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Virtual Commissioning Implementation of Side Panel Assembly Process for Automotive Shop Floor

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Abstract: Industry 4.0 has established new standards in manufacturing and quality processes, which are mainly based on the type and efficiency of the different components of an industrial system. Virtual commissioning (VC) is an approach that allows the user to propose a commissioning solution using computer models of industrial systems to speed up and improve the traditional processes. This paper presents a VC solution for an industrial automotive assembly line process using toolchains of standard and off-the-shelf software and hardware components, including physical PLC and HMI. The virtual assembly line environment was developed using digital mock-ups of industrial robots, smart conveyors, controllers, and sensors. The toolchains share most of their components, virtual and physical, and can be classified as pure software or software and hardware applications. The connection between the elements of the toolchain is done using industrial protocols like Modbus TCP and APIs, ensuring complete data transfer. After several tests, the results have shown that by performing the simulated process with the VC platform, it is possible to verify automation hardware and software, with a representative digital robotic cell, thanks to the applied simulation technique.

Keywords: Virtual commissioning, Virtual engineering, Automotive industry, Functional modeling, Multi-software toolchain.

1. Introduction

Nowadays, simulation systems are recommended for engineering, research, design, and decision-making tasks. [1] Simulation models from different fields are combined, using multi-domain simulation tools, to create a complete model of the system specifications and behaviors, considering the different physical interactions and communication protocols. [2,3] A digital factory, also known as Smart Factory or Cyber-Physical Production Systems, is the generic term for a network of digital models. Also, it considers methods and tools integrated in the life cycle phases of a production system, characterized by their scalable and modular structure based on the idea of concurrent engineering and computer integrated manufacturing. [1, 2, 4-7] This approach eases the integration and replacement of production lines whilst being flexible to disruptions and failures. This type of simulation generates model-based copies, known as digital twins, that can be defined as virtual representations of a physical assets enabled through data for real-time prediction, optimization, monitoring, controlling, and improved decision making. The added value of a digital twin improves the following tasks: real-time remote monitoring and control, efficiency and safety, predictive maintenance and scheduling, scenario and risks assessment, team synergy and collaboration, efficient decision support system, customization of product and services, and better documentation. [8, 9]

It is worth noting that digital twins can be as detailed as the user desires, considering that some specifications are fundamental to represent the system.

Virtual Commissioning (VC) focuses on the optimization and validation of automatic systems, increasing quality and efficiency in production engineering whilst decreasing required time, through using Smart Factories and commission them in a simulation environment. [4, 10, 11] As mentioned in [1], VC can be considered as the quality gate of the mechatronic, robotics and automation engineering results, and the first step on the development process that ensures their interoperability.

Increasing the production of complex and/or customized products with short life cycles, like in the automotive and electronics industries, requires a lot of engineering and planning effort. [1, 3, 12-15] VC is the best option for these scenarios, reducing ramp-up time, resulting in shorter product's time to market. These intangible costs and benefits have been deeply studied and evaluated for different scenarios in [16]. The use of this technology allows to verify the functionality of systems, through the testing of off-line programs for specific devices, and avoid unexpected expenses due to inadequate component selection or damage during testing. [17] VC can be seen as a part of the modern approach to Product Lifecycle Management (PLM), being mostly used for product design inception through its manufacture. [18]

Research has been done regarding the standardization and hierarchy categorization of VC to identify its level of complexity, detailing functions, with the main goal to ease its implementations and business model. [19] This standard categorizes VC into 5 increasing levels, 1 to 5, according to the functionality and accuracy of the solutions. Level 1 allows emulation and verification of controller codes, level 2 adds the signal and communication protocols, level 3 enables the simulation of sensors, devices, and actuators, using their behavior models, level 4 includes the mechanical analysis of mechatronic systems, and level 5 covers the interconnection of systems and IT tools. The selection of level for VC implementation is a fundamental step due to its involved complexity and implicit costs.

This document is an extended version of the work presented in Virtual commissioning of an automotive station for door assembly operation, during the 2nd IFSA Winter Conference on Automation, Robotics & Communications for Industry 4.0. [20] The additional information covers virtual commissioning and process design methodologies followed to develop the solution, a description of the logic for programming the PLC, and detailed explanation of the 3D environment.

This article presents the following organization: first, an introduction of the studied virtual commissioning methodology; secondly, a summary of the process design of the analyzed system the description of a level 5 VC Toolchain and the automotive use case; thirdly, the simulation and results are studied; lastly, conclusions and ongoing work are discussed.

2. Methodology

Assembly lines are the most used method in mass production environments due to its low level of required training for generating complex products. The main objective of assembly systems design is to increase line efficiency by maximizing the ratio between throughput and required costs. Assembly line efficiency can be measured using performance indices like cycle time and the number of stations involved, while other factors such as traffic problems, station congestion, and transportation network are considered marginal in the design stage of the assembly line. [21] In traditional industries where the customization and variability of manufactured products is limited or inexistent, the optimization in design and production processes can be achieved by modifying a minimal number of variables and parameters. However, the automotive industry is constantly evolving due to its high competitively environment, always requesting more complex and personalized systems. Considering the quantity of independent systems and subsystems, it is possible to imply a modular manufacturing process that can be handled by a flexible manufacturing cell. This approach will increase the flexibility of the manufacturing operation in terms of its range of function, product, and service by modularizations and its ability to be easily reconfigured in the face of changing conditions [22].

As commented in the introduction, there are several approaches to develop a VC implementation, where the adequate selection depends on the level of detail required, and involved resources (workforce, time, budget, among others). In this project, a functional and behavioral modeling was used for the process definition. In order to have reliable models of the jigs & tools from the assembly stations, we follow a decoupling strategy which consists of separating the high-level components, and the low-level components. Given that the virtual commissioning simulation platform implies an interaction of several real and simulated signals between execution and simulation functions, having a modular modeling strategy enables the platform to be less prone to have errors due to the digital modeling. Let us briefly recall the modular strategy of station components presented in [13]. For all station components, as shown in Fig. 1, we will use the following modeling strategy:

- Each station component will be decomposed into several macro-components, and the low-level components of such macro-component, will be splitted into elementary components
- Each elementary component will be modeled according to its input and output specifications, including features such as safety functionalities, control capabilities, redundancy specificities, etc.

- Once each elementary component is modeled, such functions will be instantiated as many times as necessary to build the macro-component
- Finally, the mapping between the execution layer and the behavioral models, representing the simulation platform, will be performed, while following the defined protocol of communication. In this study we use toolchains based on API, and Modbus TCP network communication.

It is worth noticing that in our case, for this study, we use the software ControlBuild to perform the modeling of the different components, which allows to develop the models by means of PLCOpen languages [23]. Nonetheless, any other software allowing to perform behavioral modeling for validation & verification of automation software and hardware, could be used and follow the modeling strategy.

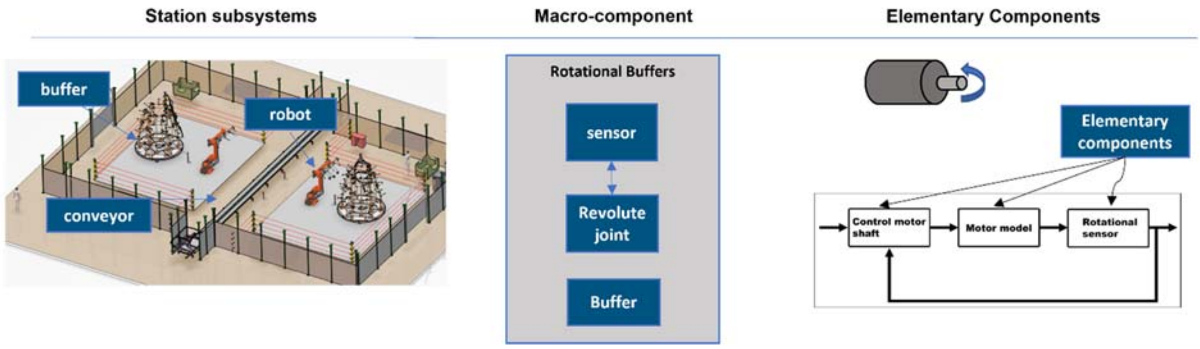

Fig. 1. Decomposition of station components.

3. Virtual Commissioning Toolchain

As it was previously introduced, VC consists in modeling functional and 3D kinematized models to do Verification and Validation (V&V) of automation hardware and software. The advantage of doing such virtual engineering techniques, is that the V&V of automation solutions can be done offline by connecting the simulation platforms to the operational technologies, e.g., PLCs. Leading to not impact the production in the assembly lines, since the production process does not require to be interrupted. Depending on the phases within the workflow from engineering until real commissioning, one might need to implement different simulation technologies. Because of the previous, we show an implementation of three simulation approaches permitting to validate requirements during different project phases. The targeted architecture can be shown in Fig. 2. The modeling and simulation tools are based on:

- *ControlBuild*: For functional and behavioral modeling of the mechatronic components of the automotive assembly station
- *Delmia*: For modeling 3D kinematized components.

The operational technologies are based on Siemens and Schneider editors, with their appropriated programming environments, respectively TIA Portal, and Control Expert. To apply such global architecture into the automotive use case, in the next section we show the application of the simulation platform for a door assembly process of an automotive use case, extensively described in [10]. Additionally, the three types of simulation approaches, i.e., Model-in-the-Loop (MiL), Software-in-the-Loop (SiL), and Hardware-in-the-Loop (HiL), are shown, thus validating high and low-level automation and robotics requirements.

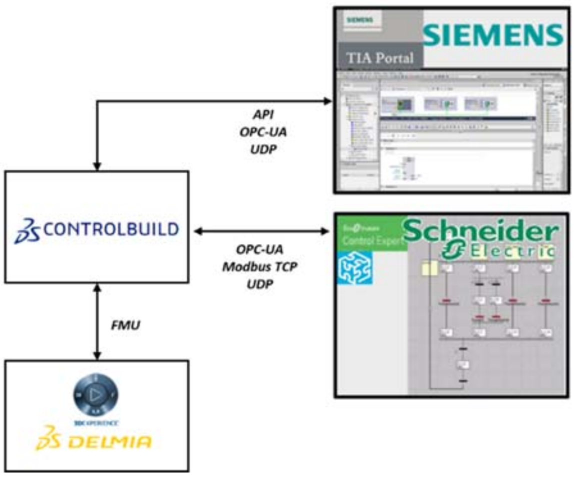

Fig. 2. Targeted Virtual Commissioning toolchains.

4. Simulation and Testing Specification

The automotive assembly cell consists of a smart conveyor (used to carry the car body through the cell), a couple of robots (LRo and RRo), buffers (LB and RB), positioning sensors (WA1 and WA2), safety gate sensors (LSG and RSG), and safety barrier sensors (SLBX). All those components are arranged in a mirror manner, as shown in Fig. 3. Control and power electronic components, like PLC, drives, relies, robot controllers, industrial cabinets, etc., physical models are omitted in the 3D environment as their location in the real world is expected to be in the control components area of the shopfloor.

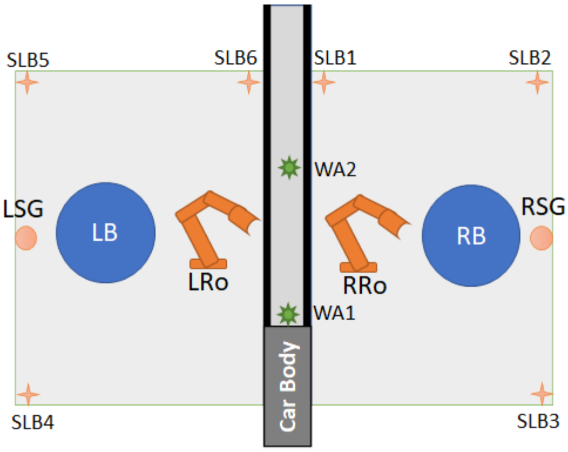

Fig. 3. Automotive cell 2-D layout.

The main process of the proposed use case was broken down into a series of interconnected tasks; a brief description of them is shown in Fig. 4 and listed below:

- *Start cycle:* Absences of faults are acknowledged in the station, afterwards, a signal is sent to start the production process.
- *Production mode:* The production sequence is launched. Signals are sent in parallel to the different devices in the cell to begin their processes.
- *Switching car:* The conveyor brings the car body into the assembly area. The conveyor linear velocity and position are controlled using position sensors and a motor drive unit.
- *Check buffer:* Right and left buffers rotate to bring the body sides to the position where the two pick-and-place robots can perform the assembly. The angular positions of the buffers are measured by absolute encoders.
- *Side car positioning:* The robots assemble the body sides to the chassis. When the task is finished, the car continues along the conveyor to the following process, outside of the current robotic cell.
- *Safety flag system:* Safety sensors, emergency buttons, and circuit breaker systems are monitored during the entire process. This task possesses the highest priority of the whole operation, whenever a single alarm and/or fault is detected, the process enters in safety mode and stops the production.

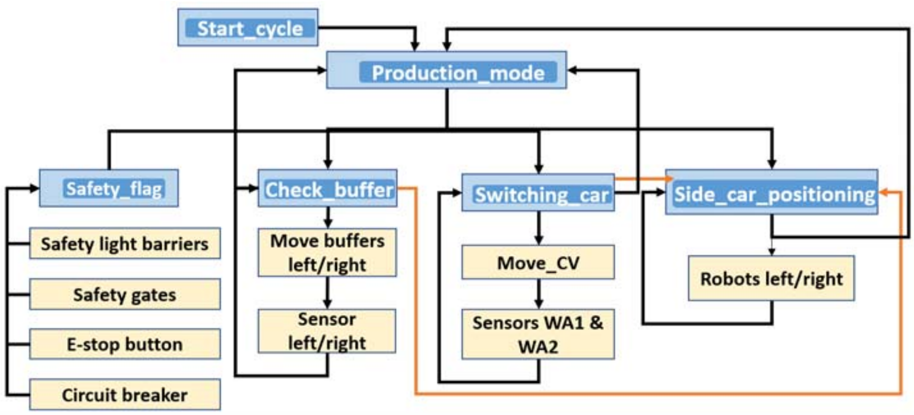

Fig. 4. Door assembly operation functional diagram for a single cycle. Logical functions are blue blocks, component models are yellow blocks, orange arrows represent dependency links, and black arrows are logical links.

Each one of the tasks was designed using the standardized finite-state-machine approach called Graphe Fonctionnel de Commande Etape Transition (GRAFCET), allowing to sequentially establish the process through the definition of events and steps. The events are actions triggered by simulated sensors, HMI inputs, or process internal conditions, while the steps are system states, an example of this approach is shown in Fig. 5, where the switching car process is described.

To V&V the automation process, we focused on the use of two validation environments: Siemens and Schneider automation software. According to Fig. 5, there are two toolchains permitting to perform both SiL, and HiL techniques. On the upper right of the toolchain in Fig. 5, the system to be commissioned is a Siemens virtual PLC 1515F-2 PN, and a virtual HMI KTP700F. These automation components are connected to the simulation platform via shared memory, permitting to exchange data bidirectionally, to V&V the programs and routines computed in the virtual PLC and HMI through SiL. On the bottom right of the Fig. 6, a physical HMI is connected to the simulation platform. In this case a virtual PLC Modicon 580 and a physical HMI Harmony STU855 from Schneider Electric are used. The communication between the simulation platform and the execution layer based on Schneider automation software is done via Modbus TCP. From the system setup, it has been accomplished the end-to-end communication and digital continuity from the simulation to the execution layer, permitting thus to improve the commissioning process for an automotive scenario.

In terms of network and infrastructure architecture, Fig. 7, and Fig. 8, respectively for the Siemens and the Schneider toolchain, show a schematic of the communication protocols among the several components. According to Fig. 6, it can be seen that the network exchange performed between ControlBuild and the simulated PLC is done via the PLCSimAdvanced API, allowing thus to exchange the different operative and safety I/O's. It is worth noticing that to instantiate the PLC, the PLCSim softbus is used. On the other hand, according to Fig. 7, for the commissioning of the Schneider components (PLC, and HMI), the communication between the simulation PC and the physical HMI is done via a physical connection to the local network of both components establishing an exchange through Modbus TCP. The virtual PLC runs in the simulation PC, which is virtually connected to ControlBuild via Modbus TCP. Finally, the communication between ControlBuild, and Delmia, for the visualization of the 3D kinematized components is done via FMU.

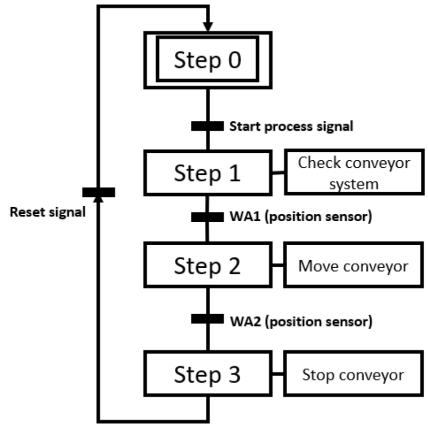

Fig. 5. GRAFCET diagram for Switching car task.

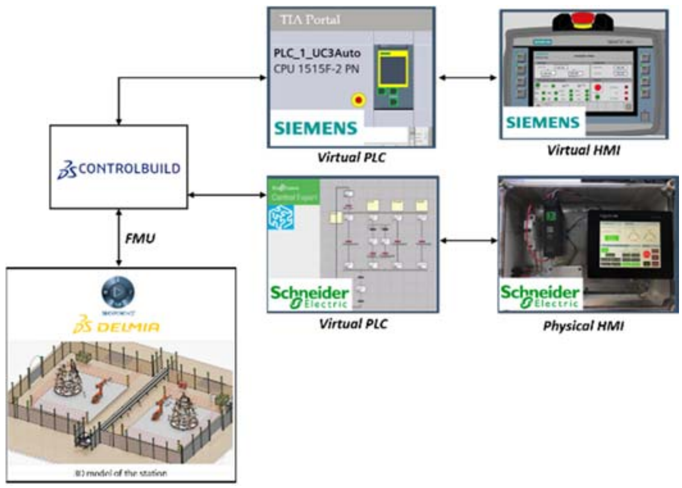

Fig. 6. System to be commissioned through MiL, SiL, and HiL.

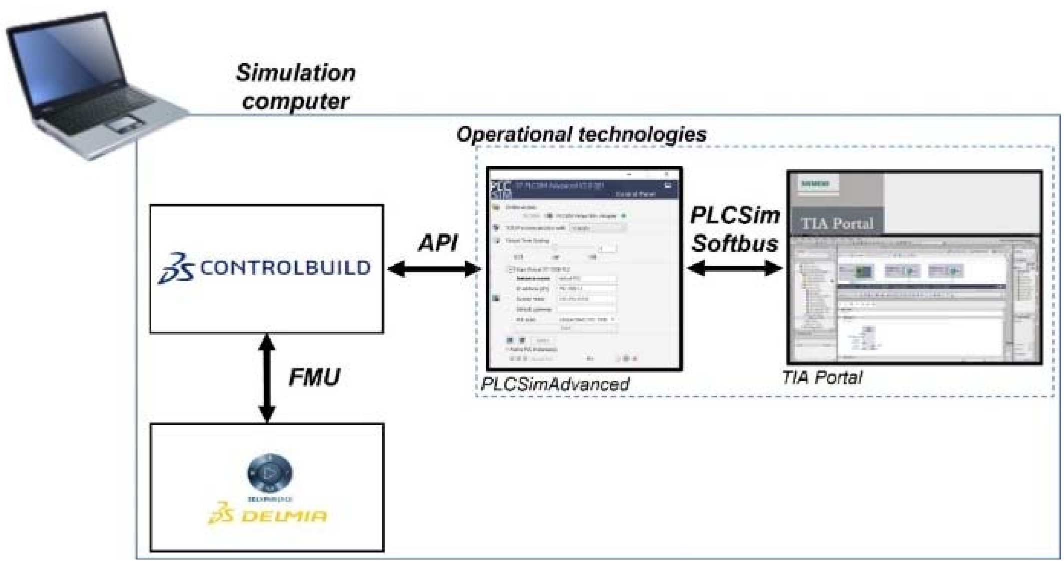

Fig. 7. Network setup for SiL with Siemens virtual PLC and virtual HMI.

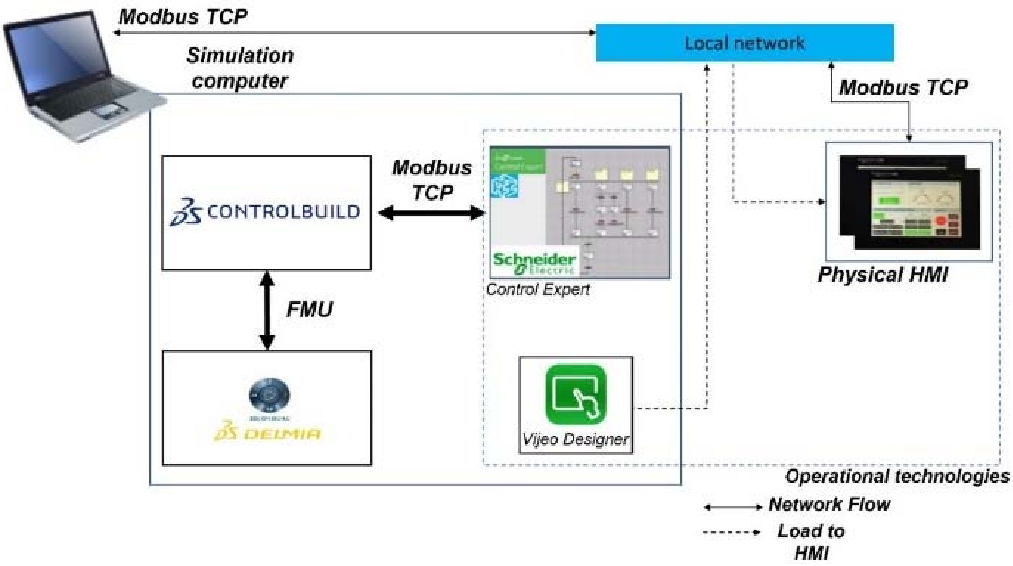

Fig. 8. Network setup for HiL with physical HMI.

Fig. 9 permits to visualize the mechanism of variable exchange performed between the PLC's (From TIA Portal and ControlExpert) and ControlBuild. It is worth noticing that the communication is done via a coupling driver respectively, using the PLCSimAdv API of Siemens, for TIA Portal, and Modbus TCP for ControlExpert. Additionally, to associate the variables between the PLC and ControlBuild, output and input mapping tables are created to properly match the variables, ensuring thus, a bidirectional communication. It is worth noticing that safety and control signals, as well as the information generated by simulated sensors in Delmia and Controlbuild provide the required data for closing the control loop with the PLCs (physical or simulated), meaning that the proper mapping of these variables along the toolchain is in high regard and data loss must be minimized.

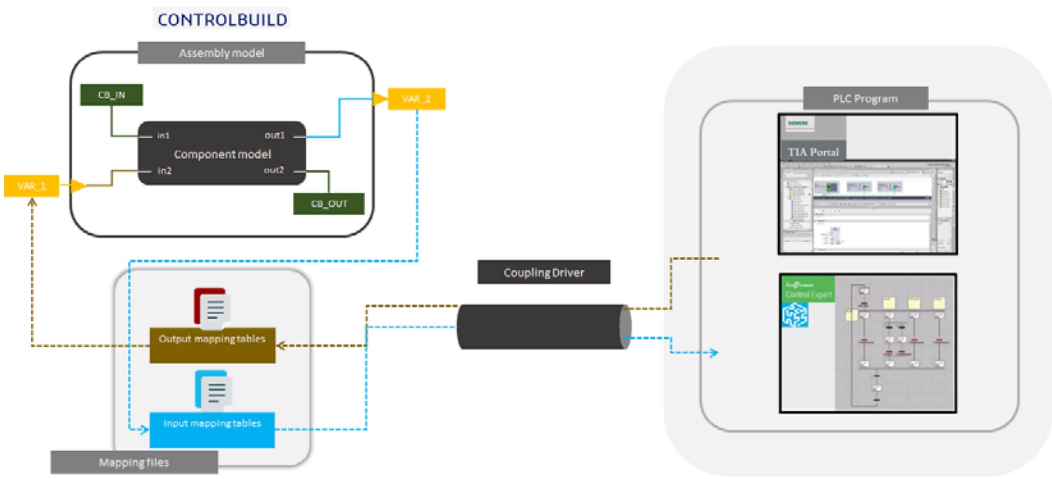

Fig. 9. Communication and mapping.

5. Conclusions

VC implementations allow the user to design, develop, simulate, test, and optimize different industrial scenarios and processes. These simulations can be as complex and detailed as the developer requires, to provide sufficient information for the V&V process. The use case studied in this research has the goal to represent welding and pick and place tasks in industrial automotive shopfloors. It was tested with MiL, SiL, and HiL toolchains, demonstrating the feasibility to simulate operations with different control components without losing any of its features and reliability. It is worth noticing that the 3D simulation environment requires a computer with enough graphical and processing resources to perform a smooth simulation, being this the biggest bottleneck of the toolchain. The previous comes from the fact that the robotic and motor applications require kinematic and dynamic constraints, resulting in the need of enough computational resources for their controllers.

Regarding the proposed control devices and software, since the process was well analyzed, designed, and interpreted, the logic behind the solution was implemented in an optimal manner, allowing the virtual PLCs to run it without any setback.

The current and future work involves the use of open communication protocols, like Open Platform Communications Unified Architecture (OPC UA), to create a network of different vendor agnostic devices. The openness that is being proposed, will allow the developer to fulfill requirements and functionalities that might not be available in some specific software, like advanced computer vision algorithms, complex sensor simulations, handheld devices communication, IIoT applications, and robotics hardware implementations. Respecting processes to be simulated, a series of flexible manufacturing cells is being developed to complement the full chassis assembly shop floor.

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