Modular Production System Control Using Supervisory Control Theory Method

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Abstract. Modular Production System (MPS) is a mini industrial automation process that simulates product processing. MPS uses a Programmable Logic Controller (PLC) to observe and control system processes. The MPS used is the Festo Processing Station which is composed of several components that are numerous and varied so that the control is quite difficult, especially when using a basic PLC program. Therefore, this paper proposes that MPS is classified as a Discrete Event System (DES). The method used to control DES is the Supervisory Control Theory (SCT). MPS is used to process two types of materials (metal and non-metal). The drilling process is carried out only for metal. PLC-based MPS is successfully controlled using the SCT method. MPS with the SCT method can process the material with 100% success. The PLC program using the SCT method can save data memory by 2.3% compared to without SCT.

1. Introduction

In industrial systems, especially in automation systems, supervisory control systems are used to control the process of a system. Modular Production System (MPS) is a miniature industrial automation process that consists of various standard components and is used to simulate product processing (Systems & Training, 2018) [1]. MPS can simulate that production is always consistent and high quality. MPS This system is generally implemented using a PLC (Programmable Logic Controller), which runs the program as needed to maintain security and sort the system [2]. But the use of a large number of components varies, and controlling the MPS using the basic PLC program is quite difficult.

Discrete event system (DES) is modelling that is useful for certain systems. Events can occur synchronously and instantly at separate time intervals. DES behaviour is explained by the sequence of events that occur, and the sequence of circumstances visited [3]. The supervisory control theory (SCT) is a general approach to the synthesis of control systems for DES. SCT is a theory for supervisor automatic synthesis based on the plant and certain specifications. The supervisor of the SCT method is used to control the Discrete Event System (DES) model of a system [4].

MPS is classified as a Discrete Event System (DES) because MPS has a discrete state and changes in state caused by the occurrence of an event. The method used to control DES is Supervisory Control Theory (SCT). The SCT method synthesizes automatically a supervisor based on certain specifications. The supervisor synthesis results are used to control events that affect DES behaviour. In this paper, MPS based on Programmable Logic Control (PLC) is controlled using the SCT method.
1.1. Modular Production System

The MPS (Modular Production System) used is the MPS Festo part of the material processing process [5]. The processed materials are of two types, metals and non-metals. Silver metal material, while non-metallic material is red. The processing process focuses on the drilling process for metal materials, while non-metallic materials are not perforated. The MPS used can be seen in Figure 1. Figure 1(a) is processing station MPS that have drilling machine and rotating disk in Figure1(b), and checking machine in Figure 1(c).

The components contained in the MPS are connected to PLC hardware. Hardware PLC is located in the panel box. The connection between MPS components and PLC hardware can be seen in Figure 2. Indicator component lamp, normally open push button (N.O.), and push button normally close (N.C). installed in the panel box. Indicator lamp to indicate the condition of the system. Normally open push button (N.O.) to turn on the system, while the push button normally close (N.C) to turn off the system.

The rotary index table module component makes the system have six stations (0, 1, 2, 3, 4, and 5):
- Station 0: there is a rotary proximity sensor used so that the rotary index table module rotation is exactly 600.
- Station 1: there is a proximity sensor 1.
- Station 2: there are two components (proximity sensor 2 and testing module).
- Station 3: there are three components (proximity sensor 3, drilling module, and clamping module).
- Station 4: there is only one component (sorting module).
- Station 5: no components installed.

The working process of the MPS processing station can be seen in Figure 3. The first process
is material input. Material is entered manually at station 0, 1 or station 5. When the material is at station 1, the type of material is detected by proximity sensor 1. After the material type has been detected, the material will be brought to the next process. Switching between processes is carried out by the rotary table module by bringing material to the next station. The transfer between processes by the rotary table module will be called the rotating process.

The next process is the detection of material direction. This process is carried out at station
2 when the material is detected by proximity sensor 2. The direction of the material can be in an open or closed condition. If the material is open, testing the module at station 2 will work full. After the process of detecting the direction of the material is complete and the material detected is open, it will continue to the next process. Whereas if the material is closed, the testing module cannot work full. The process will stop and cannot proceed to the next process. The process of detecting the direction of the material by a testing module will be called the testing process.

After the testing process at station 2 is complete, then the next is the process of drilling metal material. The drilling process occurs at station 3 when the material is detected by proximity station 3. This process is carried out by a drilling module to drill and clamping the module to hold material during the drilling process. The material being drilled is metal only, while the non-metallic material is not drilled. The process of drilling metal material by the drilling module and clamping module will be called the drilling process.

After the drilling process at station 3 is complete, then the next is the process of removing material from the system. Material expenditure process occurs at station 4. At station 4, there is no proximity sensor to detect material. The process of removing material is carried out by a sorting module. This process will be called the sorting process.

To meet the expected work process and system behavior, there are several specifications that need to be considered. These specifications are:

(i) If the indicator lamp does not turn on, then the process of rotating, testing, drilling, and sorting cannot occur.
(ii) If the rotating process occurs, the process of testing, drilling and sorting cannot occur. Vice versa, if the process of testing, drilling, or sorting occurs, the rotating process cannot occur. This specification is needed to prevent the material being processed from moving station.
(iii) The testing process occurs if there is material at station 2. In other words, if the proximity sensor station 2 detects material, then the testing module will work.
(iv) Sorting process occurs at station 4. Because there is no proximity sensor at station 4, the sorting process will occur if a material is detected in station 3 before.
(v) The drilling process occurs if the material detected is metal. Because the classification of material types occurs at station 1, the drilling process at station 3 will work if the proximity sensor 1 is on.

It should also be noted that the amount of material that can be processed is not limited to just one material. In other words, the system can process more than one material simultaneously. Therefore, the process of testing, drilling, and sorting must occur in parallel.

1.2. Supervisory Control Theory

Supervisory Control Theory (SCT) is a general theory about automatic synthesis of supervisors based on plant and related specifications [4]. The SCT method is used to control the DES form of a system. DES from a system is represented by automata. Automata, denoted by G, is 6-tuple \((X, E, f, \Gamma, x_0, X_m)\). \(X\) is the set of states. \(E\) is the set of events associated with \(G_f X \times E \rightarrow X\) is a transition function. \(\Gamma_{X} \rightarrow 2^E\) is an active event function. \(x_0\) is the initial state. \(X_m \subseteq X\) is a set of marked state.

In general, when modeling a system composed of interacting components, the set of events contained in each component includes the same private event and event. A common way to make the overall system model from an individual system component model is with parallel compositions, denoted by [13–24].

The situation that needs to be considered is that there is a DES whose behavior must be modified with feedback controls to meet a specification. Automata \(G\) models behavior that has
not been controlled from DES. What needs to be considered is that the behavior has not been as expected and must be modified with the controller. The purpose of modifying behavior is to limit system behavior. To limit the behavior of $G$, supervisor ($S$) is introduced.

One of the important elements of continuous control is the idea of feedback. One or more signals from the system are used to calculate the best input signal to influence system behavior and output. This idea also applies to supervisors on discrete event systems.

Supervisors, symbolized by $S$, are expected to fuse with $G$ to interact with each other in a feedback manner. Because automata is used to represent a system, automata is also used to represent $S$. Automata which represents supervisor $S$ is called $S$ realization.

1.3. Implementation Supervisory Control Theory to Modular Production System
After collecting information about MPS, the next step is implementing the SCT to MPS. There are three processes in SCT implementation: subplant modeling, specification modeling, and supervisor synthesis.

Subplant Modelling
Based on information about the MPS used, the system will be modeled into a DES form. To make a plant model of the system, the whole modeling is not made directly. However, a number of subplant models will be made from the entire plant. Subplant is modeled on IDES3 software [7].

There are eight subplant models that represent the MPS plant model, namely indicator lamp ($M_0$), testing machine ($M_1$), drilling machine ($M_2$), sorting machine ($M_3$), rotating machine ($M_4$), proximity sensor station 1 ($M_5$), proximity sensor station 2 ($M_6$), and proximity sensor station 3 ($M_7$). Testing machines represent machines that carry out the testing process. The drilling machine represents the machine that performs the drilling process. The sorting machine represents the machine that performs the sorting process. The rotating machine represents the machine that performs the rotating process.

Each of the automata $M_0$, $M_1$, $M_2$, $M_3$, and $M_4$ has two states which can be seen in Figure 4, with $n = \{0, 1, 2, 3, 4\}$. Each of the automata $M_0$, $M_1$, $M_2$, $M_3$, and $M_4$ has two events. $a_n$ event means an event that causes the engine to start working. The $b_n$ event means the event that causes the machine to finish working. The $a_n$ event causes a transition from state 0 to state 1, while the $b_n$ event causes a transition from state 1 to state 0.

An $a_n$ event is classified as a controllable event to control when the machine is working or not working. Whereas the $b_n$ event is classified as an uncontrollable event because it is chosen as a higher priority than the controllable event.

Each of the automata $M_5$, $M_6$, and $M_7$ has one state and one event that can be seen in Figure 5, with $m = \{5, 6, 7\}$. At $M_5$ there is $b_5$ event, in $M_6$ there is $b_6$ event, and in $M_7$ there is $b_7$ event. The initial state and marked state are located in state 0. The $m$ event represents an event when the sensor detects material. The $b_m$ event causes a transition from state 0 to state 0 (self-loop). The $b_m$ event is classified as an uncontrollable event because the event when the sensor detects material cannot be prevented.

Modelling Specifications
To control the MPS plant, a supervisor is required to control the plant based on the expected specifications. The specifications in the form of natural language need to be modeled by the automata. The specification model uses an event set from sub plant that forms a simple process. The specification model is made in IDES3 software. There are five specifications in the MPS so that the work process and system behavior are as expected.
The first specification is to ensure that if the lamp indicator \( M_0 \) is not lit, then no other machine is working. The machine is testing machine \( M_1 \), drilling machine \( M_2 \), sorting machine \( M_3 \), and rotating machine \( M_4 \). Conversely, when the lamp indicator lights up, another machine can work. The first specification is modeled with automata \( E_0 \) which can be seen in Figure 6.

The second specification ensures that if the rotating machine \( M_4 \) works, then the testing machine \( M_1 \), the drilling machine \( M_2 \) and the sorting machine \( M_3 \) do not work. Conversely, if one of the testing machines, drilling machines or sorting machines is working, the rotating machine cannot work. The second specification is modeled with three automata \( E_1, E_2 \) and \( E_3 \) which can be seen in Figure 7, Figure 8, and Figure 9.

The third specification focuses on the testing process. In station 2, if the proximity sensor 2 \( M_6 \) detects material, then the testing machine \( M_1 \) works. The third specification is modeled with \( E_4 \) automata which can be seen in Figure 10.

The fourth specification focuses on the sorting process at station 4. If the proximity sensor 3 \( M_7 \) detects the material at station 3 then the rotating machine \( M_4 \) works once, then the sorting machine \( M_3 \) works. The fourth specification is modeled with \( E_5 \) automata which can be seen in Figure 11.
The fifth specification focuses on the drilling process in station 3. The drilling process ($M_2$) will only occur in metal materials. Material classification occurs at station 1 by proximity sensor 1 ($M_5$). Therefore, if proximity sensor 1 classifies material as metal, then after the material is in station 3 with a rotating machine ($M_4$), the drilling process will occur. The fifth specification is modeled with automata $E_6$ which can be seen in Figure 12.
Supervisor Synthesis

There are two types of supervisors that can be synthesized, namely monolithic supervisors for the overall specifications and modular supervisors for each specification. For monolithic supervisor, the synthesis results only have one model, but usually have a large number of states. As for the modular supervisor, although the number of models produced is in accordance with the number of specifications, the number of states on each supervisor is not much. Therefore, modular supervisors will be synthesized in this journal.

Supervisors are synthesized by synchronizing the sub plant model and related specifications. To synthesize modular supervisors, to synchronize one specification, there is no need to synchronize all sub plants. If there is a partial set of events in the specification that is an element of one of the event sets in the sub plant, then the sub plant is used to synchronize the local plant (\(G_{loca}\)).

Modular supervisors are synthesized by synchronizing the local plant model (\(G_{loca}\)) with the specification model (\(E_n\)). Modular supervisors that have been synthesized need to be examined properly or not. The supcon operation on the IDES3 software is used to create automata that
produces a supremely controllable language from a modular supervisor. The modular supervisor model that has not been examined in IDES3 software is called the local specification ($E_{loc\,n}$), while the automata that meets the supremal controllable language of the modular supervisor is called the local modular supervisor ($S_n$). The results of the comparison of the number of states between the specification model, local plant, local specification, and local modular supervisor can be seen in Table 1.

The $S_n$ model is compared to $E_{loc\,n}$ to find out the language that is generated and marked by $S_n$ is the same or not with the language generated and marked by $E_{loc\,n}$. Because all $E_{loc\,n} = S_n$, then actually model $E_{loc\,n}$ is well controlled. None of the uncontrollable events are disabled by the modular supervisor.

The results of the local modular supervisor model are examined for non-conflicting conditions or modularity conditions [8]. Modularity conditions are needed to ensure that the modular approach does not cause a loss of performance compared to the monolithic approach.

Local modular supervisors that have been synthesized generally still have a large number of states. Therefore, local modular supervisors will be reduced in number, but with the same control capabilities. TCT software has operations that can be used to reduce the state of the supervisor [9]. The DES model created in IDES3 software can be exported to TCT software. The reduced procedure in TCT makes an automata model from a local modular supervisor with a local plant and associated condate data. The model of the reduced procedure results from the supervisor $S_n$ is denoted by $R_n$. The results of the comparison of the number of states between local modular supervisor and reduced supervisor can be seen in Table 2.

The model that has been made and synthesized can be simulated with the Supremica software [10]. The model used for simulation is $M_n$ as a plant and $R_n$ as a supervisor. This simulation is used to observe and analyze state changes in the plant model and supervisor caused

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### Table 1: Comparison of the number of states $E_n$, $G_{loc\,n}$, $E_{loc\,n}$ and $S_n$

| $n$ | $E_n$ | $G_{loc\,n}$ | $E_{loc\,n}$ | $S_n$ |
|-----|------|-------------|-------------|------|
| 0   | 2    | 32          | 32          | 32   |
| 1   | 2    | 4           | 3           | 3    |
| 2   | 2    | 4           | 3           | 3    |
| 3   | 2    | 4           | 3           | 3    |
| 4   | 2    | 2           | 4           | 4    |
| 5   | 4    | 4           | 16          | 16   |
| 6   | 8    | 4           | 32          | 32   |

### Table 2: Comparison of state amount on $S_n$ and $R_n$

| $n$ | $S_n$ | $R_n$ | Compression Ratio |
|-----|------|------|-------------------|
| 0   | 32   | 2    | 16                |
| 1   | 3    | 2    | 1.5               |
| 2   | 3    | 2    | 1.5               |
| 3   | 3    | 2    | 1.5               |
| 4   | 4    | 2    | 2                 |
| 5   | 16   | 4    | 4                 |
| 6   | 32   | 8    | 4                 |
by the occurrence of an event.

Based on reference [11], the sub plant and reduced supervisor models can be changed to PLC code. PLC codes are made using the Ladder Diagram program language. The PLC used is the Schneider PLC. The PLC program is used to control the MPS to meet the expected specifications [12].

2. Results and Discussion
The MPS system will be tested through observation data for analysis. The data includes material combination tests, specification checks, program comparisons, and tests with interference.

2.1. Material Combination Test
The amount of material that can be processed in MPS is not limited to just one material. Therefore, the system must be able to process material in parallel. For that, the system will be tested using several variations in the amount of material. There are three variations in the amount of material tested, namely testing the system with one, two, and three materials. The combination of material tested uses two types of material, namely metal and non-metal.

Material combination test results can be seen in Table 3, Table 4, and Table 5. Table 3 shows the system test using one material, Table 4 shows the system test using two materials, while Table 5 shows the system test using three materials. The process seen is three, namely the testing process at station 2, the drilling process at station 3, and the sorting process at station 4. The number 1 on the test results shows that the process occurs, while 0 means the process does not occur.

From Table 3, Table 4 and Table 5 can be seen that MPS can process material with 100% success. The process of testing and sorting processes always occur for both types of material.
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Table 5: Three Material Test

| No | Material   | Cycle 1 | Cycle 2 | Cycle 3 | Check |
|----|------------|---------|---------|---------|-------|
|    |            | testing | drilling | sorting | testing | drilling | sorting | testing | drilling | Sorting |
| 1  | 1. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
|    | 2. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
|    | 3. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
| 2  | 1. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
|    | 2. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
|    | 3. Non-Metal | 1  | 0       | 1     | 1     | 1     | 1       | True    |
| 3  | 1. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
|    | 2. Non-Metal | 1    | 0       | 1     | 0     | 1     | 1       | True    |
|    | 3. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
| 4  | 1. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
|    | 2. Non-Metal | 1  | 0       | 1     | 0     | 1     | 1       | True    |
|    | 3. Non-Metal | 1  | 0       | 1     | 1     | 1     | 1       | True    |
| 5  | 1. Non-Metal | 1    | 0       | 1     | 1     | 1     | 1       | True    |
|    | 2. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
|    | 3. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
| 6  | 1. Non-Metal | 1    | 0       | 1     | 0     | 1     | 1       | True    |
|    | 2. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
|    | 3. Non-Metal | 1  | 0       | 1     | 0     | 1     | 1       | True    |
| 7  | 1. Non-Metal | 1    | 0       | 1     | 1     | 1     | 1       | True    |
|    | 2. Non-Metal | 1    | 0       | 1     | 0     | 1     | 1       | True    |
|    | 3. Metal   | 1       | 1       | 1       | 1       | 1       | 1       | True    |
| 8  | 1. Non-Metal | 1    | 0       | 1     | 1     | 1     | 1       | True    |
|    | 2. Non-Metal | 1    | 0       | 1     | 1     | 1     | 1       | True    |
|    | 3. Non-Metal | 1  | 0       | 1     | 1     | 1     | 1       | True    |

Table 6: Specifications Test on the MPS Process

| No | Specification                                                                 | Check |
|----|-------------------------------------------------------------------------------|-------|
| 1  | The new MPS process can work if the lamp indicator lights up                    | True  |
| 2  | The rotating process cannot occur if the process of testing, drilling or sorting is happening, and vice versa. | True  |
| 3  | When the material is at station 2, the testing process occurs                   | True  |
| 4  | When metal material is at station 3, the drilling process occurs               | True  |
| 5  | When the material is at station 4, the sorting process occurs                  | True  |
| 6  | The process of testing, drilling and sorting can occur in parallel             | True  |

The drilling process only occurs in metal materials. There is no change from the first cycle to the third cycle. So for the next cycle and so on there will be no process changes.

**Specifications Check**
In order for the work process and behavior of the MPS to be as expected, the MPS must meet several specifications. The results of inspection specifications on MPS can be seen in Table 6. All specifications have been fulfilled so that the work process and behavior of the MPS are in accordance with the expected specifications.
The MPS process can work if the lamp indicator lights up True. The rotating process cannot occur if the process of testing, drilling or sorting is happening, and vice versa. When the material is at station 4, the sorting process occurs. When metal material is at station 3, the drilling process occurs. When the material is at station 2, the testing process occurs.

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The process of testing, drilling and sorting can occur in parallel. The results of the MPS test with the second disturbance can be seen in Table 9. For both types of material, only the testing process at station 2 occurs. Then the material is taken when it is between station 2 and 3. After the drilling process at station 3 and the sorting process at station 4 does not occur. For the first glitch, the MPS system has no problems and the system can continue the process.

Table 7: Comparison of PLC Program Result

| Compare                  | Program without SCT | Program with SCT |
|--------------------------|---------------------|------------------|
| Memory Bits              | 0.1 %               | 0.2 %            |
| Memory Words             | 1.8 %               | 0.0 %            |
| Available Memory Data    | 84.8 %              | 87.1 %           |
| Executable Code          | 4.7 %               | 10.8 %           |
| Program Data             | 0.1 %               | 0.6 %            |
| Available Code Memory    | 93.6 %              | 87.5 %           |

Table 8: One Material Test with First Disturbance

| No | Material | Cycle 1 | Cycle 2 | Cycle 3 | Check |
|----|----------|---------|---------|---------|-------|
|    |          | testing | drilling | sorting | testing | drilling | sorting | Check |
| 1  | Metal    | 0       | 0       | 0       | 0       | 0       | 0       | True  |
| 2  | Non-Metal| 0       | 0       | 0       | 0       | 0       | 0       | True  |

2.2. Comparison of Program Results

The results of general program comparisons can be seen in Table 7. Programs that are compared are programs from the results of SCT implementation and programs that are based on programmer experience. Compared programs can control the MPS process with the same system behavior. Programs created without the SCT method based on the flowchart in Figure 2. Programs are created using basic PLC programs such as self-holding, flip-flops, interlocks, and so on.

Programs with SCT use more memory bits, but don’t use memory words. Therefore, the remaining memory data in programs with SCT is greater than 2.3% compared to programs without SCT. Whereas the remaining memory code in programs with SCT is 6.1% smaller than programs without SCT.

2.3. Material Combination Test

The MPS system will be tested with a disturbance. The system is tested using a program with SCT. Two types of disorders will be tried on MPS. The first disturbance is material taken when the material is between station 1 and 2. While the second disturbance is material taken when the material is between station 2 and 3. Testing is done with 1 material.

The results of the MPS trial with the first disturbance can be seen in Table 8. For both types of material, the testing process at station 2, the drilling process at station 3, and the sorting process at station 4 did not occur. For the first glitch, the MPS system has no problems and the system can continue the process.

The results of the MPS test with the second disturbance can be seen in Table 9. For both types of material, only the testing process at station 2 occurs. Then the material is taken when it is between station 2 and 3. After the drilling process at station 3 and the sorting process at station 4 does not occur. For the second glitch, the MPS system has no problems and the system can continue the process.

For the MPS system with a program without SCT, the results of the disruption test on the system are the same as the MPS system test with a SCT based program. Both programs have
been able to overcome these two disturbances. Programs without SCT must take safety into account in order to overcome the disturbance. Whereas for programs with SCT, although it does not take into account safety for the disorder, it can overcome these two types of disturbance.

3. Conclusion
The SCT method was successfully implemented in PLC programming for MPS control using IDES3, TCT and Supremica software. The MPS plant is modeled into the DES model, then by synthesizing the modular supervisor from synchronization between the sub plant model and specifications, a close-loop between the plant and the supervisor is obtained. The plant model and supervisor are used in making PLC codes to control MPS. Based on the results of material testing, the MPS with the SCT method can process material with 100% success. Based on the comparison between the two programs for MPS, the PLC program with SCT has 2.3% more data remaining than the PLC program without SCT.

Programs without SCT must take into account safety to deal with interference. Whereas programs with SCT, although not taking into account safety, have been able to overcome interference because the techniques in the SCT method utilize the state to overcome various conditions that may occur in that state. In making a specification model, it will be easier to make if you make a simple process sequence for those specifications compared to if you directly make the model. Each process is denoted by an event that causes the process to occur. From the sequence of events, then the specification model is created that represents the sequence of processes.

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