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SIMULATION-BASED AUTO-GENERATED PLC PROGRAM VALIDATION FOR ESTABILISHING AUTONOMOUS MANUFACTURING IN THE AUTOMOTIVE SECTOR

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ABSTRACT

As automotive manufacturing systems grow in complexity, the demand for efficient and dependable PLC programming continues to rise. Conventional manual programming is reliant on individual expertise so that leading to many points of human error. This study introduces a framework that automates PLC code generation using flowchart-based logic and validates the output through simulation. The approach translates flowcharts into IEC 61131-3 compliant ladder logic via domain-specific language and verifies functionality using 3D simulation environments integrated with OPC UA protocols. This method improves consistency, shortens development cycle of control logic, and reduces programming errors. Its effectiveness and scalability are demonstrated through a real-world application in an electric vehicle body shop process.

1 INTRODUCTION

Programmable Logic Controllers (PLCs) are foundational components in industrial automation, extensively employed across automotive manufacturing facilities in applications ranging from body and paint shops to final assembly and logistics. They govern the operation of manufacturing equipment and manage the communication of inspection data. Historically, the creation and modification of PLC programs for new vehicle introductions, model changeovers, or maintenance have been manual processes. This dependency on individual engineer expertise and programming habits often results in programmatic inconsistencies and a higher potential for error. In response, the industry is pursuing technologies to mitigate these issues by reducing manual effort and improving error detection. A notable approach, pioneered by Hyundai Motor Company (HMC) and Kia, involves the automatic generation of PLC programs from high-level flowchart-based process descriptions. These auto-generated programs are then validated through co-simulation with 3D digital twins of the manufacturing process, enabling the early detection of physical collisions and logical programming faults. This paper details this methodology for automated PLC program generation and verification.

2 PLC PROGRAM AUTO-GENERATION

International standards for industrial automation and control systems, such as IEC 61131 (IEC 2013) for PLCs and related equipment, and IEC 61499 (IEC 2005) for distributed intelligent systems, provide foundational frameworks for system design and implementation. However, in this study, we focus on IEC 61131, which is predominantly adopted in discrete manufacturing environments, particularly in automotive production lines. Among the sections of IEC 61131, IEC 61131-3 standardizes programming languages for PLCs, defining five types: Ladder Diagram (LD), Instruction List (IL), Sequential Function Chart (SFC), Structured Text (ST), and Function Block Diagram (FBD). Among these, LD is widely used in automotive manufacturing plants. However, as discussed in Section 1, LD is challenging to write and interpret, and unlike general-purpose programming languages, it poses difficulties in extending to code generation using language models such as LLMs and SLMs. To address these limitations, HMC has adopted a method where

process logic is represented as flowcharts, which are then converted into a Domain-Specific Language (DSL) and used to automatically generate PLC programs, thereby overcoming the challenges.

3 3D SIMULATION PROCESS FOR PLC PROGRAM VALIDATION

A method for validating PLC programs for automotive production lines uses a 3D digital twin simulation. Equipment models designed in SolidEdge are integrated into a virtual production line using DMWorks and NVIDIA Omniverse, with robot trajectories defined to create a realistic environment. The PLC program is then downloaded to a PLC emulator, which is connected to the 3D simulation via the OPC UA protocol. This closed-loop system exchanges virtual I/O signals, allowing real-time visualization of equipment operation based on the PLC control logic. This process enables the early detection of PLC program errors, design conflicts, and safety issues without the need for physical equipment. As a result, it significantly reduces commissioning time and development costs while improving program reliability.

4 VALIDATION OF AUTO-GENERATED PLC PROGRAM WITH 3D PLC SIMULATION

PLC simulation offers significant advantages in detecting programming and equipment design errors by emulating newly developed or modified PLC programs typically created during new vehicle production, future model planning, or improvement projects-using virtual PLCs. Based on the input/output signals of these PLC programs, the simulation software activates equipment modeled within 3D graphic files, enabling comprehensive validation. The overall process illustrated in Figure 1 is using for automatic generation of PLC program and verification of it.

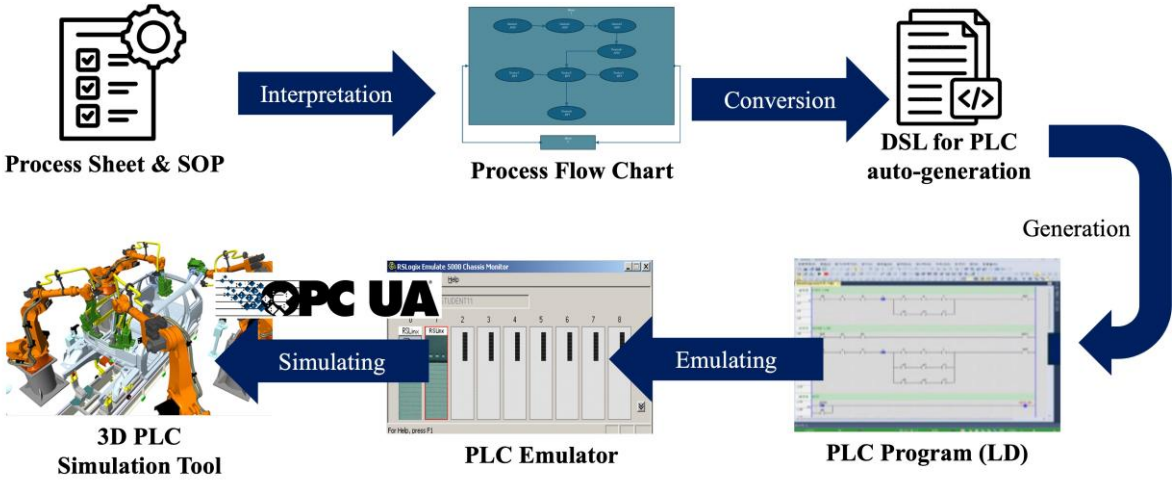

Figure 1. Overall process of PLC program auto-generation and validation.

Building upon the previously discussed flowchart-based automatic PLC generation and PLC simulation technologies, HMC applied this methodology to the body shop processes of a newly constructed plant. As a result, both programming time and error rates were significantly reduced. environment, in which PLC program is generated using LLM and optimized based on Key Performance Indicators (KPIs) derived from PLC simulation environments.

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