Cyber-Physical Production Systems supported by Intelligent Devices (*SmartBoxes*) for Industrial Processes Digitalization

Pedro Torres*¶, Rogério Dionísio*¶, Sérgio Malhão*¶, Luís Neto†‖, Ricardo Ferreira‡**, Helena Gouveia§†† and Hélder Castro§††

*Escola Superior de Tecnologia
Instituto Politécnico de Castelo Branco, Castelo Branco, Portugal
†SYSTEC (Research Center for Systems & Technologies)
FEUP, Faculdade de Engenharia, Universidade do Porto, Porto, Portugal
‡INL - International Iberian Nanotechnology Laboratory, Braga, Portugal
§*Intelligent & Digital Systems, R&Di*
ISQ - Instituto de Soldadura e Qualidade, Oeiras, Portugal
¶Email: {pedrotorres,rdionisio}@ipcb.pt
smalhao@ipcbcampus.pt
‖Email: lcneto@fe.up.pt
**Email: ricardo.ferreira@inl.int
††Email: {hngouveia,hfcastro}@isq.pt

***Abstract*—The Industry 4.0 paradigm is a reality in the digitization of industrial processes and physical assets, as well as their integration into digital ecosystems with several suppliers of the value chain. In particular, Industry 4.0 is the technological evolution of *embedded systems* applied to *Cyber-Physical Systems (CPSs)*. With this, a shift from the current paradigm of centralization to a more decentralized production, supported by Industrial Internet of Things (IIoT), is implied. The work reported in this paper focuses on the development of *smart devices* (*SmartBoxes*), based on low-cost hardware such as *Raspberry Pi* and also platforms certified for industrial applications, such as *NI CompactRIO*. Both platforms adopted the OPC-UA architecture to collect data from the shop-floor and convert it into OPC-UA Data Access standard for further integration in the proposed CPPS. Tests were also performed with the MQTT protocol for monitorization. Each SmartBox is capable of real-time applications that run on OPC-UA and MQTT, allowing easy interaction between supervisory systems and physical assets.**

***Index Terms*—Cyber-Physical Production Systems, IIoT, OPC-UA, MQTT, SmartBox, RAMI4.0**

I. Introduction

Globally, the industry is going through a digital transformation that is being accelerated by new technologies that are evolving exponentially, such as robotics, autonomous systems, 3D printing, Artificial Intelligence and so on. In this way, companies's industrial processes need to quickly adapt to these new trends, otherwise it will become obsolete. It is increasingly common to talk about Cyber-Physical Production Systems (CPPS), where a set of physical assets forms networks supported by interoperability between information technologies with mechanical and electronic components. In this context, smart machines constantly share information on stock levels, problems or failures, as well as changes in production orders. Processes and deadlines are coordinated with the aim of promoting efficiency and optimizing processing times, promoting the use of installed capacity and quality in the areas of development, production, marketing and sales.

By allowing the interconnection of physical assets (e.g. machines, intelligent products and people), CPPSs form intelligent networks within the factory, and also across the entire value chain and the entire life cycle of products. Sensors and control systems allow machines to be linked to factories, logistic actors and people.

As a result of the digitization of society and industry, the end customer is now more informed and connected with access to a global offer. This phenomenon creates a more competitive environment raising new challenges for companies and the need for being better prepared. In fact, at the company's disposition are innovative technologies in terms of trade, production and logistics that transform the relationship with the end customer, workers and between companies. The use of available technologies and a customer-focused approach dictate the success of manufacturers to the challenges of today's markets.

Following the new trends associated to Industry 4.0 there is the emergence of a lot of research to response the industrial pre-requisites [1]. In [2], it is proposed the development of a CPPS based on low-cost hardware platforms, such as Raspberry Pi, to implement an OPC-UA solution that allows the integration of equipments data processing. In [3] is proposed an OPC-UA architecture, based on the Reference Architecture Model for Industry 4.0 (RAMI4.0) specifications [4], where OPC-UA servers and clients exchange data acquired from industrial nodes in the shop floor with an IIoT cloud platform.

In Portugal, the PRODUTECH cluster (cluster for the Production Technologies) launched a project with the aim at contributing to the digitalization challenge at the shop floor. This project, which is presented in more detail below, intends to give a relevant contribution to the digitalization process in different economic sectors.

A. PRODUTECH-SIF - Solutions for the Industry of the Future

PRODUTECH SIF (Solutions for the Industry of the Future) is a Portuguese funded project that aims at developing solutions for the future production systems, based on advanced technologies and approaches that meet industry 4.0 requirements. PRODUTECH SIF is an umbrella project, that counts on the integrated efforts from different industrial actors, as manufacturers of equipment and components, technological service providers, research and development entities, gathering the critical mass required for the effective development and deployment of new solutions/products and advanced knowledge and technologies.

As shown in Fig. 1 the architecture of PRODUTECH SIF comprises three horizontal sub-projects that are base developments of cyber-physical systems and three other, vertical ones, that use the embedded data and technology to develop specific applications and services. The consortium involves 47 National partners, that includes 29 companies, 18 universities and research centres and 1 Industrial cluster. More information in [9].

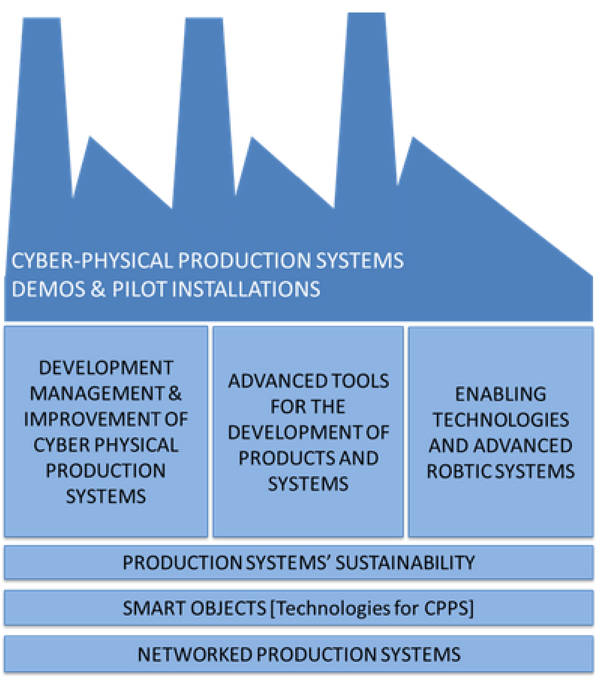

Fig. 1. Global architecture of the project.

One of the challenges of the umbrella project PRODUTECH SIF is the development of base technologies for the cyber-physical production systems. This paper presents the work developed in the scope of the project "Base Technologies for CPPS" (2nd horizontal layer in Fig. 1).

The main developments are focused in the *SmartObject* concept which enable the integration and management of existing and new components in an *IIoT* platform. Also includes developments in Human Machine Interfaces (HMIs) through wearable & sensing technologies and virtual / augmented reality as well as developments of new sensors and electrical / mechanical tests of all devices produced in the project.

A *SmartBox*, i.e., a smart device that runs and enables the operation of the *SmartObject* was also developed. It is the gateway between the machines / equipments in the shop floor and the *IIoT* platform. It enables the interaction with machines of different technologies and allows them "to talk" the same language.

The remainder of the paper is organized as follows. The *SmartBox* description is performed in section II. Section III describes the concept of SmartObject and the data model used to encapsulate the shop floor information. Section V presents case studies and experimental results obtained with the SmartBox implementation. Conclusions and future work are presented in Section VI.

II. SmartBox

The *SmartBox* is a hardware platform that allows the integration of machines on the shop floor in CPPS. Taking into account the diversity of equipments and specificities that integrate the various types of industries, the hardware must have general characteristics, easy to adapt to each type of equipment. It consists of a "master" controller that function as an OPC-UA server, which allows communication between machines through different protocols and also the direct interconnection with sensors and actuators. The *SmartBox* is also scalable, it allows to add new I/O modules according to new signal condition requirements for sensors and actuators, or to work with heterogeneous communication protocols. Figure 2 shows the generic design of a *SmartBox*. It should be able to collect and process data in real time, extract knowledge from data through machine learning and export this information to other devices in the same network or in the cloud, through the IIoT platform implemented in each company.

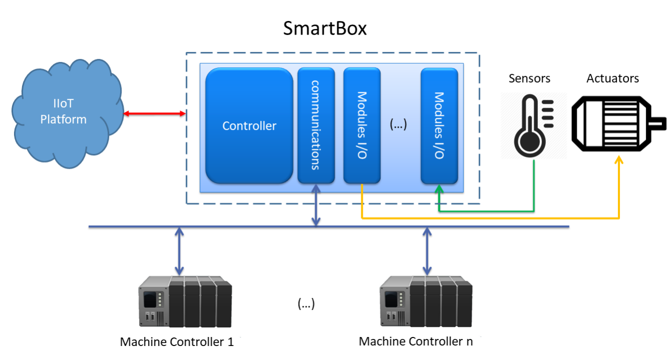

Fig. 2. SmartBox layout.

III. SmartObject

In a CPPS logic, all physical assets must have a digital twin. The combination of all virtualized assets result in a collaborative network. An effective CPPS results [5] from combining this network with computational power, control, information management and heterogeneous communication capabilities (Figure 3).

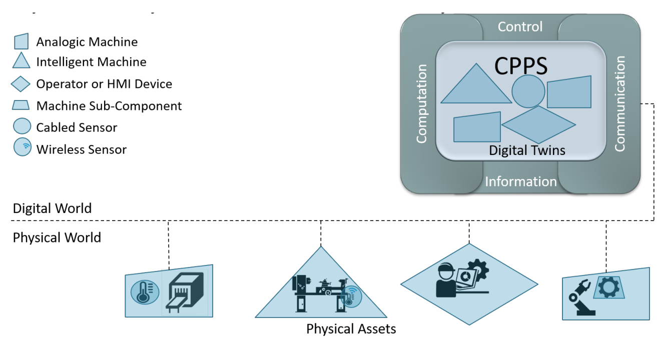

Fig. 3. A CPPS composition.

In the proposed architecture, the SmartObject is the software running inside each SmartBox. The SmartObject is in line with the concepts *Component I4.0* [6] and *Administrative Shell* [7] introduced by RAMI4.0. Therefore, the SmartObject will act as the *Administrative Shell* for encapsulating the assets in shop floor and convert these assets in *Component's I4.0*. To make assets transparent to each other, i.e. capable of mutual cooperation and understatement, the SmartObject will create and make available to the CPPS a *manifest* describing each asset. The assets virtualized in this project will be essentially: machines, machine components, sensors and actuators. A common data model was created for this purpose, the *Smart Object Self Description (SOSD)*. To build the model, the following requirements were taken in consideration:

- **Assets:** The model should be capable of represent: machines, machine components, sensors and actuators. It also must be capable of representing dependencies and connections between these. This is of major importance if we want to contextualize information of a given sensor, or if components need to be represented as parts of some machine.
- **Services and service Instances:** A service, in the SOSD context, represent some algorithm or computation that is available in the CPPS network. This way, a SmartObject or any other node in the CPPS network can announce its capabilities, e.g. data processing services like Fast Fourier Transform (FFT) or a simple alarm. A service can be instantiated by creating a new instance to which providers and subscribers will be added, e.g. creating an FFT instance in a given SmartObject, associate some sensors as inputs, and an HMI device as output.
- **Endpoints:** An Endpoint will represent a node in the CPPS network, e.g. an HMI device used by the operators to check production or a cloud computing platform to host production data.
- **Variables and Parameters:** All static and dynamic variables and parameters associated to assets, services or endpoints must be represented. Static variables represent information about some entity, e.g. in case of machine, the manufacturer, model and serial number. Dynamic variables represent information generated during production, e.g. a sensor value or a service output. Parameters represent values that can be changed to modify or tune some process, e.g. a welding machine laser power or an alarm minimum and maximum thresholds.
- **Methods:** A Method represent an simple routine that can be invoked, e.g. a calibration method for a sensor or a stop routine for a machine.

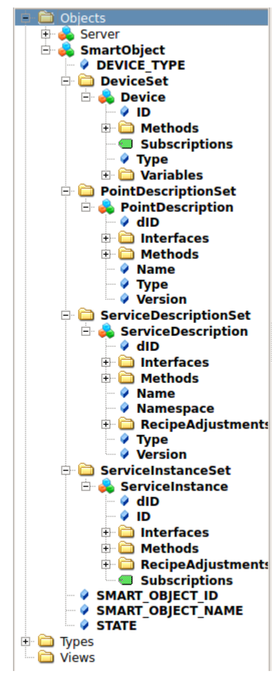

Fig. 4. SOSD model mapped in OPC-UA server.

The SOSD model was entirely mapped in the OPC-UA native and Data Access types. Meaning that once an asset is physically or wireless connected to the SmartBox, it information will be mapped in the SOSD model (Figure 4), and make available to the CPPS by a local OPC-UA server instance. By having a modular I/O interface, the SmartBox will be capable of abstracting the low level details of integration between heterogeneous assets and the SmartObject.

In terms of software engineering, given the requirements presented above, the SmartObject must be extensible to accommodate new software (e.g. for interacting with asset drivers and new algorithms). Also, it must provide a runtime environment for algorithms and other services to be instantiated and invoked. Therefore, a component model architecture will be applied [8]. As the most capable version of the SmartBox will offer real-time and hardware reconfiguration capabilities, the SmartObject component model will also be extended to deal with real-time services and hardware components.

IV. Case Studies

In PRODUTECH-SIF, a methodology was developed in order to identify industrial scenarios inside the companies of the consortium where the *SmartBoxes* can be implemented. Of the several companies where the requirements survey was done, only two scenarios are described in this paper to support the use of *SmartBoxes* as a component of a CPPS.

A. Scenario 1

The first application scenario is set-up in a clothing label factory, where is expected to integrate the *SmartBox / SmartObject* into legacy looms. Planning for this scenario includes sensing the older looms to enable the collection of operational information already available on new looms. Predictive maintenance functionalities based on information such as temperature, humidity, noise and vibration will also be implemented. Finally, Human Machine Interface (HMI) functionalities will be developed for interaction with looms in maintenance tasks and also graphical load through a tablet/smartphone for new orders. Figure 5 shows an old loom where the *SmartBox* will be implemented.

Fig. 5. Clothing label factory loom.

B. Scenario 2

The second scenario is a company that manufacturers metal parts for the automotive industry (Figure 6). SmartBoxes will be used in production lines for data acquisition/processing and interaction with virtual and augmented reality devices. In the area of metrology/quality control the process of collecting data on the stamping process will be automated through augmented reality glasses. Machine Learning Algorithms (ML) will be implemented in SmartBoxes to assist the operator in accepting or rejecting parts. The ML methods will also be implemented to estimate the fine-tuning parameters of the welding jigs in order to adjust them to the dimensions of the parts, sometimes variable due to differences in raw materials. Currently, fine tuning is done manually. The final goal for this company will be the development of an HMI components for visualization of key performance indicators (KPIs) at each workstation and also to assist the operator in predictive maintenance procedures.

V. Experimental results

This section presents the preliminary experimental results of the implementation of *SmartBoxes* in industrial scenarios. The *SmartBox* concept has been performed in two versions (Fig. 7), the first one complying with all industrial requirements with *NI cRIO-9040*, certified for industrial applications and the second, a low cost device developed on *Raspberry Pi* only to demonstrate the concept and adapt to the builders of machines. *SmartBoxes* are the gateways between sensors, actuators, machine controllers and IIoT platforms. Each *SmartBox*

Fig. 6. Company marketing image illustrative of the construction of metal parts for automotive.

is installed on machines or in a physical topology that groups more than one machine on the shop floor. To demonstrate the concept of *SmartBox*, the topology shown in Figure 8 was setup. Each *SmartBox* runs an OPC-UA server to provide the information of shop floor in a data model dedicated to IIoT as is the OPC-UA. MQTT (Message Queuing Telemetry Transport) also is implemented on the *SmartBoxes* for the communications machine-to-machine (M2M). Each device publishes the information of the sensors / actuators and allows interaction with another controller in the production line or with the SCADA (Supervisory Control and Data Acquisition), MES (Manufacturing Execution Software) or ERP (Enterprise Resource Planning) systems. These systems operate as an OPC-UA client or a MQTT subscriber to access the information.

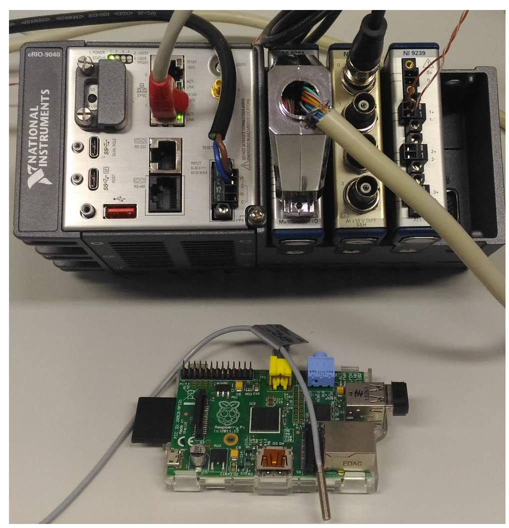

Fig. 7. *SmartBox* physical aspect. a)NI CompactRIO 9040 b) Raspberry Pi.

The dashboard illustrated in Figure 9 helps technicians to show the current and historical values of the different parameters. The screenshot is representative of an example where the ambient temperature is recorded at two different locations and the daily fabric production meters, is recorded through the information of inductive sensors installed in the

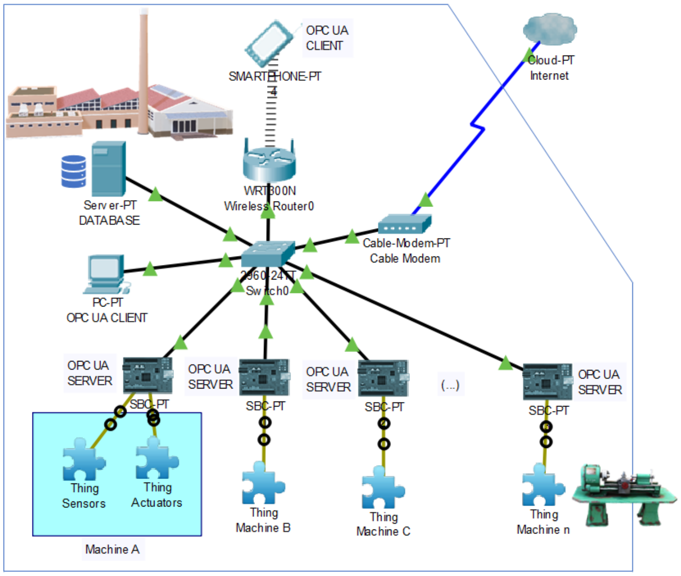

Fig. 8. Network topology.

engines of the machines. The same information is available on the cloud through the platform *ThingSpeak* as shown in Figure 10.

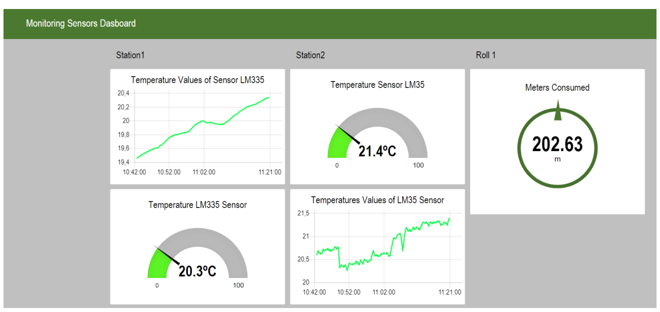

Fig. 9. Dashboard with indication of the reported values of sensors.

VI. Conclusions and Future Work

This paper presents the early-stage results of intelligent device development, called *SmartBox*, and an architecture for implementing CPPS over OPC-UA and MQTT. The work reflects part of the developments of technologies for CPPS developed on of the second layer of the PRODUCT-SIF project. NI-cRIO was chosen as the platform for running the *SmartObject* and to serve as gateway within the machines installed in factories. It was chosen taking into account its real-time processing capability and all requirements for the presented case studies industrial applications. Alternatively, and only for proof of concept was used the *Raspberry Pi*. MQTT and OPC-UA enables the M2M communications, and with supervision systems in real-time, also improves the developments dedicated for IIoT applications. As future work machine learning techniques will be implemented in smartboxes, such as estimation and classification to assist technicians / supervisors in predictive maintenance and machine calibration procedures.

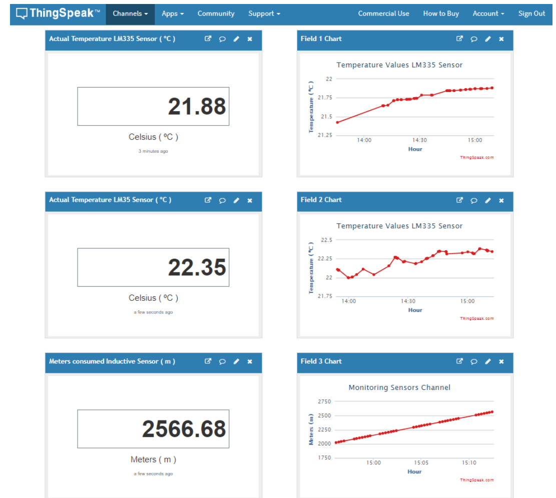

Fig. 10. Information available on the cloud.

Acknowledgment

This research was supported by the project *PRODUTECH-SIF - Solutions for the Industry of the Future*, financed by the Portuguese National program COMPETE 2020 and by Portuguese funds through FCT – Fundação para a Ciência e a Tecnologia (UID/EMS/00712/2013).

References

[1] Rúbio, E.M., Dionísio, R.P., Torres, P.M.B., "Industrial IoT devices and cyber-physical production systems: Review and use case," 2019 Lecture Notes in Electrical Engineering, 505, pp. 292-298.

[2] M. V. García, F. Pérez, I. Calvo and G. Moran, "Developing CPPS within IEC-61499 based on low cost devices," 2015 IEEE World Conference on Factory Communication Systems (WFCS), Palma de Mallorca, 2015, pp. 1-4.

[3] M. Ghazivakili, C. Demartini and C. Zunino, "Industrial data-collector by enabling OPC-UA standard for Industry 4.0," 2018 14th IEEE International Workshop on Factory Communication Systems (WFCS), Imperia, 2018, pp. 1-8.

[4] Adolphs, Peter, et al. "Reference architecture model industrie 4.0 (RAMI 4.0)." ZVEI and VDI, Status Report (2015).

[5] Lee, Jay, Behrad Bagheri, and Hung-An Kao. "A cyber-physical systems architecture for industry 4.0-based manufacturing systems." Manufacturing letters 3 (2015): 18-23.

[6] Bedenbender Heinz et al., Relationships between I4.0 Components, ZVEI and Plattform Industrie 4.0, June, 2016, https://www.plattform-i40.de/I40/Redaktion/EN/Downloads/Publikation/relationships-i40-components.pdf, "Last accessed 22 February 2019"

[7] Adolphs P, Aur S, et al. Structure of the Administration Shell Continuation of the Development of the Reference Model for the Industrie 4.0 Component. Federal Ministry for Economic Affairs and Energy (BMWi) 2016; Spree Druck Berlin GmbH.; https://www.plattform-i40.de/I40/Redaktion/EN/Downloads/Publikation/structure-of-the-administration-shell.pdf, "Last accessed 22 February 2019"

[8] Neto, Luis, et al. "A component framework as an enabler for industrial cyber physical systems." 2018 IEEE Industrial Cyber-Physical Systems (ICPS). IEEE, 2018.

[9] PRODUTECH-SIF, http://mobilizadores.produtech.org/en/produtech-sif, "Last accessed 07 March 2019".