Multi Agent Systems based CPPS – An Industry 4.0 Test Case

Abdelhamid Bendjelloul [1-2], Mehdi Gaham[1], Brahim Bouzouia[1], Mansour Moufid[2]
and Bachir Mihoubi[1]

[1] Center of Development of Advanced Technologies, CDTA, SRP Team, Baba Hassan, Algiers,
Algeria
[2] USTHB University, LRPE Laboratory, BP 32, El Alia, Bab Ezzouar, Algiers, Algeria

Abstract.
With the rise of the Industry 4.0 Revolution, Artificial Intelligence, digitalization, and connectivity have been more than ever; adopted in the industrial world. This adoption is leading to the transformation of the mechatronic systems used in production into Cyber-Physical Production Systems. Such a concept is taking industrial Automation and computer integrated manufacturing to the next level. The massive migration of traditional production systems into Cyber-Physical Production Systems, including the MAS-based CPPS, made the reviewing of the traditional methods of Engineering and Commissioning a must. Which explains the increase in the number of research works during recent years about the application of these Architectures on practical cases. In the present paper, we propose a way of developing and implementing MAS-based CPPS on an Industry 4.0 Assembly Platform. Moreover, we test the behavior of the Multi-Agent systems with interaction with SIEMENS Programmable Logic Controllers via OPC UA Protocol, during a Software-In-the-Loop “SIL” Test on a 3D Model of the Platform running on a separate Computer. The test assesses the behavior of the components of a typical Cyber-Physical production module during the treatment of a given operation on the product, to extract the vulnerabilities in the treatment of the operation and search for appropriate improvements.

Keywords: Multi Agent Systems, Cyber Physical Production Systems, Intelligent Manufacturing Systems, SIL-Testing

1 Introduction

Nowadays, the rise of competitiveness in several industries like electronics, cars, accessories or even clothes, lead to the fast development of products into better versions and the demand on more and more new features which lead to the mass personalization in one hand. And in the other hand the need of better competitiveness in the market. That means the need for more reliable plants with less downtime due to unpredicted breakdowns, with faster response time of maintenance staff and logistics to react to every new situation, which make the use of software more important than ever, a gen-

eralization of software use in every aspect of the production, leading to its digitalization. Without omitting the importance of more data availability at all levels of the factory and control systems, which is only possible by more connectivity.
Lot of initiatives were made to meet these requirements, making the Industry migrating to an entire digitalization and connectivity, from where was born the Industry 4.0 [12]. The fourth industrial revolution is based mainly on cyber physical production systems, which include smart machines and production facilities that have been developed digitally, and having their logistics, production, marketing and service entirely integrable basing on ICT [13]. In fact, the transformation of mechatronic systems into cyber physical systems (CPS) is the source of some of the main Industry 4.0 objectives [14].

Being a founding brick of the industry 4.0 [1], Cyber Physical Production systems are defined by *Monostori et al* [17] as following "CPPS consist of autonomous and cooperative elements and sub-systems that are getting into connection with each other in situation dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks." Moreover, the cyber physical systems architecture is divided into 5 Levels [7], [18] and [2] as follow: The connection level, the conversion level, the cyber level, the cognition level and the configuration level. Several papers highlights the requirements that has to be met for Cyber Physical Production Systems [3], [4], [5] and [6]. In [3] CPPS characteristics are categorized in four groups. The first group is Architectural models which could be based on SOA or MAS due to their openness. The second group is Communication and data consistency. The third group is intelligent products and production facilities inside a CPPS, which are able to flexibly adapt to change in customer requirements, variation in the demands, and breakdowns during production. The fourth group is Data Preparation for Humans, about the CPPS, its architecture, products and production as long as the concepts support the CPPS engineering and capability to pre-process production data.

In this context, several practical applications have already emerged. Among them, we can cite the work of [9], where the authors developed a method for the systematic engineering of industrial CPS. They applied modularity under consideration of smart factory, smart data, smart products and smart services. In [10], the authors proposed a modular MAS based CPPS architecture where software agents are running on the fog level. In [11] the authors developed an efficient MAS based CPPS for a discrete flexible manufacturing system. In the same direction, we propose in the present paper a MAS based CPPS architecture, for the Management and control of an Industry 4.0 Assembly Platform situated in SRP Lab "Robotized Systems for Production" at the "Robotics and Integrated Manufacturing" division in Algerian Center of Development of Advanced Technologies CDTA. This case study covers the development and the virtual commissioning of the proposed CPPS Architecture.

The rest of this paper is organized in the following way. Section 2 describes the use case platform subject of the study. In section 3, we describe the CPPS Architecture developed in this paper. Section 4 is dedicated to the Software-In-the-Loop "SIL" Testing procedure. Finally, section 5 concludes the paper.

2 Laboratory Assembly Cell Use Case

The use case studied in this paper is an Industry 4.0 platform made by the Robotized Production systems team at the Robotics and Industrial Automation Division of CDTA (Centre de Développement des Technologies Avancées) in Algeria with collaboration of SIEMENS Algeria.

The cyber physical system in case of the study is a robotized cell made up of four stations “One pic and place station for Entry/Exit of shuttles to the platform, and two pic and place workstations for part feeding the product shuttles with spare items. One Assembly Station, and a closed loop conveying system. Each station is equipped with a photoelectric sensor in order to detect the presence of a product shuttle in front of the Workstation, and an RFID reader; to read / write the product specific data on the RFID TAG fixed to the product Shuttle.

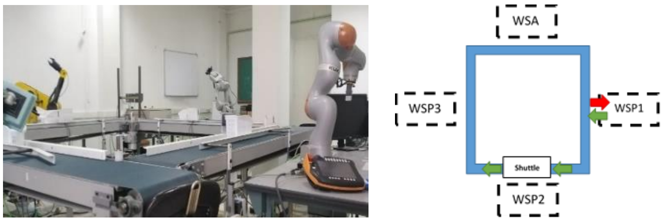


Fig. 1. General overview of The Assembly Platform at SRP Laboratory

The production system represented by the robotic platform is a synchronous flow shop.

During the rest of this paper we will call the pic and place station for Entry/Exit of shuttles as “WSP1”. The two pic and place workstations for part feeding as “WSP2” and “WSP3” respectively. The Assembly Station will be called “WSA”.

The product Shuttle is put in the system at the first station “WSP1”, after that the initial information is written to the corresponding TAG by the RFID reader on this station; the conveying system transports then the Shuttle to the next station “WSP2” where the RFID reader of this one reads the Shuttle TAG, to determine what has to be done on this product, in this case it’s part feeding of product shuttle. The Robotic station executes then the operation, and the conveying system transports the Shuttle to the third station “WSP3” where another part feeding operation is executed.

The product shuttle is then transported to the Assembly Station “WSA”, where the spare items are extracted from the shuttle, and assembled by a collaborative robot with the help of a human operator. Then the assembled product is put in the shuttle, and placed by the robot on the conveyor.

Finally the product return to the first station “WSP1” where it is verified and extracted from the production system.

As there is not yet installed Robot in the “WSP1”, the results obtained in the virtual commissioning of the MAS based CPPS architecture presented in the next section will partly contribute to a successful integration of a future installed Robot in this Workstation to the production cell.

3 The Developed CPPS Architecture

In the present work, a cyber-physical system Architecture is presented, where the control tasks are divided between PLCs and Multi Agent systems.

One of the benefits of the proposed MAS based CPPS solution is a smooth integration in existing Manufacturing Plants based on traditional control systems. By the fact that everything is controlled by the PLC, with a listing of tasks that can be executed by its corresponding resource to be transferred to the Resource Agent which can combine these tasks into a set of different operations, dynamically modifiable without the need to modify the PLC logic. So the Production become partly controllable by the Software Agents via the PLC inside each individual Cyber Physical Module CPPM. This is useful in the case of plants where it is not allowed to give a full control of the production by the Software Agents for different reasons including safety or security requirements

The division of control functions between PLC and the different software agents are described below.

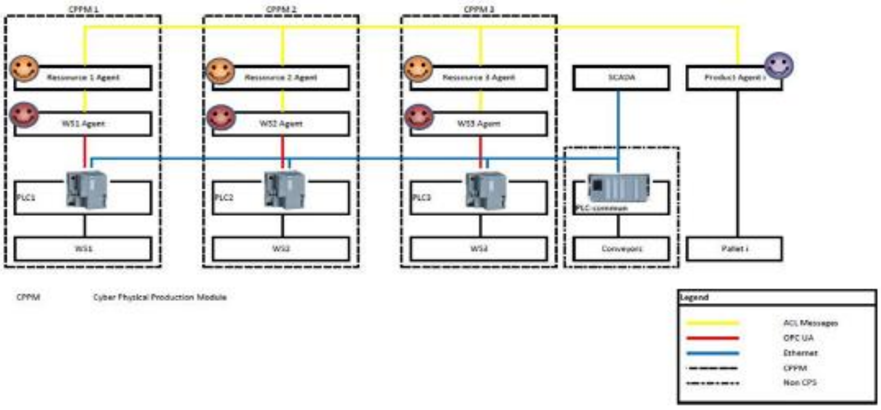


Fig. 2. Developed MAS based CPPS Architecture

3.1 Description of the CPPS Architecture

Since the assembly cell is constituted of four workstations and a conveying system, among them three workstations are concerned by this work. The aim of this work is to design a CPPS Architecture of the cell, the workstations are considered to be the cyber physical modules, and the conveying system will be considered in the present as a Non-

Cyber-Physical Entity. In this section we present the system Architecture. At the beginning we will describe the different types of the Agents and their functions, then the interaction between them, inside the CPPM. Among different MAS Architectures proposed for CPPS, there are MAS Architectures, where they may have also different degrees of control of the process, along with the Edge controller. In this work, the Software Agent of each WorkStation control high level operations, and only supervise the low level operations done by the respective PLC of this Workstation.

In this Architecture, there are three types of Software Agents: Product Agents, Resource Agents responsible of the resource (like: Machine or Robot…), and the Workstation Agent. This later is responsible of the corresponding Workstation and ensuring the abstraction of the PLC Data to usable information by the Resource Agent, and the transfer of instructions in the opposite direction.

The Cyber Physical Modules

Each station in controlled by a distributed controller SIEMENS ET200SP with a S7 1500 CPU, and a couple of agents. The ET200SP is responsible of the low level control functions of the robotic station. A software agent is associated to the resource, and it is responsible for the decision and / or the personalization of the products by the workstation. Then there is a Workstation Software Agent for the interface between the PLC and the resource agent. It transforms the data produced by the PLC to semantics utilizable by the resource agent, sent to this one by ACL messages [19]. The workstation Agent is connected to the PLC via OPC UA. In the normal case, the operations to do on the product by the workstation are stored on the product RFID Tag. In this study, the RFID TAG does not contain the information on the operations; they are stored in a PLC data bloc, which is modifiable by the product Software Agent. Up-on the arrival of the product Shuttle to the Work-station, the RFID reader reads the Tag on the Shuttle; then send it to the PLC. This later reads the operations to be done on the product from the product data-bloc. The operations Data is provided by the Product Software Agent. This gives the possibility to modify the operations list by the software agent at any time. This is very useful in the case of personalization or correction that has to be done on the product.

Different layers inside the CPPM

Description of the different layers of the CPPS Architecture and the responsibilities of each layer. The first Layer includes the physical parts of the system, represented by the workstations with their different components (Robot, part feeding system) as physical modules. The second layer is composed of the Programmable Logic Controllers, responsible of the low level control functions, at the operational level. The third layer is an abstraction layer, represented by the Workstation Agent, also called PLC Agent. It is responsible of the abstraction of the data collected from the PLC to an understandable information by the software Agents in the upper layer, and the translation of their instructions sent via ACL messages into precise commands to send by the Interface Agent to PLC via OPC UA. The Final layer, contains the Resource Agents, and the product Agents, responsible of the High level control operations, at the information level.

Communication between the CPPMs and with non-CP entities

The communication between the CPPM is performed at both the operational level (see **Fig. 2**) between the PLCs via Ethernet communication, and at the information level between the software Agents at the Multi Agent System.

The communication between the CPPS and the non-Cyber-Physical “non-CP” entities is ensured by the Programmable Logic Controllers in the control network, while the pertinent information is transferred to the Multi Agent system, creating an indirect interaction with the rest of the plant.

3.2 The Multi Agent System

The Multi Agent System in this CPPS Architecture is divided between two layers. One layer containing the Main Agents in the Multi Agent System, responsible of Management and control of the Cyber Physical Production System (Resource Agent, Product Agent). And, one layer containing the secondary Agents (Workstation Agent) responsible of the workstation “WS” inside each Cyber Physical Production Module, and ensuring the interface between the PLC controlling the Workstation and the “Resource Agent” corresponding to the physical resource (Machine, Robot…) in the Main Multi Agent System.

The Agents of the MAS

The Main Agents of the Multi Agent System are the resource Agents and the Product Agents.

Resource Agents

It is responsible of the Management of the affected physical resource inside the MAS, it can inform the other Agents about the state of the resource (Free, occupied, out of service…etc.) and take a decision to accept or not to perform a given operation of a product at a given time.

Products Agents

It represents the associated product in the MAS, it can give the user and the other Agents the state and the progress of the scheduled operations on the product, and it can ask a resource Agent to allocate its physical resource to perform a given operation at a given time according to its production schedule.

Workstations Agents

The secondary Agents called here the Workstation Agents, also called “PLC Agents” are situated at the abstraction layer of each Cyber Physical Module, and they are responsible of the abstraction of the PLC data to a usable information by the upper layer represented by the resource Agents. They ensure the transfer of the requests from the resource agent to the PLC of the Workstation, so the PLC can pass the order to the individual controller of the physical resource (Robot or Machine).

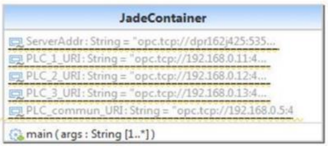
Detail of implementation

The Multi Agent System is implemented on JADE (Java Agent Development Framework) with JAVA.

There are three Agent Classes:

- The Workstation Agent Class called “Agent_PLC”
- The Resource Agent Class called “Agent_Ressource”
- The Product Agent Class called “Agent_Produit”

The Agents of type “PLC Agent” are declared using each corresponding PLC OPC UA Server URI as shown in the Jade Container UML Diagram below.



JadeContainer

ServerAddr : String = "opc.tcp://dpr162j425:535...
PLC_1_URI : String = "opc.tcp://192.168.0.11:4...
PLC_2_URI : String = "opc.tcp://192.168.0.12:4...
PLC_3_URI : String = "opc.tcp://192.168.0.13:4...
PLC_commun_URI : String = "opc.tcp://192.168.0.5:4

main (args : String [1..*])

Fig. 3. JADE Container Diagram

4 The Virtual Commissioning

4.1 General Description

Virtual commissioning is usually used to reduce the costs of validating solutions on real equipment **[15] [16].**

In our case, three reasons motivated the choice of virtual commissioning approach:

- Seize the time while the platform was under assembly
- Faster tuning of the PLC logic comparing to the traditional commissioning
- Drastically reduce the risk to damage equipment later, at real commissioning

In order to commission virtually the Robotized manufacturing cell. We first created the virtual model of the cell in 3D environment using FLEXSIM, by emulating the robotic workstations, in each workstation; we have replicated the robot and spare parts buffers. The RFID readers and photoelectric sensors has been replicated also in the virtual model, as well as the product Shuttles and the conveying system **Fig. 4.**

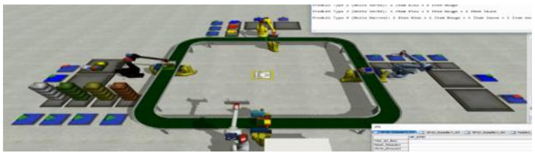


Fig. 4. The 3D model of the Robotized cell in FLEXSIM environment

After that, we connected the Virtual PLCs to the emulated model of the platform, and performed an overall testing of Input/Output signals, with respecting the following order: The PLC 1 is controlling the Workstation WSP1, the PLC 2 for WSP2 and PLC 3 for WSP3. The Assembly workstation WSA containing the collaborative robot KUKA IRB IIWA is not included in the present work, as its virtual commissioning has been treated in a separate work.

Therefore, the complete system is available to implement and validate the solution developed in the previous section.

4.2 SIL Testing Validation

The complete software in the loop (SIL) Validation test included the four Virtual PLCs and the Multi agent system, for controlling the virtual Model of the production cell.

During the SIL test, the Simulation of the four programmable logic controllers was performed using SIEMENS PLCSIM ADVANCED software. The Multi Agent System was developed under JAVA using JADE platform, with Eclipse Editor. Both were executed on the same Personal Computer communicating via OPC UA protocol, while the FLEXSIM 3D Model of the production system was running on another PC. On the same Local Area Network of the first PC, and communicating with the Virtual PLCs via OPC UA Protocol.

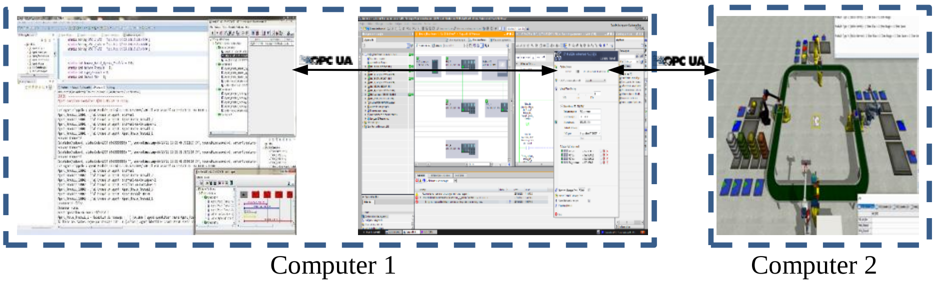


Fig. 5. SIL-Testing Validation

Test Case

In order to validate the developed MAS based CPPS Architecture, we used SIL validation technique cited above in practical cases during production. The first case was the entry of the products to the system, and the way their request is handled and executed. The second case was the execution of an operation on a given product in a workstation, and how the detailed list of tasks is loaded to the PLC, and executed by the Resource (Robot).

To illustrate the scenario, we considered the two first operations to be done on four different jobs. Where the first operation is loading of the product shuttle to the conveyor by the robot 1 (Workstation 1). The second operation is filling of the shuttle with the corresponding spare items needed for the product assembly, this operation is done by the Robot2 (Workstation2).

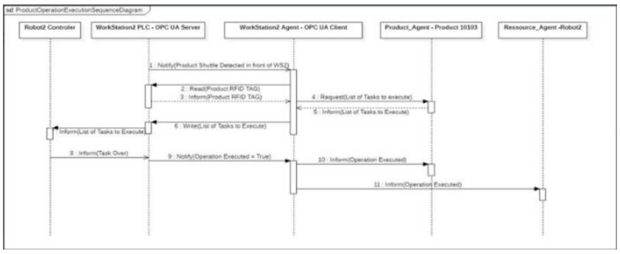


Fig. 6. - Sequence Diagram of interaction among Agents and PLC for Operation Execution on a Product with TAG 10103 at WorkStation N°2

5 Conclusion

The existence of several patterns and standardization works regarding MAS based CPPS makes their development much easier than before. However, lot of aspects regarding the adoption of Multi-Agent systems in the development of CPPS are continuously evolving. Indeed, MAS are well adapted for the development of distributed intelligent systems, featuring flexibility, agility and self-configuration. In this paper we proposed MAS based CPPS Architecture, in an Industry 4.0 context production system, where the Cyber Physical Production system was composed of three Cyber physical modules. Each CPPM was composed of four layers; the first layer includes the physical resources. The second layer contains Programmable logic controllers to perform lower computing tasks and controlling the physical resources. The third and fourth layers includes the Software Agents of the MAS. The communication inside the CPPM was via OPC UA and ACL. We used a SIL virtual commissioning validation approach in a practical case during production in Industry 4.0 context. The SIL testing has proven it’s adequacy for the assessment and tuning of the control logic and it’s interaction with the Multi-Agent System inside the CPPS. As perspective, the Commissioning of the system will be completed by a Hardware-in-The-Loop HIL Validation, and an implementation in the real Assembly platform at SRP Lab in CDTA.

References

1. Leitao, P., Karnouskos, S., Ribeiro, L., Lee, J., Strasser, T., & Colombo, A. W. (2016). Smart agents in industrial cyber–physical systems. Proceedings of the IEEE, 104(5), 1086-1101.
2. Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., ... & Ueda, K. (2016). Cyber-physical systems in manufacturing. Cirp Annals, 65(2), 621-641.

3. Vogel-Heuser, B., Diedrich, C., Pantförder, D., & Göhner, P. (2014, July). Coupling heterogeneous production systems by a multi-agent based cyber-physical production system. In 2014 12th IEEE International Conference on Industrial Informatics (INDIN) (pp. 713-719). IEEE.
4. Cruz, S. L. A., & Vogel-Heuser, B. (2017, July). Comparison of agent oriented software methodologies to apply in cyber physical production systems. In 2017 IEEE 15th International Conference on Industrial Informatics (INDIN) (pp. 65-71). IEEE.
5. Salazar, L. A. C., Mayer, F., Schütz, D., & Vogel-Heuser, B. (2018). Platform independent multi-agent system for robust networks of production systems. IFAC-PapersOnLine, 51(11), 1261-1268.
6. Salazar, L. A. C., Ryashentseva, D., Lüder, A., & Vogel-Heuser, B. (2019). Cyber-physical production systems architecture based on multi-agent's design pattern—comparison of selected approaches mapping four agent patterns. The International Journal of Advanced Manufacturing Technology, 105(9), 4005-4034.
7. Lee, J., Bagheri, B., & Kao, H. A. (2015). A cyber-physical systems architecture for industry 4.0-based manufacturing systems. Manufacturing letters, 3, 18-23.
8. Drath, R., Weber, P., & Mauser, N. (2008, September). An evolutionary approach for the industrial introduction of virtual commissioning. In 2008 IEEE International Conference on Emerging Technologies and Factory Automation (pp. 5-8). IEEE.
9. Oks, S. J., Fritzsche, A., & Möslein, K. M. (2018). Engineering industrial cyber-physical systems: An application map based method. Procedia CIRP, 72, 456-461.
10. Rocha, A. D., Tripa, J., Alemão, D., Peres, R. S., & Barata, J. (2019, July). Agent-based Plug and Produce Cyber-Physical Production System–Test Case. In 2019 IEEE 17th International Conference on Industrial Informatics (INDIN) (Vol. 1, pp. 1545-1551). IEEE.
11. Mihoubi, B., Bouzouia, B., Tebani, K., & Gaham, M. (2020). Hardware in the loop simulation for product driven control of a cyber-physical manufacturing system. Production Engineering, 1-15.
12. Rasche, C., Tinkleman, M.: Industry 4.0 - A Discussion of Qualifications and Skills in the Factory of the Future: A German and American Perspective. VDI, ASME, Düsseldorf, Germany, (April 2015).
13. Kagermann, H., Wahlster, W., Helbig, J.: Recommendations for implementing the strategic initiative INDUSTRIE 4.0 - Final report of the Industrie 4.0 Working Group. acatech – National Academy of Science and Engineering, Germany (April 2013).
14. DIN and DKE ROADMAP German Standardization Roadmap Industrie 4.0. Standardization council Industrie 4.0. Germany (2016)
15. Berger, T., Deneux, D., Bonte, T., Cocquebert, E., & Trentesaux, D. (2015). Arezzo-flexible manufacturing system: A generic flexible manufacturing system shop floor emulator approach for high-level control virtual commissioning. Concurrent Engineering, 23(4), 333-342.
16. Quintanilla, F. G., Cardin, O., l'Anton, A., & Castagna, P. (2016). Virtual commissioning-based development and implementation of a service-oriented holonic control for retrofit manufacturing systems. In Service orientation in Holonic and multi-agent manufacturing (pp. 233-242). Springer, Cham.
17. Monostori, L. (2014). Cyber-physical production systems: Roots, expectations and R&D challenges. Procedia Cirp, 17, 9-13.
18. Vogel-Heuser, B., Lee, J., & Leitão, P. (2015). Agents enabling cyber-physical production systems. at-Automatisierungstechnik, 63(10), 777-789.
19. FIPA Homepage, http://www.fipa.org/specs/fipa00061/index.html.