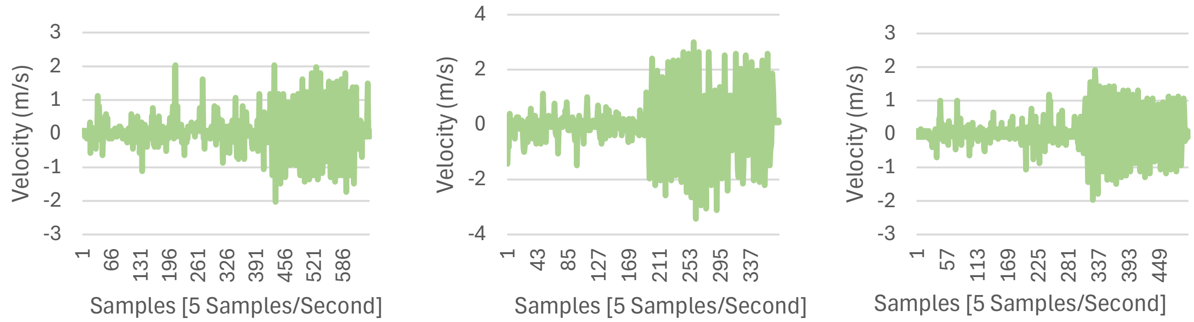

Figure 5: Data collected from the Doppler radar sensor at 5 samples per second rate from three degrees of freedom robots

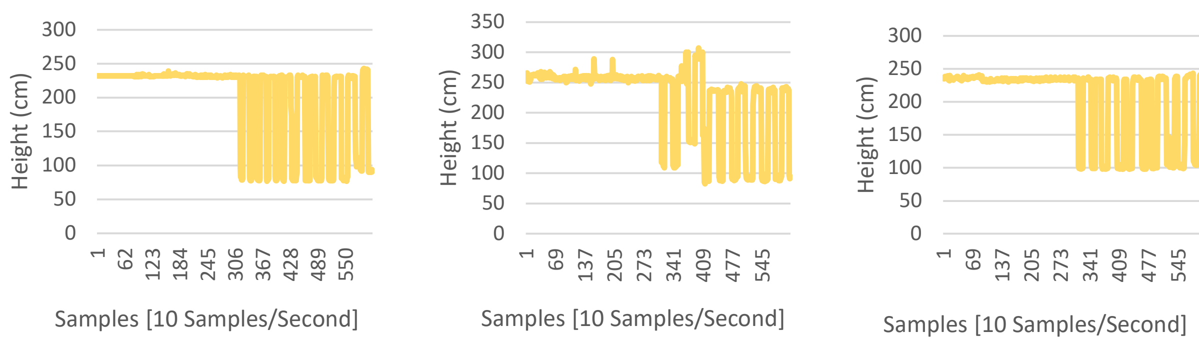

Figure 6: MaxSonar ultrasonic rangefinder sensors from three degrees of freedom robots

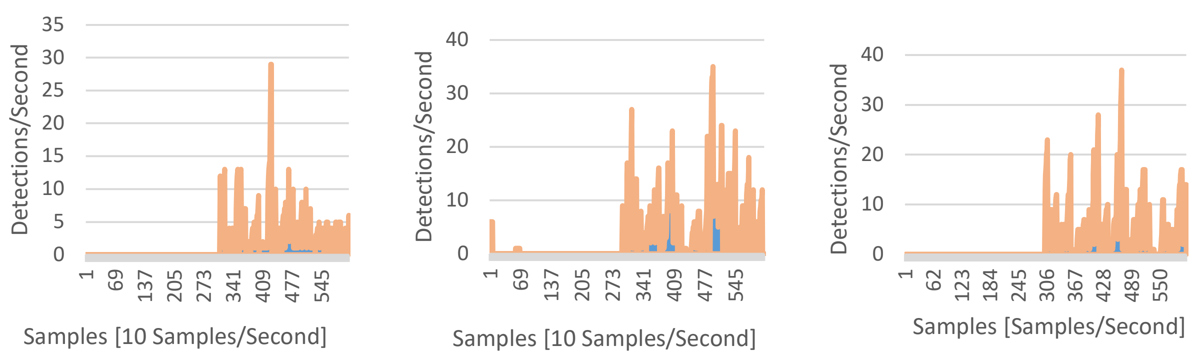

Figure 7: Doppler microwave sensor data from three degrees of freedom robots

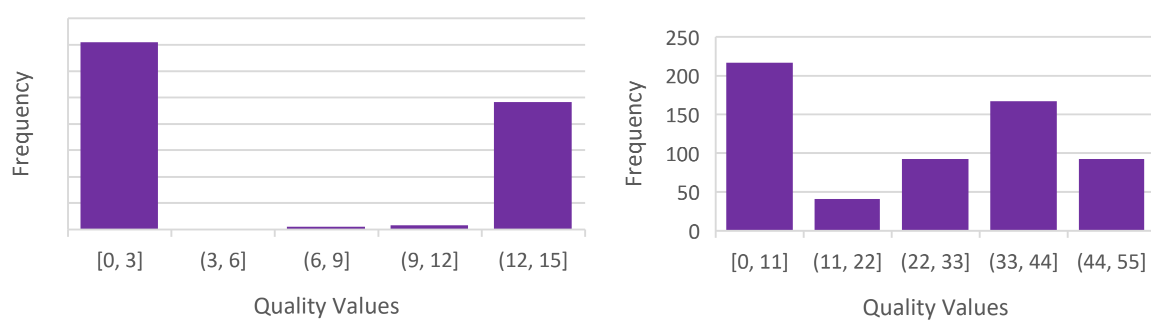

Figure 8: LiDAR A1 (Left) and LiDAR C1(Right) quality data

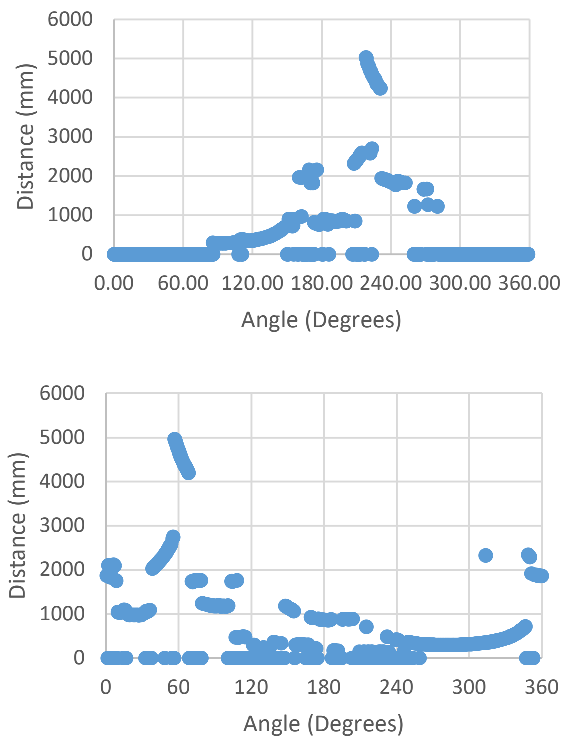

Figure 9: LiDAR A1 (top) and LiDAR C1(bottom). Distances in cm and angle measurements in degrees.

VI. Conclusion

The results of the research are in line with coordinating the motion of 3DoF robot arms in a way that would be functional in industry. The coordination algorithm accounted for the proximity of objects to avoid collisions with obstacles greatly increasing the overall safety of the implementation. The addition of the multi-sensor platform allowed for forming a consensus on times when there were multiple obstacles and objects in the environment where the 3DoF was operated. Detection from most of the sensors prevented the system from running while there was an obstacle to the system. The control actions were within milliseconds of time duration on the multi-sensor platform. The use of the platform on edge computing devices could not have been done using traditional programmable logic controllers because of the higher communication requirements. Future work would consider using the coordination algorithm for other types of autonomous systems including connected vehicles and aerial systems.

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