ENHANCING COLLABORATIVE ROBOT COMMUNICATION WITH ELECTRICAL DISCHARGE MACHINE THROUGH MODBUS TCP INTEGRATION: A FEASIBILITY AND APPLICATION STUDY

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Abstract - This paper represents a detailed analysis of the synergy between unconventional electrical discharge machining (EDM) technology and collaborative robots. The authors have adopted a technological approach in this research, focusing on communication using the MODBUS TCP protocol between a collaborative robot and two electrical discharge machining (EDM) machines. By integrating the collaborative robot and EDM machines into the local network or organizational infrastructure, it has been demonstrated that these technologies can harmoniously function, efficiently communicating through a simple Ethernet cable. Intriguingly, the research illustrates how EDM machines can dynamically modify the values of registers within the collaborative robot, which acts as a server in this context. A conclusive case study has outlined the process of establishing communication infrastructure within the collaborative robot and showcased how it can implement and manage the necessary conditions for the manufacturing workflow. Through the use of existing industrial protocols, this research opens up fascinating possibilities regarding communication between collaborative robots and EDM machines. This could significantly reduce the complexity and costs associated with electrical I/O connections, enabling efficient transmission of multiple types of information between equipment using a single Ethernet cable. In essence, this paper offers a vision of the future where innovative technologies intersect and collaborate to streamline industrial processes while reducing the complexity and expenses associated with electronic connectivity.

Keywords: Collaborative robots, Unconventional technologies, Electrical erosion, Manufacturing process, Industrial protocols.

1. Introduction

The current study describes a communication protocol for an unconventional piece of equipment, the Electrical Discharge Machine (EDM), and a collaborative robot (Cobot). The communication between EDM and Cobot falls under the category of M2M (Machine to Machine).

Machine to Machine (M2M) communications refers to the communication between machines without the need for human intervention. They are still in the early stages of development, but the basic idea is to connect a client to an autonomous network of equipment via a wired or wireless connection [1].

G. Lawton is of the opinion that M2M is the technology of data transmission, from machine to machine, from one terminal to another, but in some cases also from human to machine or from mobile to machine [2].

M2M communication generally refers to any methods of connecting machines, people, and systems. The network's computers communicating with one another is the ultimate goal, therefore interconnection is crucial. When M2M is stated nowadays, it usually refers to interactions between non-IT devices and other IT hardware over an infrastructure [3].

The manufacturing systems have the potential to enable collaborative manufacturing, which promises higher production flexibility and product variety with less human inputs. This cutting-edge industrial concept is referred to by a number of recently created words, including Manufacturing 2.0, Industry 4.0, Industrial Internet, smart factory, and

IoT. The fundamental concepts for enhancing the performance process of industrial processes through interactive collaborations and intelligent machine optimizations with connection are shared even though they are suggested in many application contexts. Innovations in applications for industry will be boosted by reliable connectivity and pervasive M2M communications. The organization, cooperation, and intercommunication of connected machines are still difficult challenges, according to industrial norms [4].

The communication between the Cobot and the non-conventional EDM equipment in this scenario is as simple and efficient as feasible.

2. Internal Communication Processes from Non-conventional EDM Equipment

To connect with the Cobot, the Electrical Discharge Machine relies on the Ethernet network as the physical medium. Modbus is a client-server communication protocol. In this scenario, the EDM is the client, and the Cobot is the server. EDM connects to Cobot (server) through IP address 192.168.0.10. The mechanism of sending information from EDM to Cobot is done by writing well-defined registers from Cobot.

The Cobot has 4 registers available that are controlled by the EDM, as shown in figure 1 a), all the signals described below represent the input registers that the EDM will write and the Cobot will read them:

- “ri_M1_Ready”: If the value received on the register is 1, it means that the equipment is in automatic mode and ready for processing;
- “ri_M1_Pick”: If the value received on the register is 1, it means that the equipment asks to pick up the part;
- “ri_M1_Place”: If the value is 1, it means that the equipment asks to place the piece;
- “ri_M1_Result”: If the value is 1, it means that the piece is pass. If the value written in the register is 2, it means that the part is fail.

Figure 1 b) shows that the non-conventional EDM machine's working algorithm begins with the „Start” P050 process. In reality, P050 is the first step that runs when the EDM machine is turned on. The P110 procedure then begins, which includes the EDM initialization phase. All EDM subsystems, including the „ri_M1_Place” signal to Cobot, are initialized here.

The P120 process continues to flow. This technique is crucial because it marks the starting and returning point of EDM after a whole machine cycle. At this stage, the Cobot's „ri_M1_Result” and „ri_M1_Pick” signals are initialized and reinitialized (in the case of a new cycle). At process step P130, the EDM sends the „ri_M1_Ready” signal to the Cobot, indicating that the system is ready to take over the workpiece. The Cobot must supply the EDM with the Unit to be handled by electrical discharge.

In the loop established by procedures P140, P150, and P160, EDM will wait for the Unit.

The EDM executes a one-second delay during the P140 operation. The EDM then writes the value 1 to the register „ri_M1_Place” in the Cobot in P150. In this manner, the EDM communicates the Cobot that it is awaiting the processing of a Unit. The P160 procedure checks to see if the Cobot has inserted a part into the EDM feed slot for processing. This verification is made possible by the sensor that detects the presence of the part in the nest. If the part is missing, the program returns to the „NO” branch of process P160 at the start of process P140. If the Unit is present in the nest, the program continues on the „YES” branch of the P170 process by resetting the „ri_M1_Place” register in Cobot to 0.

Process P180 „Read Barcode from Unit” continues the program flow. A scanner is used to read the bar code of the Unit in the EDM loading nest on this instance. The P190 process determines whether or not the printed barcode was successfully read.

If there are reading errors, the unit is rejected in the P195 process on the „NO” branch. Then informs the Cobot in the P255 process, via the „ri_M1_Pick” register with the value 1, that the piece must be picked up by the Cobot, and the P265 process, via the „ri_M1_Result” register with the value 2, that the piece is FAIL and must be placed in the FAILs area. Until the Cobot takes over the track, the EDM machine remains in this state. This inspection is performed as part of the evaluation process P275 „Check: Unit Still Present in Input Nest?”. Following the Cobot's takeover of the piece, EDM detects this by verifying the Unit's presence sensor in the P275 procedure. Then the program returns to the starting point P120, explained previously and resets, brings to zero, the values of the „ri_M1_Result” and „ri_M1_Pick” registers.

Returning to the P190 process, if the barcode is successfully read, proceed to the P200 evaluation procedure „Traceability Check: unit to the right process?” on the „YES” branch. The database is examined here to see if the part needs to be treated at the EDM process station. If the unit piece is not at the correct process station, i.e. certain intermediate technology procedures have been skipped, it is rejected on the „NO” branch, at process P195, as previously explained.

If the Unit is acknowledged by the traceability system, P200 moves to the „YES” branch, indicating that the Unit is ready for electrical discharge processing. Furthermore, at process P210, the Cobot „ri_M1_Ready” register is set to 0. As a result, Cobot is informed that the EDM machine is no longer ready to take components for processing because it is already occupied with the Current Unit. The unit is loaded from the nest into the EDM machine for processing using the P220 process. The part is treated by electrical discharge in the P230 process. This is a particularly slow procedure, with hours spent here.

In process step P240, the Unit is unloaded from inside the machine and placed in the nest after it has been processed.

P250 in the evaluation process „Unit processed OK? Process finished well?" determines whether the Unit was processed successfully or not.

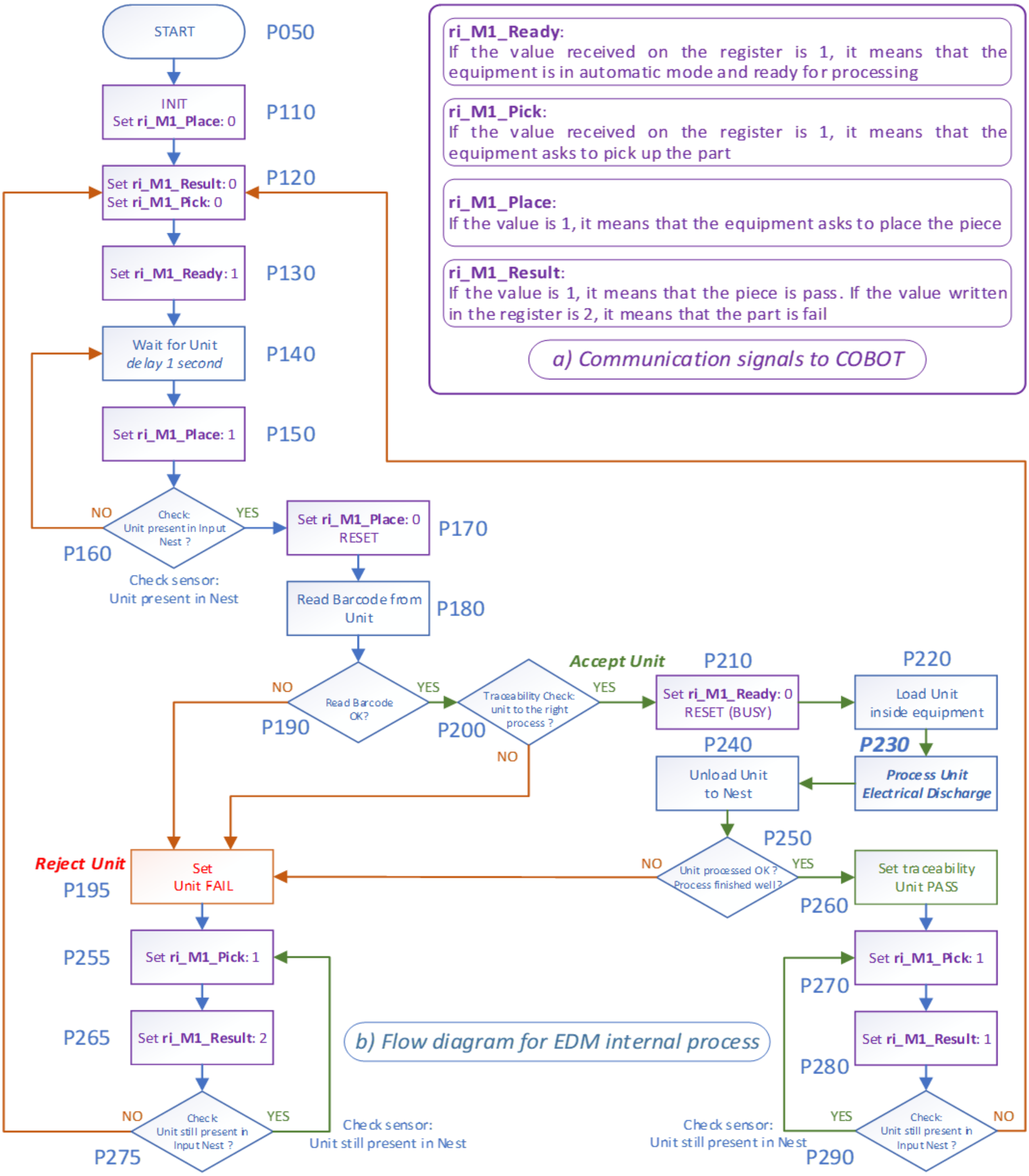

Figure 1: The communication algorithm between EDM and COBOT

If Process P230 did not go as planned, the unit is returned to P195. If everything went as planned, the program flow continues with the P260 step, in which the positive outcome based on the Unit's barcode is entered in the traceability system.

Furthermore, the value 1 is written in the register „ri_M1_Pick" and the value 1 is also stored in the register „ri_M1_Result" during the P270 process. As a result, the Cobot is told that the Unit is available, and the result of the electrical discharge processing is PASS, allowing the Unit-ul to be placed with the other compliant parts. If the Unit has been taken over by the Cobot, the P290 procedure checks through the presence sensors of the nest.

If the Unit is taken over, the program returns to the „NO" branch of the process from P120, where the EDM machine is ready to process the next part for processing.

As the P230 "Process Unit Electrical Discharge" process takes many hours, one more EDM2 machine should be added to run in parallel with EDM1 to significantly shorten processing cycle time. This way, two units can be processed in the same amount of time. The program flow for EDM2 is the same as for EDM1. The single Cobot is capable of servicing two EDM stations. EDM2 must employ Cobot-like registers. The following registers are designated for this purpose: ri_M2_Ready, ri_M2_Pick, ri_M2_Place, and ri_M2_Result.

3. Analysis of the Communicative Interaction between Collaborative Robots and Electrical Discharge Machining Equipment

The ideal robotic paradigm materializes through the substitution of human activity with complex automated systems, capable of efficiently executing tasks assigned by humans without the need for real-time human intervention [5].

Industrial robot applications are prevalent; however, they often lack the capability to coexist in a shared workspace with human operators [6].

To explore the potential of communication between the collaborative robot and electrical discharge machining (EDM) equipment, the authors have developed a specific layout within a relevant production workflow.

In the system configuration, aside from the collaborative robot, the authors have considered four pieces of equipment, as illustrated in Figure 2:

- Two electrical discharge machining (EDM) machines;
- An input conveyor for parts;
- A dual-output transporter for parts, equipped with one conveyor belt for "PASS" result parts and a second conveyor belt for "FAIL" result parts.

Collaboration between humans and robots can lead to significant risks in the absence of proper consideration of the human factor throughout the entire process [7].

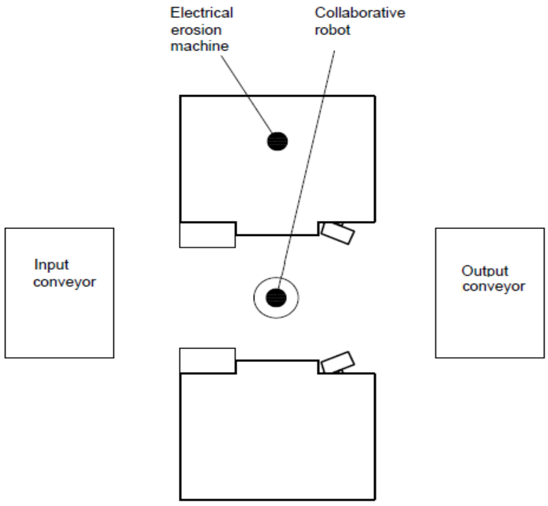

Figure 2: Analyzed workflow layout

The emergence of collaborative robots has led to the elimination of safety enclosures, as these robots are specifically designed to interact safely and effectively with humans [8].

The manufacturing process is assessed as an autonomous system capable of functioning independently without human intervention. The collaborative robot has the ability to operate autonomously within this production workflow. The operator or worker will only be required to feed the input conveyor with the parts to be processed and to retrieve the produced parts, whether they have a conforming or non-conforming result, from the output conveyor.

For an increase in:

- productivity, a viable option would be to expand the electrical discharge machining (EDM) capacity, necessitating the installation of the collaborative robot on an axis to ensure its accessibility to each EDM unit;
- production line autonomy, this objective can be achieved by maintaining a stock of raw materials on the input conveyor and a corresponding stock of processed products. This must be adjusted accordingly to the line cycle time.

Such a case has been presented through a layout as per [9].

A similar argument for boosting capacity was also made in [10], where the authors describe how they improved the Kanban technique by doubling the number of downstream EOL (End of Line) processing stations. Also, in the present case, considering that the processing times at the EDM station can be hours, it was decided to double them.

Collaborative robots can communicate through various methods: I/O, ModBUS TCP, Ethernet IP, Profinet [11].

4. Establishing Communication Infrastructure through Collaborative Robot's Basic Settings

In the context of developing the communication infrastructure for the collaborative robot, the initiation of the process must begin with configuring the basic settings.

Considering that the collaborative robot will serve as a MODBUS server for communication with the equipment, the first necessary step is configuring the IP address. As per the presentation in Chapter 2 of this paper, the IP address of the server (collaborative robot) is set to 192.168.0.10. This configuration can be done by accessing the "Setup Robot" menu, followed by selecting the "Network" submenu. In this section, the user will have the option to configure, as shown in Figure 3:

- IP address, which in this context will be 192.168.0.10;
- Subnet mask, which in this case will be 255.255.255.0;
- Default gateway, which in this context will be 192.168.0.1.

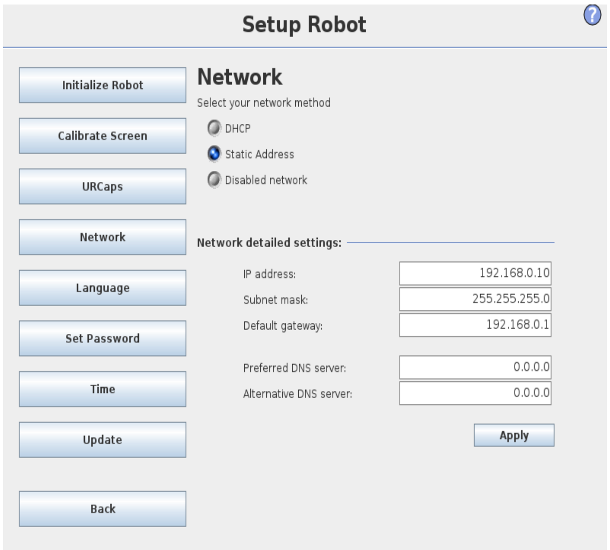

Figure 3. Collaborative robot IP setting

In the application outlined in this paper, we will illustrate how the collaborative robot can interact with the equipment using various communication methods. In this context, the collaborative robot will communicate through input-output (I/O) with the conveyors and through the ModBUS TCP protocol with the electrical discharge machining (EDM) processing equipment.

The local registers of the collaborative robot can be accessed through the "Installation" menu, submenu "MODBUS". Once this menu has been accessed, the required IP address for the local MODBUS server, where registers will be configured, is 127.0.0.1. This represents the IP address through which the internal MODBUS server of the collaborative robot can be read and modified.

In this context, the following types of MODBUS communications can be configured:

- Digital input;
- Digital output;
- Register input;
- Register ouput.

In the context of digital input, the equipment has the ability to activate or deactivate a signal through the MODBUS protocol, and the collaborative robot will be able to receive it.

Regarding digital output, the collaborative robot can trigger or deactivate a signal, and the equipment can detect it.

In the case of using register input, the equipment has the ability to rewrite the desired numeric value in the respective register, and the collaborative robot will pick it up.

When using register output, the collaborative robot can modify the registered numeric value, and the equipment will be able to read it.

Through input or output registers, various scenarios can be defined programmatically for how the collaborative robot can respond. In the given example, the result of processing the product can either be "PASS", in which case the EDM will update the robot's register to the value 1, or "FAIL", at which point the EDM will update the robot's register to the value 2.

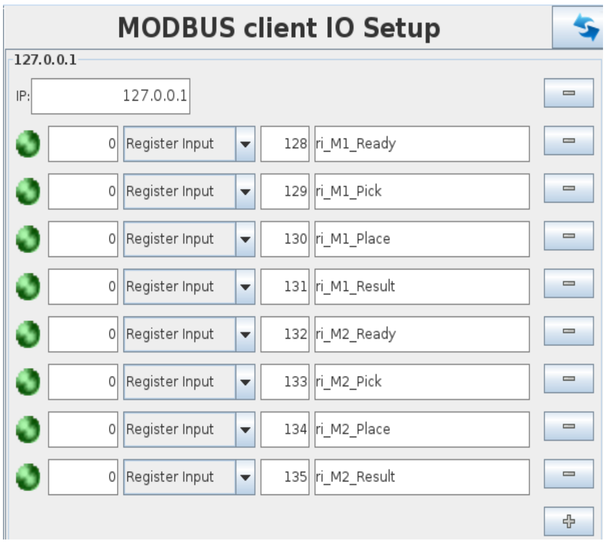

Figure 4: Establishment and Designation of MODBUS Input Registers

Communication through the MODBUS protocol offers the advantage of being able to communicate with multiple devices using a single Ethernet cable, simplifying the connections.

However, it should be noted that when communicating through an Ethernet-based protocol, the collaborative robot must be integrated into the network along with the other machines [12]. This integration can be achieved either through a local network or by connecting them to the organization's network. To establish communication via the MODBUS TCP protocol between the collaborative robot and EDM in the application presented in this paper, it will be necessary to create specific input registers for each piece of equipment and assign them appropriate names, following the communication steps outlined in Chapter 2, as illustrated in the example in Figure 4. As can be observed, in this scenario, the authors have opted to exclusively utilize input registers concerning the electric discharge machining (EDM) equipment. Furthermore, for communication with the input and output conveyors, electrical inputs were employed, and they were defined in accordance with the illustration depicted in Figure 5.

Input	
DI[0]	i_pick_i_conv
DI[1]	i_pl_o_conv_P
DI[2]	i_pl_o_conv_F

Figure 5: Renaming of electrical input signals

These have been configured in accordance with the following specifications:

- "i_pick_i_conv" represents a 24 V DC electrical input, which, when activated, allows the input conveyor to signal to the collaborative robot that a product is ready for pickup;
- "i_pl_o_conv_p" represents a 24 V DC electrical input, which, when activated, allows the output conveyor to signal to the collaborative robot that the conveyor for "PASS" parts is full;
- "i_pl_o_conv_f" represents a 24 V DC electrical input, which, when activated, allows the output conveyor to signal to the collaborative robot that the conveyor for "FAIL" parts is full.

Depending on the requirements, both electrical inputs and outputs, as well as MODBUS registers, can be utilized to create common conditions upon which the collaborative robot can perform specific operations.

5. Creating Parameters in the Collaborative Robot Program for Manufacturing Flow Management

Based on the signals and conditions described, specific criteria have been implemented in the collaborative robot's program, as illustrated in Figure 6.

```
Robot Program
  If i_pick_i_conv≟ True  and ri_M1_Ready≟1 and ri_M1_Place≟1
    Call Pick_Input_Conveyor
    Call Place_M1
  Elseif i_pick_i_conv≟ True  and ri_M2_Ready≟1 and ri_M2_Place≟1
    Call Pick_Input_Conveyor
    Call Place_M2
  If ri_M1_Ready≟1 and ri_M1_Pick≟1 and ri_M1_Result≟1
    Call Pick_M1
    Wait i_pl_o_conv_P=LO
    Call Place_Output_Conveyor_P
  Elseif ri_M1_Ready≟1 and ri_M1_Pick≟1 and ri_M1_Result≟2
    Call Pick_M1
    Wait i_pl_o_conv_F=LO
    Call Place_Output_Conveyor_F
  Elseif ri_M2_Ready≟1 and ri_M2_Pick≟1 and ri_M2_Result≟1
    Call Pick_M2
    Wait i_pl_o_conv_P=LO
    Call Place_Output_Conveyor_P
  Elseif ri_M2_Ready≟1 and ri_M2_Pick≟1 and ri_M2_Result≟2
    Call Pick_M2
    Wait i_pl_o_conv_F=LO
    Call Place_Output_Conveyor_F
```

Figure 6: Collaborative robot program

Here are the conditions that can be distinguished:

- If "i_pick_i_conv=True and ri_M1_Ready=1 and ri_M1_Place=1", it means the input conveyor has a product ready for pick-up, and electric discharge machining equipment 1 (EDM 1) is automatically set and requests the placement of the product. In this scenario, the collaborative robot will call the "Pick_Input_Conveyor" subroutine to pick up the product from the input conveyor and place it in machine 1 (EDM 1) using the "Place_M1" subprogram;
- If "Elseif i_pick_i_conv=True and ri_M2_Ready=1 and ri_M2_Place=1", it means the input conveyor has a product ready for pick-up, and electric discharge machining equipment 2 (EDM 2) is automatically configured and requests the placement of the product. In this situation, the collaborative robot will call the "Pick_Input_Conveyor" subroutine to pick up the product from the input conveyor and place it in machine 2 (EDM 2) using the "Place_M2" subprogram;
- If "Elseif ri_M1_Ready=1 and ri_M1_Pick=1 and ri_M1_Result=1", it means EDM 1 is set automatically, has completed the machining, and requests the pick-up of the product with a "PASS" result. In this case, the collaborative robot will call the "Pick_M1" subroutine to pick up the product from EDM 1 and place it on the output conveyor's compliant product belt through the "Place_Output_Conveyor_P" subroutine. Through the intermediate condition "Wait i_pl_o_conv_P=Low", the collaborative robot checks whether the compliant product belt of the output conveyor is not full before placing the product;

- In the event of "Elseif ri_M1_Ready=1 and ri_M1_Pick=1 and ri_M1_Result=2", EDM 1 is automatically configured, has completed processing, and requests the retrieval of the product with a "FAIL" result. In this case, the collaborative robot will call the "Pick_M1" subroutine to pick up the product from EDM 1 and place it on the non-compliant product belt of the output conveyor using the "Place_Output_Conveyor_F" subroutine. Through the intermediate condition "Wait i_pl_o_conv_F=Low", the collaborative robot checks whether the non-compliant product belt of the output conveyor is not full before placing the product;
- If "Elseif ri_M2_Ready=1 and ri_M2_Pick=1 and ri_M2_Result=1", it means EDM 2 is automatically configured, has completed processing, and requests the retrieval of the product with a "PASS" result. In this situation, the collaborative robot will make a call to the "Pick_M2" subroutine to pick up the product from EDM 2 and place it on the compliant product belt of the output conveyor using the "Place_Output_Conveyor_P" subroutine. Through the intermediate condition "Wait i_pl_o_conv_P=Low", the collaborative robot checks the availability of space on the compliant product belt of the output conveyor before placing the product;
- In the case of "Elseif ri_M2_Ready=1 and ri_M2_Pick=1 and ri_M2_Result=2", EDM 2 is automatically configured, has completed processing, and requests the retrieval of the product with a "FAIL" result. In this scenario, the collaborative robot will call the "Pick_M2" subroutine to pick up the product from EDM 2 and place it on the non-compliant product belt of the output conveyor using the "Place_Output_Conveyor_F" subroutine. Through the intermediate condition "Wait i_pl_o_conv_F=Low", the collaborative robot checks whether the non-compliant product belt of the output conveyor is not full before placing the product.

Each specific step of movement, alteration of the TCP (Tool Center Point) mass, gripping device closure, or opening will be performed through calls to the respective subroutines. In the collaborative robot's program, only calls to these subroutines will be made based on the conditions defined within the collaborative robot.

6. Conclusions

This paper represents a convergence of unconventional technologies, focusing specifically on the electric discharge machining process and the collaboration of collaborative robots. The authors have taken a technical perspective in this study, demonstrating communication using the MODBUS TCP protocol between a collaborative robot and two electric discharge machining machines.

From this research, it can be concluded that the collaborative robot and the electric discharge machining machines must be integrated into the local network or organizational network to facilitate communication, with this connection being established through a simple Ethernet cable.

The logic by which electric discharge machining machines can real-time modify the values of the registers running on the collaborative robot, which in this context acts as a server, has been illustrated. The presented case study has clearly highlighted the method of creating communication infrastructure within the collaborative robot and also how the conditions in the collaborative robot's program can be implemented.

In conclusion, communication through existing industrial protocols appears to be a feasible opportunity in the context of collaborative robots and electric discharge machining machines (EDMs). This could significantly reduce the complexity of cables required for I/O electrical connections, allowing efficient transmission of multiple types of information between equipment through a single Ethernet cable.

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