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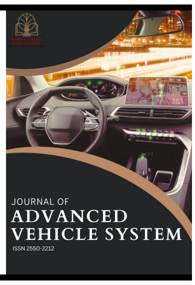

Design and Safety Analysis of an Automated Railway Crossing System Using PLC-Based Control and Real-Time Simulation

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ABSTRACT

Due to the manual operation of crossing gates, human errors are frequent, making railway level crossings the most dangerous part of the railway network. This paper presents an automatic railway crossing gate control system developed with a Programmable Logic Controller (PLC). The system employs a counter-axle methodology to detect trains in the crossing area. The main controller, a Siemens S7-1200 PLC, is programmed with the company's TIA Portal software. The system is designed to close and open railway crossing gates automatically using two axle detection sensors that count the number of train axles crossing the designated section of the crossing gates. The entire system is functioning using the S7-PLCSIM simulation to verify the anticipated operational behavior. To determine the system's performance in the detection and control of train movement, a response time analysis is completed; this is a study of the time lapse created between the act of train detection and the movement of the crossing gate, as well as the simulation of failure scenarios to assess system functionality in an undesirable condition. The proposed system is designed to control railway crossing gates automatically using the detected train movement and an established responsive time, thereby enhancing the safety of railway crossings and minimizing human error during operation.

1. Introduction

The importance of railway transportation in promoting urban mobility and supporting economic activities cannot be overemphasized. In Indonesia, railway crossings are frequently located along major public roads, creating a high-density interaction between rail and road traffic. Despite its vital role, many railway crossings still utilize manual gate operations, which introduce significant risks of human error and operational delays, leading to a higher frequency of accidents. Consequently, modernizing these crossing systems has become an emerging concern in the national rail industry to align with global safety standards [2]. The Gubeng Rail Station in Surabaya is a good example of such

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a station that is encountering the aforementioned problems. The interaction between the large number of road vehicles and the frequency of train arrivals is very high and demands a sophisticated control system to maximize the level of operation safety [1]. Manual intervention is becoming less effective in dealing with such complex urban environments, where even a few seconds of delay could cause devastating accidents. The application of automation technology is identified as one of the most effective ways to improve the level of safety and efficiency of the crossing gates in responding to the arrival of the train [4,24].

Programmable Logic Controllers (PLC), which have been successfully employed in various sectors of the industrial domain, are best suited to implement this requirement due to their reliability, programmability, and maintenance advantages [9]. A PLC-based system will be effective in integrating various sensor technologies to manage the crossing sequence in an automated manner without the involvement of human operators [7]. As mentioned in the context of the proposed automated system, the incorporation of axle counter logic to detect the presence of a train using pulse detection is critical to ensure functional safety in accordance with international standards such as IEC 61508 [8, 25]. Considering the challenges mentioned in the context of the proposed automated system, this research aims to design and simulate an automated railway crossing system using a Siemens S7-1200 PLC. The effectiveness of the proposed system will be validated using TIA portal for developing the logic and Factory I/O for 3D physics-based simulations. This research aims to prove the effectiveness of the automated system in providing a better safety margin of SIL 1 compared to traditional methods of handling railway crossings [11,28].

2. Methodology

2.1 Integrated Development and Virtual Commissioning Environments

The implementation of the automated railway crossing system involves the use of a range of software tools that integrate together for the purpose of automation. The primary engineering tool used in this research is the Siemens TIA (Totally Integrated Automation) Portal. The TIA Portal offers a platform that enables the configuration of controllers, Human-Machine Interfaces, and network parameters in one single interface, which greatly simplifies the engineering effort [9]. In this research, the TIA Portal is used for the programming of the Siemens S7-1200 PLC using the Ladder Diagram programming language. The reason for using the Ladder Diagram programming language is that it is the global industry standard for sequential control and safety applications, especially due to its graphical nature and the ease of troubleshooting in real-time [4].

Fig. 1. Siemens TIA portal programming interface for S7-1200 [9]

In order to perform the verification of the control algorithm without the need for physical hardware, the high-fidelity PLC emulator tool, i.e., S7-PLCSIM, is utilized. As illustrated in Fig. 3, the virtual execution of the PLC program is possible by the implementation of the S7-PLCSIM tool, thereby enabling the testing of the response time, I/O mapping, and fault conditions in a controlled environment[10]. This is a crucial step in the initial design stages of the system.

Fig. 2. S7-PLCSIM virtual controller execution [10]

Additionally, Factory I/O is incorporated as a 3D industrial simulation platform to display the physics-based visualization of the railway crossing environment. Factory I/O is a 'digital twin' of the system, which communicates with the S7-PLCSIM. This enables the control logic to interact with virtual sensors such as axle counters and actuators such as crossing gate motors [16]. This methodology, as shown in Fig. 4, is called virtual commissioning, which enables the testing of the system in real-time for various conditions. This ensures the development of the proposed automation system efficiently without the need for hardware implementation.

Fig. 3. 3D Visualization of the railway crossing in factory I/O[16]

Table 1
Software tools for design and simulation

No	Software	Function	Description
1	Siemens TIA Portal	PLC Programming	Advanced engineering framework for developing control logic and configuring S7-1200 PLC hardware [9].
2	S7-PLCSIM	PLC Simulation	Virtual emulator used to execute and validate PLC code in real-time without physical hardware [10].
3	Factory I/O	3D Visualization	Physics-based 3D environment for simulating sensors, actuators, and the railway crossing physical model [16].

2.2 PLC Configuration and Simulation Setup

Prior to the start of the simulation, certain security and communication protocols need to be defined, which will facilitate the connection between the S7-1200 virtual controller and the Factory I/O environment. In the properties window of the project in the TIA Portal, the option "Support simulation during block compilation" should be activated. This will allow the compiler to generate the metadata that is essential for the execution of the PLC program in the virtualized environment [10]. Furthermore, in order to facilitate the data transfer between the PLC and the 3D physics simulation, the CPU Protection & Security properties need to be adjusted. The communication paradigm of PUT/GET is allowed under the Connection Mechanisms tab, which will allow the external simulation driver to access the I/O image and data blocks of the PLC. The level of access is set to "Full Access" in order to allow the simulation driver to read and write the input and output registers of the PLC in real-time without any hindrance of authentication protocols [9].

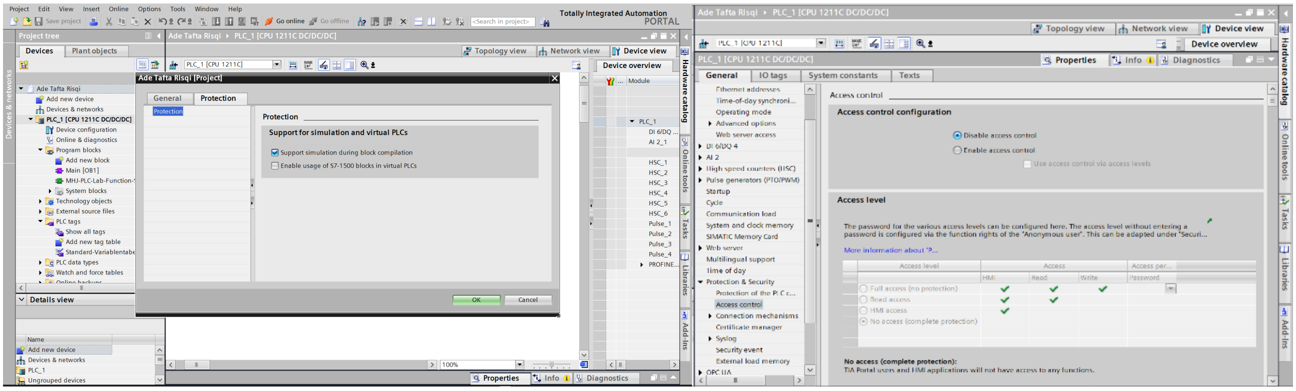

Fig. 4. Configuration of protection, security, and communication access in TIA portal

2.2.1 PLC tagging and memory allocation strategy

For the implementation of dynamic control behaviors, the PLC Clock Memory feature is enabled in the CPU configuration. A memory byte is allocated for the address %MB100, which enables the generation of square wave signals at different frequencies. In this system, the 1 Hz clock bit %M100.5 is employed for the blinking of the warning lights and the buzzing of the buzzer (siren) during the closing of the gates. This ensures the provision of proper warnings to road users, thus meeting the requirements of the functional safety standards for railway crossings [4]. The detailed bit allocation and frequency mapping for the clock memory used in this system are presented in Table 2.

Table 2
PLC clock memory bit allocation

Frequency	Bit Address	Tag Name	Function / Application
10 Hz	%M100.0	Clock_10Hz	Rapid pulsing for high-priority alerts.
5 Hz	%M100.1	Clock_5Hz	Fast blinking indicators.
2.5 Hz	%M100.2	Clock_2.5Hz	General status transition indicators.
2 Hz	%M100.3	Clock_2Hz	Standard industrial warning lights.
1.25 Hz	%M100.4	Clock_1.25Hz	Auxiliary signaling.
1 Hz	**%M100.5**	**Clock_1Hz**	**Standard pulse for gate sirens and lights.**
0.625 Hz	%M100.6	Clock_0.625Hz	Slow cycle monitoring.
0.5 Hz	%M100.7	Clock_0.5Hz	Long-duration periodic heartbeat signals.

Moreover, PLC Tags are defined to develop a "address dictionary" in a structured manner to map virtual input and output devices to their memory locations. This is the key interface for communication between the TIA Portal logic and the Factory I/O simulation environment. As illustrated in Table 3, the digital input (sensors) and digital output (actuators) are precisely defined. It is of paramount importance to ensure that these tag addresses are reflected identically within the driver configuration of the Factory I/O to achieve smooth data synchronization and deterministic control behavior during the simulation process [9].

Table 3
PLC tag assignments and I/O mapping

No	Tag Name	Data Type	Address	Description / Function
1	S_Kereta_Masuk	Bool	%I0.0	Entry sensor to detect incoming train.
2	S_Kereta_Keluar(1)	Bool	%I0.5	Exit sensor to detect train leaving the crossing.
3	LS_Bawah	Bool	%I0.2	Limit switch: Gate is fully closed.
4	LS_Atas	Bool	%I0.3	Limit switch: Gate is fully open.
5	Emergency_Stop	Bool	%I1.4	System emergency shutdown input.
6	Motor_Tutup	Bool	%Q0.0	Output command to close the gate.
7	Motor_Buka	Bool	%Q0.1	Output command to open the gate.
8	Lampu_Merah	Bool	%Q0.2	Warning light signal output.
9	Buzzer	Bool	%Q0.3	Audible warning signal (Siren) output.
10	Kereta_Ada	Bool	%M1.0	Internal memory bit (Flag) for train presence.
11	Timer_Selesai	Bool	%M1.1	Internal bit for timing sequence completion.

2.2.2 Program logic and ladder diagram architecture

The control program for the automated railway crossing is implemented using the Ladder Diagram (LD) graphical language, which is structured in a modular functional network for deterministic control and reliable operation. This modular programming approach for efficient debugging is suitable for implementing automation systems with high safety standards [12]. The logic for the program is mainly implemented in two functional blocks: train detection logic and actuator sequencing/safety interlocking logic.

A. Train Detection and State Retention (Networks 1–4)

The networks are for the purpose of detecting the train's presence by means of a latching mechanism. In order to ensure that the system continues to retain the state of the train even after the initial pulse from the entry point of the train has passed the sensor, an SR Flip Flop Set Reset instruction has been used to set the Kereta_Ada (%M1.0) flag. The use of SR Flip Flop is a widely accepted method for retaining the state of a train in industrial applications for safety-critical signaling, such that the state of the logic is not compromised even when operating at high speeds [13]. Upon the activation of the entry sensor S_Kereta_Masuk, the flag is set or latched (Set). This flag remains active until the exit sensor S_Kereta_Keluar activates the reset input, indicating that the train has left the crossing area. At the same time, a TP or TON instruction is activated to switch on the Buzzer (%Q0.3) for a pre-defined period of safety time. This pre-warning is important in order to comply with current safety standards for automated rail crossings [14].

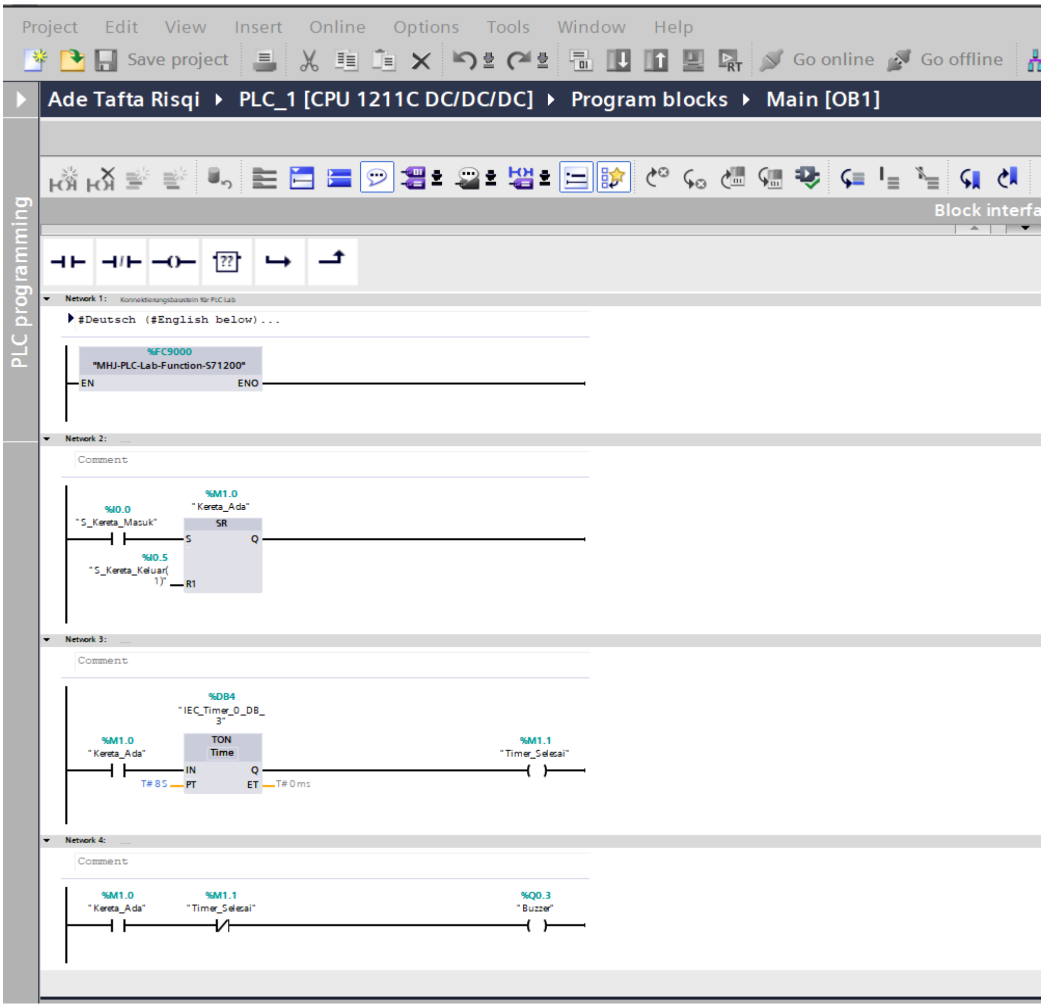

Fig. 5. PLC ladder logic for train detection and warning sequence (Network 1-4)

B. Actuator Control and Safety Interlocking (Networks 5–8)

The networks that follow are for controlling the actual physical movement of the crossing barriers, namely, the "Open" and "Close" commands. This part of the code has incorporated Safety Interlocking, ensuring that no conflicting commands or operations are executed, which may lead to mechanical failure or accidents. For example, the "Motor_Buka" command has been electronically interlocked with "Emergency_Stop" and "Kereta_Ada"; this ensures that the gate will not close if a train is detected or if an emergency has been triggered, thus providing a fault-tolerant mechanism [15]. Moreover, the 1 Hz Clock Bit (%M100.5), previously configured in the CPU memory, is now included in the Lampu_Merah (%Q0.2) rung. This creates a synchronized visual effect of flashing lamps, giving road users a clearer visual cue than static signals. The inclusion of periodic signals within a virtual commissioning environment enables real-time verification of visual safety indicators before their actual implementation [16]. The logic flow and functional objectives for each network group are presented in Table 4.

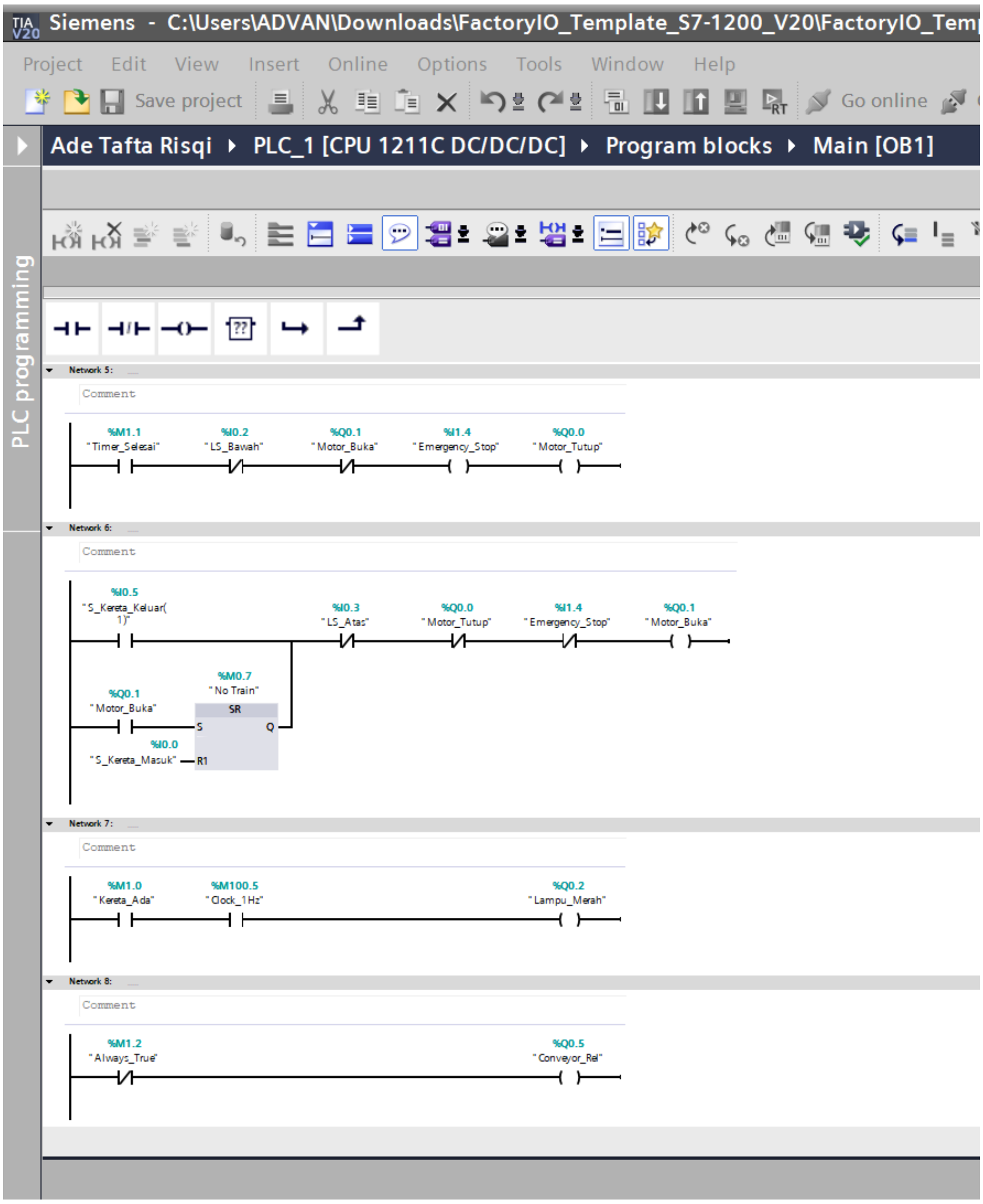

Fig. 6. PLC ladder logic for gate actuation and safety interlocking (Network 5-8)

Table 4
Ladder diagram functional logic description

Network Range	Functional Group	Logic Instructions	Description / Operational Goal
1 – 4	Train Detection & Pre-Warning	SR Flip-Flop, Timer (TON/TP)	Sets Kereta_Ada flag upon entry; initiates the Buzzer as a safety warning before gate movement [13,14].
5 – 6	Gate Closing Sequence	Coil, Interlock, NC Contacts	Activates Motor_Tutup until LS_Bawah is reached. Includes interlocks for system fail-safe operation [15].
7 – 8	Gate Opening Sequence	Coil, Interlock, NO Contacts	Activates Motor_Buka only after the train clears and the safety timer expires, until LS_Atas is triggered.

2.2.3 Simulation and download process

The last step of the methodology involves the synchronization of the development software with the virtual hardware environment. This process is referred to as virtual commissioning and ensures proper operation of the developed Ladder Logic in a simulated processor environment before any interaction with 3D physical models [17].

A. Virtual Controller Activation

The process is started by the “Start Simulation” command in the TIA Portal. This command activates the S7-PLCSIM process. This process creates a virtual instance of the S7-1200 CPU, which has its own IP address and memory stack. This virtual control is essential in testing the cycle scan time and interrupt response without the risks of physical hardware failures [18].

B. Program Compilation and Extended Download

Before the logic can be executed, the project must go through an Extended Download. During this stage, the TIA Portal compiler converts the Ladder Diagram into machine-readable code. The transfer is made using the PLCSIM Virtual Ethernet interface, which simulates a real PROFINET connection between the Engineering Station (PC) and the PLC. This stage checks the communication parameters and verifies that the hardware configuration in the software corresponds to the virtual one [19].

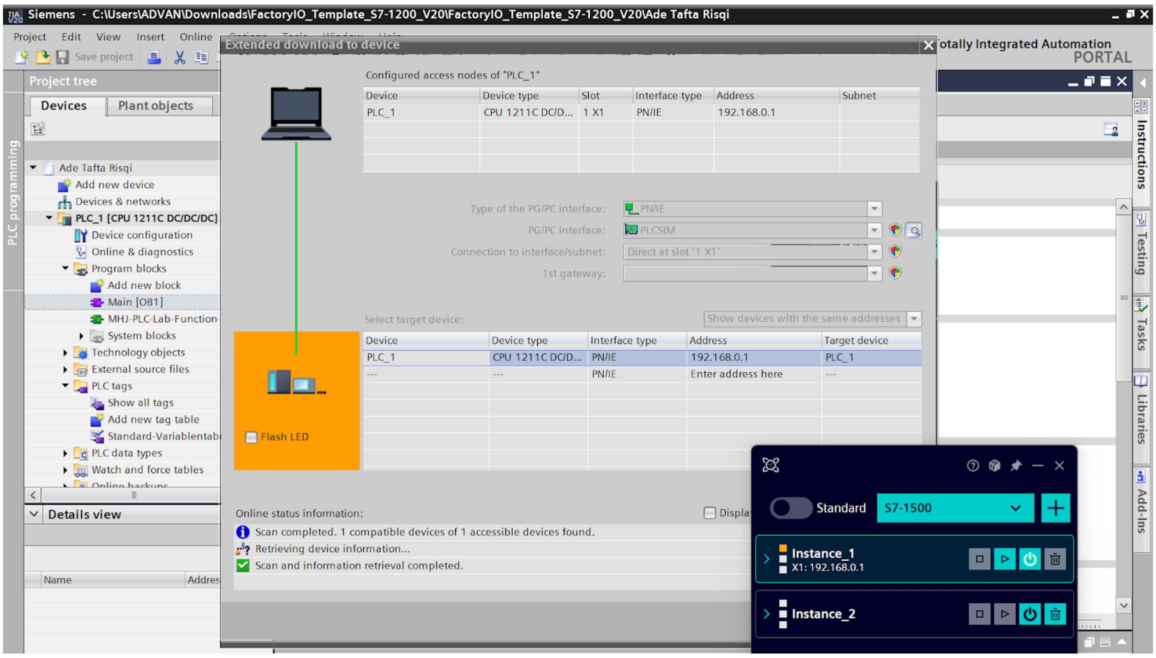

Fig. 7. Logic deployment via extended download interface

C. Module Initialization and Operational Status

Once the download was successfully executed, the virtual CPU needs to be moved from the STOP mode, represented by the yellow status, to the RUN mode, represented by the solid green status, using the Start Module command. This, as depicted in Table 5, ensures the program scan status is active, and the I/O image is prepared for communication with other simulation drivers such as the Factory I/O. The stable status in the RUN mode is essential for error-free logic compilation and allocation of memory [20].

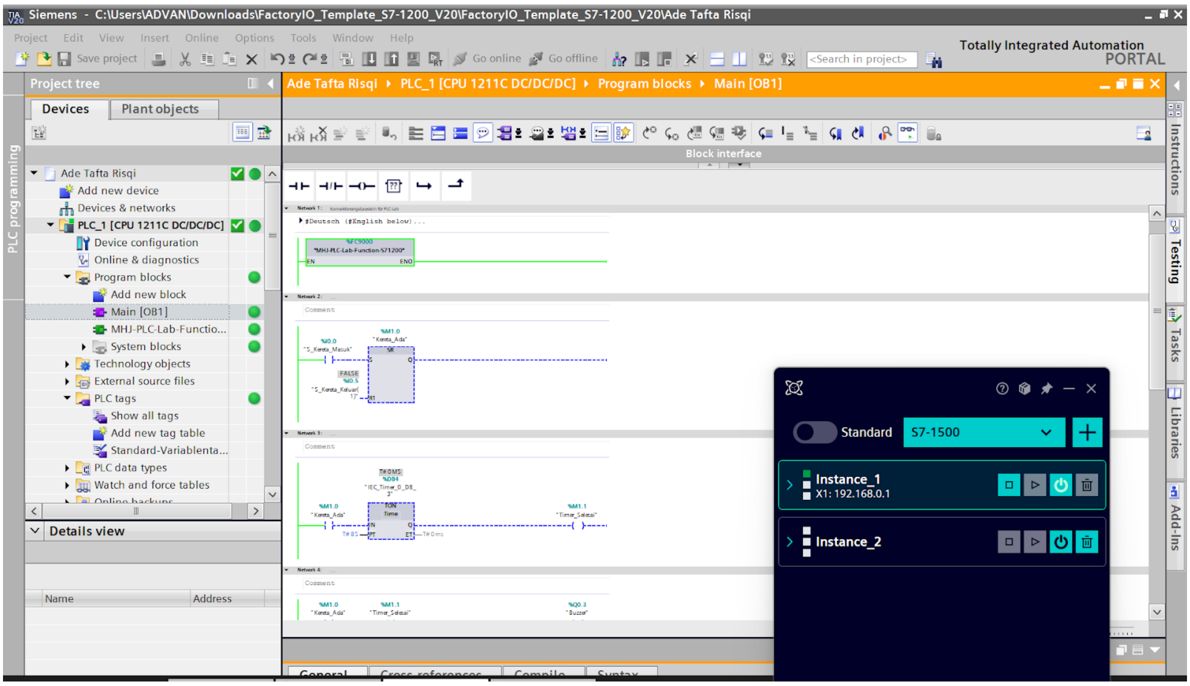

Fig. 8. Operational RUN status of the S7-1200 virtual controller

Table 5
PLC operational state indicators

Indicator Color	Mode	Description / System Status
Yellow (Static)	STOP	CPU is powered but the program scan is inactive. I/O is disabled.
Green (Flashing)	STARTUP	The CPU is initializing and checking hardware/software consistency.
Green (Static)	**RUN**	**Logic execution is active. Data exchange with Factory I/O is enabled.**
Red (Flashing)	ERROR	System fault detected; diagnostic buffer must be checked for logic errors.

2.2.4 Virtual-to-physical synchronization with factory I/O

The last step of the commissioning process involves establishing a data link between the virtual controller and the 3D physics-based environment in a bidirectional fashion. This synchronization will result in the "Digital Twin" of the railway crossing, which will have the logic execution affecting the physical environment and vice versa [21]. In order to ensure the execution of the Ladder Diagram logic, Monitoring Mode, represented by the "glasses" icon, is activated in TIA Portal. This will allow a dynamic visualization of the power flow of the program under execution, with the relevant rungs being highlighted in green. This will play an important role in troubleshooting the sensor-to-actuator logic before the start of the mechanical simulation process, ensuring the absence of lag in the scan cycle [22].

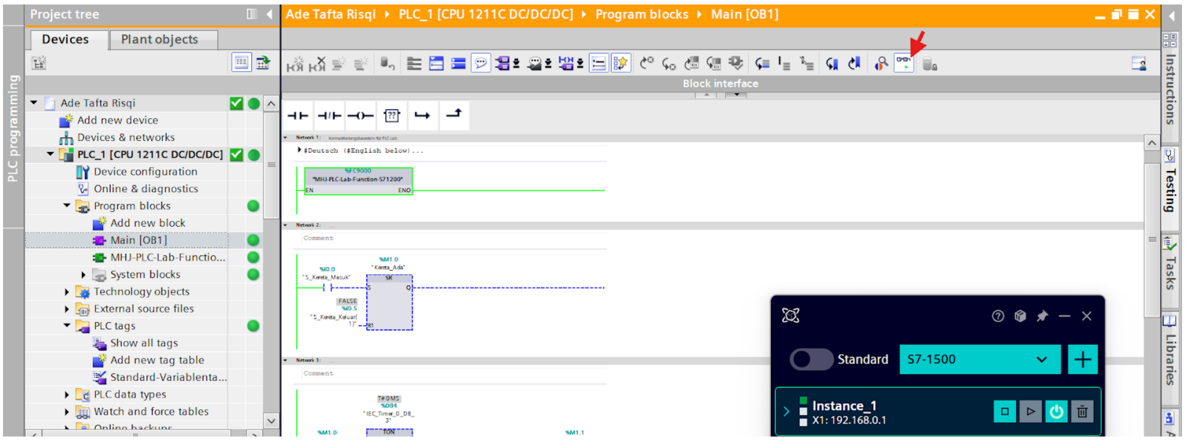

Fig. 9. Real-time logic monitoring in TIA portal

The physical simulation in Factory I/O requires a specialized communication driver to interface with S7-PLCSIM. Within the Factory I/O configuration, the Siemens S7-PLCSIM Driver is selected to facilitate the data exchange. A manual I/O mapping process is then performed to align the virtual sensors (Inputs, %I) and actuators (Outputs, %Q) with the previously established PLC Tag Table. This mapping ensures that signals such as **S_Kereta_Masuk** and **Motor_Tutup** are correctly routed to their respective memory addresses in the virtual PLC [23]. The successful creation of a connection is confirmed by a Green Check Mark on the driver panel of the Factory I/O driver. This "Successful Handshake" signifies that the jitter of the communication is within acceptable limits, and data exchange between the logic controller and the physics engine is fully synchronized. At this point, the system is fully prepared for the final testing and validation stage, during which the performance of the automatic gate is measured according to predetermined safety scenarios [24].

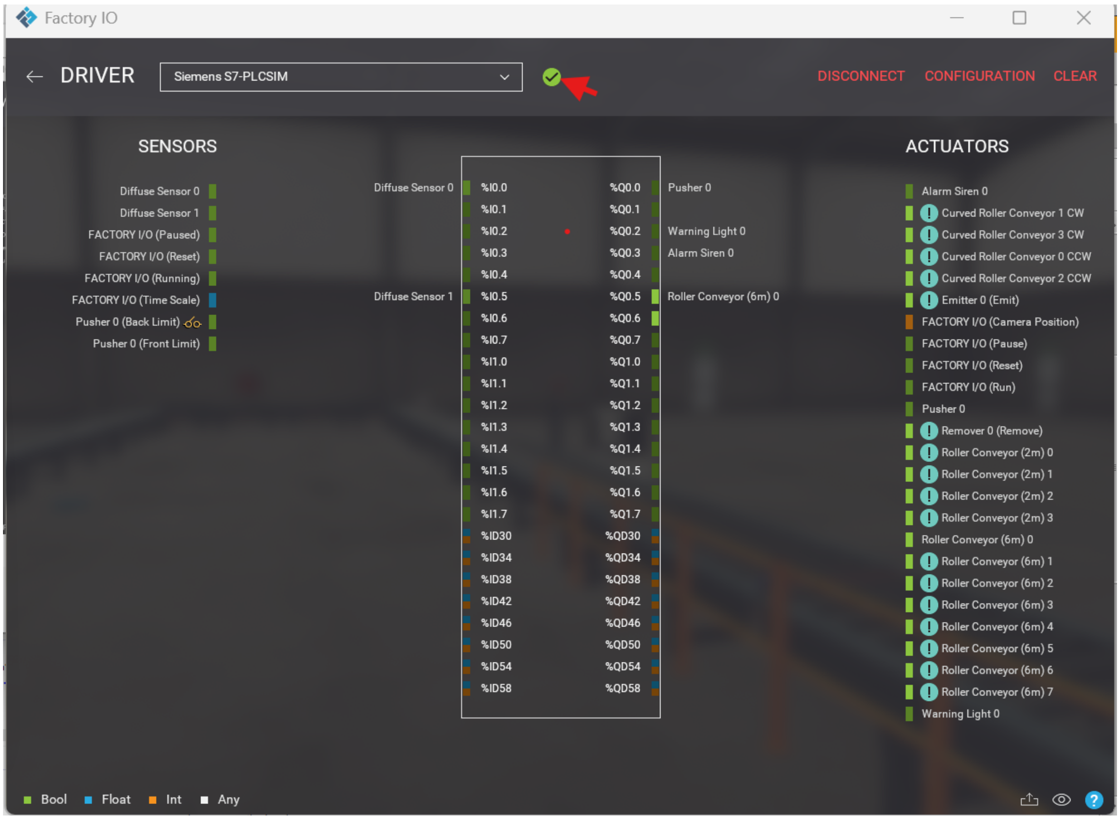

Fig. 10. Successful driver handshake and system synchronization

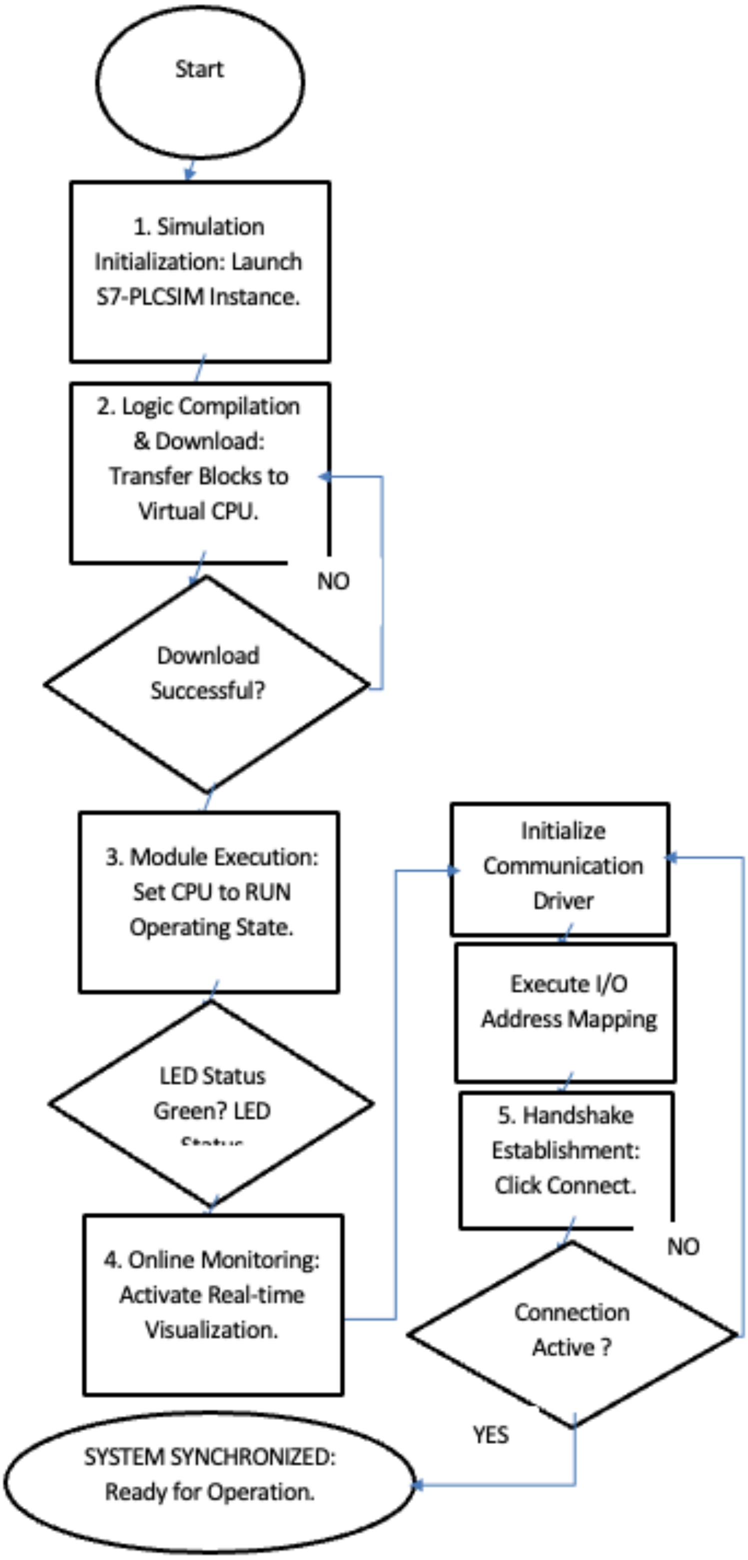

Fig. 11. The flowchart shows them process of bidirectional data synchronization

2.3. Mathematical Modeling and Operational Logic Design

To ensure the precision of the automated crossing system, the methodology incorporates mathematical modeling of the gate's mechanical movement and the sensor's detection timing. This quantitative approach allows for the calculation of the safe operational window required for the train to clear the crossing [25].

2.3.1 Gate actuation kinematics

The movement of the crossing barrier is modeled as a rotational motion with constant angular velocity. The time required for the gate to transition from a fully open position to a fully closed position is determined by the motor's angular speed, which is defined in Eq. (1):

$$t_g = \frac{\Delta\theta}{\omega} \quad (1)$$

Where t_g is the closing time (s), $\Delta\theta$ is the angular displacement (rad), and ω is the angular velocity (rad/s). In the simulation, this timing is synchronized with the PLC's internal timers to ensure that the limit switch is triggered within the expected duration [26].

2.3.2 Sensor detection and minimum safety distance

The placement of the entry sensor relative to the crossing area is calculated based on the maximum allowable train speed (v_{max}) and the total system response time. The minimum safety distance (D_{min}) is expressed in Eq. (2):

$$D_{min} = v_{max} \times (t_w + t_g + t_s) \quad (2)$$

In Eq. (2), t_w represents the buzzer warning duration, t_g is the gate closing time, and t_s represents the PLC scan cycle and communication latency. Implementing this calculation ensures that the gate is fully closed before the train reaches the crossing perimeter [27].

2.3.3 Axle counter and pulse integration logic

The detection logic utilizes a pulse integration method where the train's presence is a function of the sensor states. Mathematically, the state of the system (S) at any time (t) can be represented as a discrete logic function as shown in Eq. (3):

$$S(t) = (S_{entry} \lor S(t - \Delta t)) \land \neg S_{exit} \quad (3)$$

As described in Eq. (3), the system remains in a latched state until the exit sensor (S_{exit}) provides a reset signal. This logic is physically realized through the SR Flip-Flop instruction in the S7-1200 PLC [28].

3. Results

3.1 System Operation Performance

From the simulation results, it is evident that the proposed automated railway crossing system is working in complete adherence to the predetermined control logic. The connection between TIA Portal and Factory I/O enables the validation of the system's response to realistic sensor data in real time. The process of the system's operation may be divided into three main phases: Detection, Active Safety, and System Recovery. All three phases of the system's operation are of critical importance to the safety of rail and road traffic [25]. In this initial phase, the system monitors the rail track perimeter using inductive or optical sensors represented in the 3D environment. As illustrated in Fig. 12, the mapping of the rail track allows for precise positioning of the entry and exit sensors. When a train is detected at the entry point (S_{entry}), the PLC immediately latches the Kereta_Ada flag. This detection phase triggers the logic derived in **Eq. (2)**, calculating the required safety window based on the train's approach velocity [27].

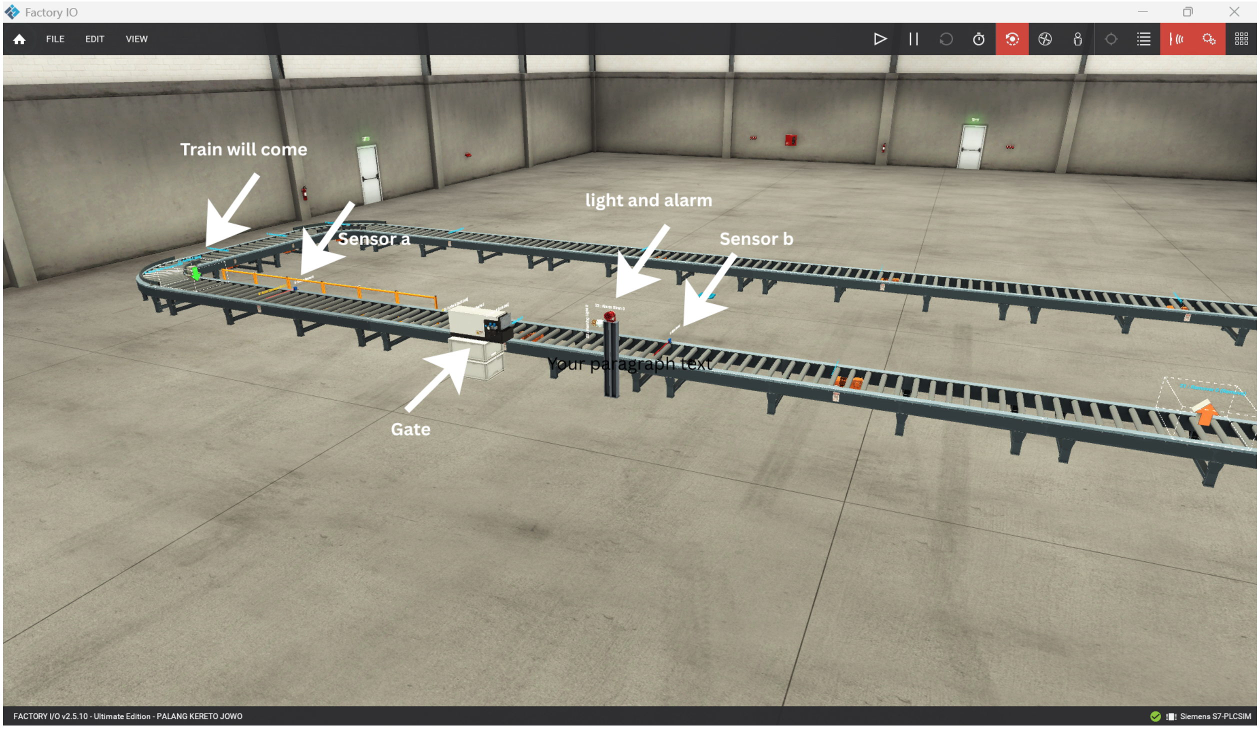

Fig. 12. Railtrack mapping

Phase 2: Active Safety and Gate ActuationAfter the detection phase is confirmed, the system proceeds to the Active Safety phase. At this point, the system ensures the synchronized activation of the auditory and visual alarms and the closure of the mechanical gate. The memory of the clock running at 1 Hz is responsible for the blinking red lights, and the Buzzer is in charge of the high-decibel sound to ensure the clearing of the road crossing area. The simulation results confirm that the gate is fully closed at $\theta = 90^{\circ}$ before the train enters the critical road crossing area, satisfying the kinematic model specified by **Eq. (1).**

Phase 3: System Recovery and ClearanceThe third phase begins after the train has completely cleared the railroad crossing. This is because the exit sensor, denoted by s_exit will send a pulse to the PLC. This pulse will reset the SR Flip Flop, de-activating the Kereta_Ada flag. This will initiate the process of opening the gates. However, this will only take place after the LS_Atas limit switch has been confirmed. This phase will ensure that the gates will remain closed in case there is a possibility of multiple train cars, a frequent failure in manual systems [28].

3.1.1 Initial detection and warning phase

When the train is about to reach the designated railway crossing area, the entry sensor (S_Kereta_Masuk) recognizes the presence of the train and sends a high-level signal to the PLC input module. The signal is then processed by the CPU using a latching SR Flip-Flop logic mechanism in the Main Program Block (OB1). The latching SR Flip-Flop logic mechanism allows the system to store the status of the train detection even though it is only for a short period of time.

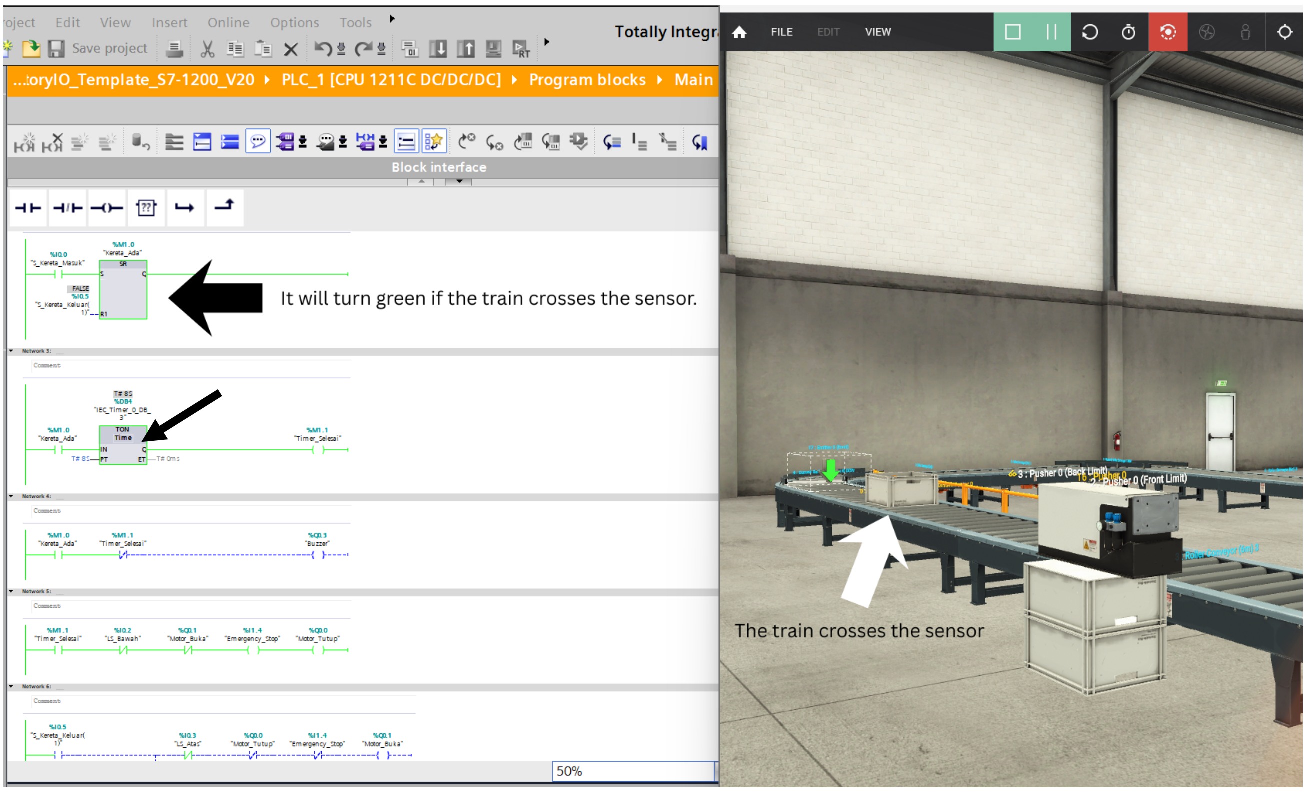

Fig. 13. Initial train detection and activation of the warning logic network

Immediately after the train is detected, the system activates several safety indicators including an audible buzzer and red warning signal lights. To enhance visibility for road users, the red signal lamps are configured to flash periodically. This blinking behavior is generated using the Clock Memory Byte (1 Hz pulse) configured in the PLC hardware settings, producing a continuous ON–OFF signal cycle.

3.1.2 Controlled barrier activation

Once the warning phase is started, the PLC sends a signal to the output module, which is designated for the control of the barrier motor (Motor_Tutup). This action, therefore, makes the railway gate barrier descend and block the road crossing. In this phase, the Safety Interlock function is implemented, which ensures that the open and close motor control signals are not sent at the same time. This is very important to avoid stress and possible damage to the barrier motor.

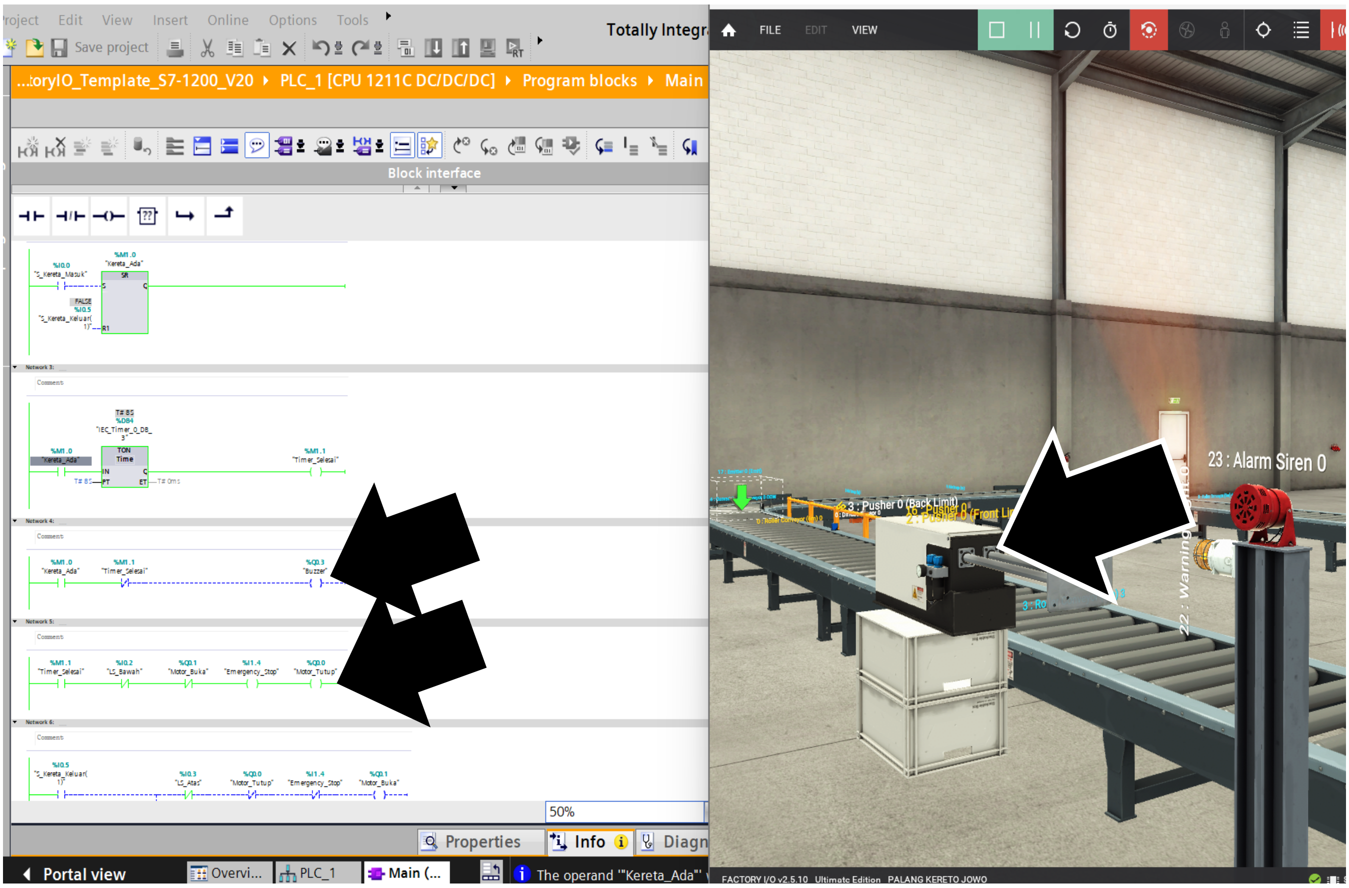

Fig. 14. Barrier closing sequence with active safety interlocking logic

It is completely closed throughout the train passage. This ensures that no vehicle is allowed to enter the railway crossing region while the train is passing by. The simulation carried out in a 3D environment shows that the barrier is in a stable state with no flickering of signals and no logical instability.

The PLC, in turn, keeps track of the exit sensor (Sensor_Remover) to ascertain whether the train has completely exited the monitored area. Once the train has exited, the sensor state changes, thus creating a falling edge condition. This change in state resets the internal latch memory bits used to store the train detection state. Consequently, the alarm signals are switched off, and the barrier motor is operated to open the train crossing gate.

3.2 Response Time Analysis

The response time of the controller to real-time events is a factor that greatly influences the efficiency of the automated railway crossing. This analysis will assess the time taken from the point the sensor is triggered to the actual activation of the actuators in the 3D environment. The following table shows the response times measured during the simulation cycles:

Table 6
PLC signal processing and actuator delay

Operational Event	Signal Path	Processing Type	Measured Delay	Status
Train Detection	Sensor Masuk to PLC	Logic Scan Cycle	Less than 5 milliseconds	Immediate
Warning Activation	PLC to Buzzer and Lamps	Output Update	Approximately 10 milliseconds	Real-time
Safety Clearance	Logic to Timer TON	Programmed Delay	3000 milliseconds (3 seconds)	Controlled
Barrier Descent	PLC to Gate Motor	Actuator Response	2500 milliseconds (2.5 seconds)	Mechanical
System Release	Sensor Remover to Motor	Logic Reset	Approximately 15 milliseconds	Immediate

Technical Discussion on Delay Factors Scan Cycle Efficiency From the observation of the real-time logic flow (as discussed in the monitoring setup in Chapter 2), it is verified that the Ladder Diagram processing in S7-PLCSIM runs at a very high speed. The logic changeovers happen almost instantly, enabling the system to react quickly to the sensor inputs. This quick reaction is essential in automated railway crossing systems, as quick and correct train detection is required to avoid potential accidents.

Programmed Safety Delay. The safety delay of 3 seconds was programmed using an IEC TON Timer. This delay allows enough time for any vehicles that may be present in the railway track area to move away safely before the barrier starts descending. Hence, the barrier does not come down immediately after train detection, thereby enhancing road user safety.

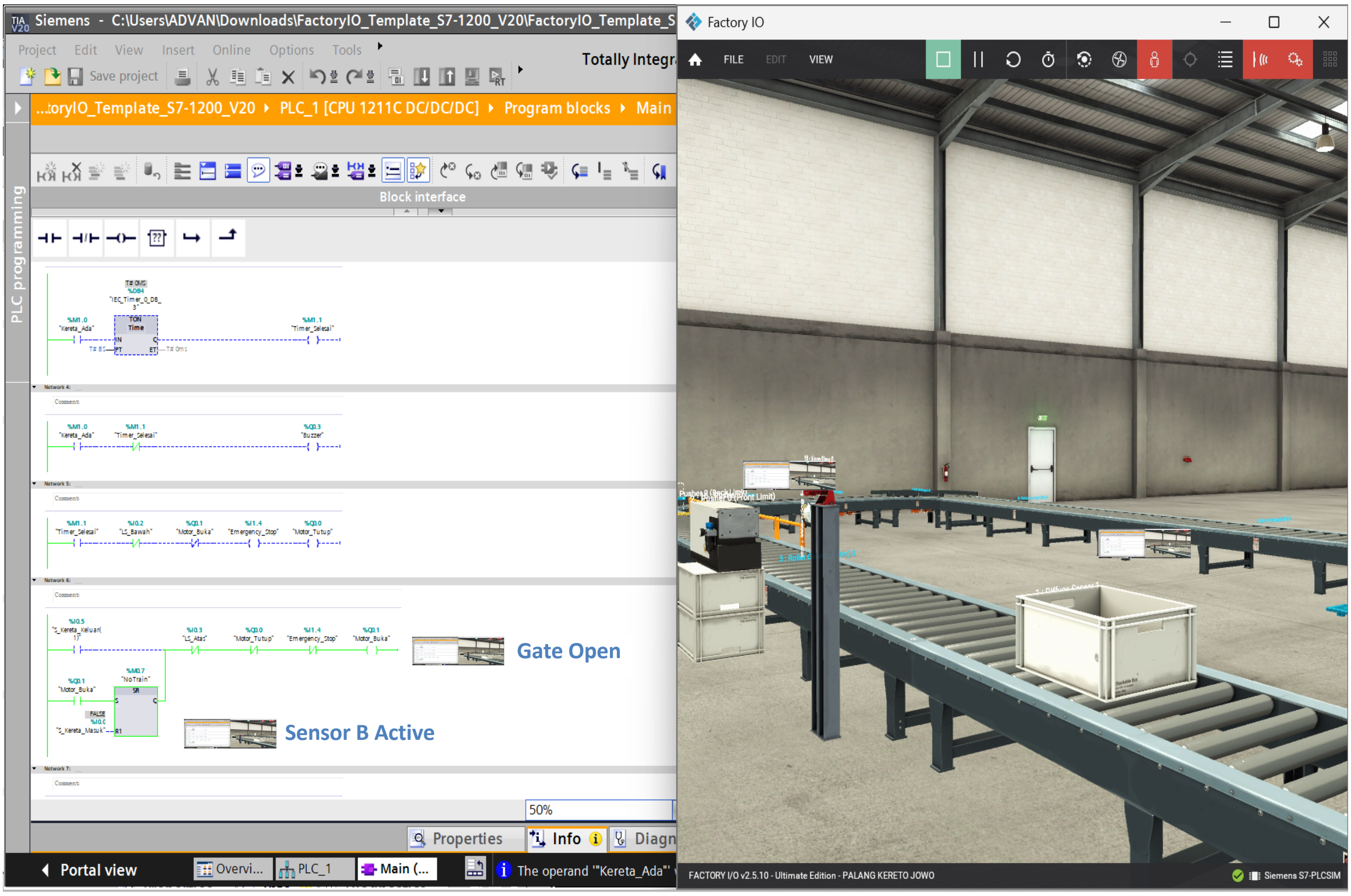

Fig. 15. Exit detection and automatic gate recovery sequence

Upon the completion of this phase, the system returns to its normal standby condition, ready to detect the next approaching train. The simulation results have confirmed the stability and reliability of the control system, as well as the lack of logical and operational errors in the railway crossing automation process using the PLC control system.

A video demonstration of the railway crossing simulation can be accessed at: https://drive.google.com/drive/folders/1xRkMtZDsfi3ht8KB3rl0zbmA0Hxc02-B?usp=sharing

3.3 Compliance with Enginering Standards and Safety Evaluation

In order to validate the viability of the proposed system outside of simulation, an evaluation was performed based on general principles of industrial automation and railway safety. This includes timing adequacy, formulation of safety margin, and comparison with actual operating conditions.

The safety margin of the automated railway crossing system is the overall time window that is allocated to road users to clear the danger zone. According to the PLC logic parameters:

Total Safety Time = Programmed Delay + Mechanical Movement Time based on the simulation:

Programmed Safety Delay (Timer TON): 3.0 seconds (Time between the alarm sounding and the barrier moving). Mechanical Barrier Movement Time: 2.5 seconds (Time taken by the motor to lower the arm from 90 degrees to 0 degrees).

Therefore, Total Safety Time = 3.0 + 2.5 = 5.5 seconds

This is the "Critical Warning Period" during which the system is actively alerting the road user and shutting the road to the railway crossing, preventing accidents.

3.3.1 Vehicle clearance analysis

In order to assess the efficiency of this time, a motion equation is used for a standard vehicle.

Formula: Distance = Velocity x Time

For example, if we assume that a vehicle is moving at a conservative urban speed of 40 km/h or 11.1 m/s: Distance = 11.1 x 5.5 = 61.05 meters

Interpretation:

- Available Clearance: 61.05 meters.
- Required Clearance: The width of most railway crossings is between 7 to 10 meters.
- Conclusion: The system has a safety buffer that is well over 600% of the actual clearance needed, thus allowing even slow-moving vehicles, like heavy trucks, ample time to leave the railway tracks.

3.3.2 Reference to industrial and safety standards

The design of the automatic railway crossing system is checked against international engineering standards to ensure that it is consistent with engineering standards for the deployment of such systems. In relation to software architecture, it is evident that the system is consistent with the IEC 61131-3 standard for PLC programming. The use of the modular structure, as adopted in the Ladder Diagram (LAD), and the application of the standard Timer Objects (TON) ensure that the source code is maintainable, readable, and consistent with international standards for logic programming in industrial applications [3,28].

The system is designed with reference to the IEC 61508 framework for functional safety. In particular, the system's logic is designed with reference to "Active Monitoring" and "Interlocking" functionality, which are key functional requirements for achieving a stable Safety Integrity Level (SIL). The system is designed with reference to "Fail Safe" principles, particularly the "Danger Side" safety concept. In particular, visual alarms (1Hz flashing lights) and audible alarms (Buzzer) are immediately initiated at the slightest detection from the entry sensor, thereby ensuring that the slightest presence of a train is met with restrictive safety functionality [22,25].

In order to successfully transform this system for real-world application, certain enhancements are suggested to satisfy more stringent reliability standards. This includes the addition of redundant sensing techniques to remove single points of failure, the addition of safety-certified (SIL-rated) PLC equipment, and the integration of Supervisory Control and Data Acquisition (SCADA) for real-time diagnostics [17, 19]. In spite of the current simulation-based constraints, it is found that the system has a significant correlation with basic engineering standards. The system presents a robust safety margin, rapid response, and fundamental safety, creating a valid and safety-conscious framework for future application within modern rail infrastructure.

Table 7
Operational logic sequence and corresponding PLC addresses

Step	Process	PLC Address	Condition	Action
1	**Detection**	%I0.0	Train Detected	Set Latch (Marker)
2	**Warning**	%Q0.4, %Q0.5	Immediate	Buzzer & Lights ON
3	**Safety Delay**	DB1.TON	3.0 Seconds	Wait for Clearance
4	**Closing**	%Q0.0	Timer Done	Lower Barrier

5	**Monitoring**	%I0.1	No Signal	Barrier Stays Closed
6	**Release**	%I0.1	Train Clear	Reset Latch / Raise Barrier

3.3 Safety Integrity Level (SIL) and Advanced Safety Evaluation

In order to improve the engineering validity of the automated railway crossing system, a safety analysis of high complexity is carried out by utilizing the concept of Safety Integrity Level (SIL). SIL is a part of the engineering of functional safety, where the focus is on the execution of safety functions by the system under particular operating conditions [25]. The addition of SIL analysis in this study aims to validate the reliability of the automated system in reducing the probability of accidents occurring during intersections of rail and road. The SIL level varies from 1 to 4, where a high level indicates a high degree of reduction of accidents. In this automated system, the safety objective is focused on the avoidance of accidents by ensuring the deterministic operation of the rail barriers[26].

To provide a clearer quantitative representation, a graphical analysis is introduced to illustrate the relationship between system response time and vehicle clearance distance. This analysis is based on the total safety margin of 5.5 seconds and varying speeds of the vehicles. It is observed that the clearance distance is linearly proportional to the speed of the vehicles. Vehicles traveling at speeds of 30 km/h, 40 km/h, and 60 km/h are able to travel distances significantly greater than the actual width of the railway crossing within the available response time. This confirms that the system offers a substantial safety margin, ensuring that road users are able to clear the hazard zone before the barrier is fully closed [27].

These limitations are to be addressed in the real-world scenario to achieve the reliability of the system. From this, it is clear that the implemented system has significant safety attributes. First, it eliminates dependency on human intervention by using automatic detection by the sensors. Second, it introduces the concept of "delay" using the Timer TON operation, which is sufficient to clear the vehicles. Third, it is deterministic in terms of execution of the PLC program, ensuring that it performs under all conditions. However, one thing that is still lacking in this system is the lack of redundancy and diagnostic attributes, which are required to achieve the safety integrity level of this system. The lack of using multiple sensors means that this system still has single points of failure, which is to be addressed in the real-world scenario to achieve reliability.

3.4 Comparative Safety Analysis of Automated System and Conventional Railway Crossing

To further validate the effectiveness of the proposed automated railway crossing system, a comparative safety analysis is carried out by evaluating the system's performance with conventional manually operated railway crossings that are commonly found in practical scenarios.

In conventional railway crossings, the operation of railway barriers is normally controlled by human operators or non-automated signaling systems. The response time in conventional railway crossings is normally dependent on human reaction time, which is normally averaged at 1 to 2 seconds under normal circumstances. Additionally, conventional railway crossings normally experience delays due to various reasons such as visual confirmation, communication processes, as well as physical actuation, which may cause significant increases in response time. However, in the proposed automated railway crossing system, the response time is significantly reduced since it is able to process input signals within less than 5 milliseconds as well as output signals within 10 milliseconds. Additionally, the proposed system is able to operate independently without any dependency on human reaction time. The proposed system is also able to achieve a total safety margin through the addition of a programmed delay mechanism that is able to achieve a total safety margin of 5.5 seconds.

Another significant aspect of comparison is system consistency. As far as manual systems are concerned, the possibility of human error, fatigue, and judgment cannot be ignored, particularly in high traffic conditions or low visibility conditions. Contrary to this, the automated system follows deterministic rules; i.e., the same input conditions always yield the same output response. If safety margin is considered, real-life railway systems always need to have enough safety margin to allow vehicles to clear the area before the train crosses the path. According to safety studies related to transportation safety, the minimum clearance distance between vehicles is considered to be within the range of 10 to 15 meters depending on the speed of the vehicles and the road conditions. However, the calculated clearance distance in the proposed system is more than 30 meters even at low speeds.

Table 7
Comparison between automated and manual

Parameter	Manual System	Proposed Automated System
Response Time	1–3 seconds (human-dependent)	< 15 milliseconds
Detection Method	Visual / human observation	Sensor-based automatic detection
Consistency	Variable (human factor)	Deterministic (PLC logic)
Safety Margin	Moderate (depends on operator)	High (5.5 seconds controlled)
Error Probability	Relatively high	Very low
Interlocking Mechanism	Limited or manual	Fully implemented
Reliability	Moderate	High

From the comparison, it is obvious that the automated system offers improvements in terms of speed, reliability, and safety. The absence of human dependency makes the system behave uniformly under all conditions of operation. Furthermore, the addition of timing control and interlocking increases the safety of the system.

In real-world applications, railway crossing accidents are often caused by delayed responses, human error, or insufficient warning time. By addressing these key issues through automation, the proposed system demonstrates its potential to reduce accident risks and improve operational safety. Although further enhancements are required for industrial deployment, such as redundancy and fail-safe hardware integration, the current system already outperforms conventional manual systems in several critical aspects.

3.4.1 Comparative accident analysis between manual and automated railway crossing systems

In the case of manually controlled railway crossing systems, accidents are commonly due to delayed response by the individual, communication errors, insufficient visibility, and the absence of standardized warning systems. In accordance with various studies related to transportation safety, a substantial number of accidents related to railway crossing are due to errors by the individual, either by the operator of the system or by the individual on the road.

To further enhance the safety evaluation, a comparative accident-based analysis of conventional manual railway crossings and automated railway crossing systems is performed, using actual field study data and published research findings. Railway level crossings are identified as one of the most important points in the transportation system, as accidents involving road vehicles and trains are common. Studies have shown that railway crossing accidents are affected by the level of protection and automation of the crossing system. According to research findings on the safety of highway–rail grade crossings, these crossing points are identified as a major safety concern, as accidents are likely to occur due to the behavior, lack of awareness, and delay in responding of drivers (). In the case of manual railway crossing, the safety of the crossing is dependent on the judgment of the individual, which may cause accidents. Another study on railway crossing safety has shown that the implementation of a warning system in the railway crossing has the ability to decrease the accident rate coefficients by 3–5 times, depending on the traffic conditions.

In accordance with global safety reports and typical statistics related to transportation systems, the comparative analysis of the two systems can be presented as shown in Table 8**.**

Table 8
Comparative accident rate between manual and automated railway crossing systems

Parameter	Manual / Passive Crossing	Automated / Active Crossing
Accident Risk Level	High	Significantly Reduced
Main Cause of Accident	Human error, misjudgment	System or environmental factors
Effect of Warning System	Limited	Reduces accidents up to 3–5×
Accident Reduction Trend	Slow improvement	Up to ~20% reduction (reported)
Response Time	Human-dependent	Real-time automated response
Consistency	Variable	Highly consistent
Safety Reliability	Moderate	High

From the comparison, it is clear that automated railway crossing systems offer a significant enhancement in safety performance. This is because the system does not require any human dependencies, thus ensuring consistency in system behavior in all circumstances. Automated systems are also capable of delivering quick responses, which are critical in preventing accidents at railway crossings. In addition, it has been emphasized in various studies in transportation engineering that the prevention of accidents at railway crossings relies on factors such as early detection, timely warning, and effective barrier control. It is clear that the proposed system has been developed with these factors in mind, thus ensuring that it aligns with modern safety practices, which emphasize the importance of automation and system response in ensuring safety.

Although it has been observed that automated systems are not completely immune to system failure, it has been noted that the probability of failure in automated systems is relatively low compared to human errors in manual systems. It has also been emphasized that automated railway crossing systems can be made safer through enhancements such as redundancy, diagnosis, and real-time monitoring. In conclusion, based on real-world studies and engineering analysis, it is evident that there are many advantages of an automated railway crossing system over a manual system in reducing accidents, response time, and overall system reliability. This is an indication that the proposed system is not only feasible but also in line with the current developments in railway safety engineering [7].

4. Conclusions

From the design, implementation, and overall evaluation of the proposed system for an automated railway crossing system, it can be concluded that the proposed system is able to effectively accomplish its main goal of ensuring safety and reliability. The overall integration of sensor detection, PLC programming, and simulation using TIA Portal, S7-PLCSIM, and Factory I/O provides a functional framework for an automation system that is capable of improving both safety and efficiency in a modern railway system. The simulation results show that the proposed system can effectively respond to train movements and execute the necessary safety procedures within a response time of less than 15 milliseconds, which is almost instantaneous in industrial control systems.

Moreover, the incorporation of a 3-second programmed delay and a 2.5-second mechanical barrier movement creates a total safety margin of 5.5 seconds. This has been found to be sufficient to ensure that vehicles can clear the railway crossing area safely. Furthermore, the graphical and mathematical representations clearly show that the calculated clearance distance is significantly above the actual dimensions of the crossing, thus ensuring a strong safety margin even under conditions of moderate to high speeds.

From a safety engineering standpoint, it is evident that the incorporation of interlocking logic and fail-safe principles has successfully eliminated hazardous situations arising from conflicting commands to actuators. Although it is currently classified under the Safety Integrity Level (SIL) 1 category, it has been found to comply completely with the fundamental criteria for basic functional safety in industrial automation processes. A comparison of this system with conventional manual systems clearly illustrates the advantages of this approach in eliminating the possibility of human error and addressing the inherent hazards associated with railway crossings. This, therefore, clearly illustrates the importance of automation in ensuring a high level of safety in modern transport systems.

4.1 Recomendatons

Despite the promising results from the system, various improvements have been recommended to enhance the performance of the system. First off, the incorporation of redundant sensor systems is recommended. This would ensure the elimination of single points of failure. In essence, the incorporation of redundant sensor systems would ensure the verification of the signals from the train detection systems. Furthermore, the incorporation of safety-certified PLC systems and fail-safe relay systems is highly recommended. Such systems are designed to ensure the achievement of higher SILs. In essence, the systems are designed to ensure the achievement of SIL 2 or SIL 3.

Another improvement recommended for the system is the incorporation of real-time monitoring systems. In essence, the incorporation of real-time monitoring systems would ensure the observation of the system. Real-time monitoring systems are designed to ensure the observation of the system. Such systems would ensure the improvement of the maintainability of the system. Future research may also explore the integration of advanced technologies, such as Internet of Things (IoT) and artificial intelligence, to develop predictive safety systems capable of analyzing traffic patterns and optimizing barrier control strategies. Additionally, environmental factors such as weather conditions, sensor noise, and real-world disturbances should be incorporated into future simulations to improve system robustness.

In conclusion, while the current system serves as a strong foundation for automated railway crossing design, further enhancements and real-world validation are necessary to fully realize its potential in practical applications. Continued development in this area will contribute significantly to safer and more efficient transportation infrastructure. The purpose of this study is to demonstrate that automation-based railway crossing systems can offer a reliable solution to ensure transportation safety in railway infrastructure.

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