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Business Experiments in footwear Cyber-Physical Production Systems

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Abstract

The Portuguese footwear industry registered a strong performance over the last few years and the openness to adopt new technologies was a key factor. Among these, the implementation of innovative logistic systems for the transport and assignment of work-in-process in manufacturing processes was a key technology.

By means of case research it was analyzed an internal logistic system, deployed in a Portuguese large footwear producer, which reveals some weaknesses at the physical and cyber levels. A lack of managing applications was detected at the factory and enterprise levels, which contribute to lower levels of visibility of production and productivity. This article presents the development of a Cyber-Physical Production System, in the context of the Horizon 2020 research and innovation program BEinCPPS, that comprises four application experiments. These experiments were successful and the results demonstrated a relevant increase of production efficiency and decrease of maintenance costs.

Keywords: Cyber-Physical Systems; predictive maintenance; production monitoring; Case Research

1. INTRODUCTION

The Portuguese footwear industry, localized mostly in the NORTE Region of Portugal, has registered a strong performance over the last five years, with exports growing by 43% while imports have risen by only 4%. Portugal is highly specialized in leather footwear, which it exports primarily to European markets (APICCAPS, 2015). In 2015 footwear exports reached 79 million pairs and 1 865 million euros (maximum historic) (APICCAPS, 2015) (APICCAPS, 2015). The NORTE region is a very receptive and creative environment for the implementation of Cyber Physical Production Systems (CPPS). In this region, the footwear and allied trade sectors are constituted mainly by SMEs that are characterized by its openness to new experiments and to adopt new technologies if they increase their competitiveness.

The production of shoes is typically organized in three main phases: the cutting of upper and lining materials, the stitching of the pieces in the shoe's upper part and the assembly/finishing of the final product. These production stages are physically separated from each other and managed in an independent way within different departments or production units managed under specific organizational processes supported by different enterprise software management subsystems. Following the traditional way of manufacturing footwear, significant levels of stock of intermediate products are the usual result caused by the lack of integration between the different production phases of cutting, stitching and assembling. Also, depending on the demand and production capacity of the manufacturer, subcontracting the stitching is the usual strategy, increasing the complexity of the problem and thus the level of intermediate stocks. Additionally, the lack of integration causes typically a product lead time between three to four weeks. On the other way, the footwear industry has been facing a set of challenges to manufacture small series of fashion based products and to reduce the product lead time.

1.1. Context and opportunities

The Portuguese footwear sector have increased the adoption of Cyber-physical systems (CPS) that may be seen as systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet (Monostori, 2014). More simply, they are integrations of networked and/or distributed feedback systems between computation and physical processes, through which physical processes affect computations and vice versa (Wang, Törngren & Onori, 2015; Krueger et al., 2016). Thus the usage of innovative production systems aims to satisfy the new challenges to respond in an agile way to the market demand.

By means of case research, a Portuguese large footwear producer, key adopter of Internal Logistic Systems in their manufacturing plants, was analyzed. These Internal Logistic Systems ensure the automatic transport of items in parts of the manufacturing process, assigning and controlling the work flow along the different production workstations. The materials transported are subject to a predefined set of production operations accomplished by the operators and machines available on the production line aiming to increase the production efficiency, optimization and flexibility. One of these internal logistic systems integrates the stitching and the assembly of shoes in a single production unit. The system comprises two sub-systems the Stitching Logistic System (Figure 1 on the left) and the Assembly Logistic System (right of Figure 1).

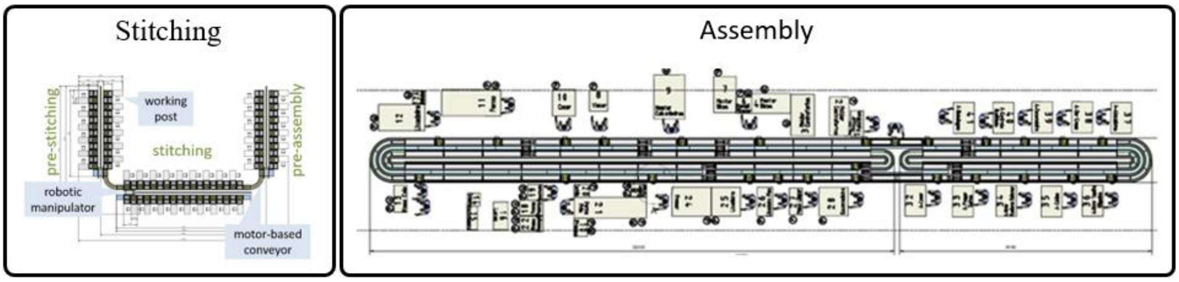

Figure 1 - Scheme of the Internal Logistic System

The Stitching Logistic System implements the activities of pre-stitching, stitching and pre-assembly along approximately 40 working posts, distributed by three manufacturing lines. The transport of materials between the working posts is made by robotic manipulators, which moving the materials inside specific boxes. The Assembly Logistic System (right of Figure 1), executes the final assembly and finishing activities on the final product. Transport of the shoes is achieved by a conveyor, capable of moving a pair of shoes to a given place, where the platform carrying the pair of shoes stops and is elevated from the conveyor system.

These two logistic systems are controlled by programmable logic controllers (PLC) that are managed at a higher level by the SmartSL, an ICT system with a back-end and front-end components. The back-end component contains a relational data base system and provides a RESTfull web service API giving access to the information related with the production process.

These Stitching Logistic System is the result of a Portuguese research and innovation project and constitutes the most recent generation being adopted in the footwear industry. Its physical elements are first type prototypes which revealed some weaknesses at the physical level, requiring constant attention from the maintenance operators to avoid the unscheduled stopping of the production system. At the factory and enterprise levels, there are no managing applications in the domains of advanced planning and scheduling, production monitoring, maintenance management, performance management and real time simulation, which contributes to low levels of productivity and tiny visibility of production.

2. Scenarios and CPPS solution

To cope with the above context, a Cyber-Physical Production System (CPPS) solution has been envisioned to be applied not only in the analyzed large footwear producer but also to other footwear producers. A Cyber-Physical Production Systems (CPPS), relying on the newest and foreseeable further developments of computer science (CS), information and communication technologies (ITC), and manufacturing science and technology (MST) may lead to the 4th Industrial Revolution, frequently noted as Industry 4.0 (Monostori, 2014). The goals for the CPPS solution concerns the gathering, publishing and storing of all shop floor events, aiming to decrease non planned down time on working posts and robotic manipulators, detecting malfunctions on these elements, and making predictions of abnormal conditions on the robotic manipulators, building a maintenance knowledge base and enabling the real time monitoring of the logistics system.

The following Figure 2 presents the abstract architecture of the CPPS solution. The footwear manufacturing lines are controlled by PLC devices connected to sensors and actuators. These sensors are “dumb” devices as all the logic is embedded in the PLCs. Access to this data will enable a real time view on the current state of the manufacturing lines. The cloud symbol in the picture represents ICT infrastructure enabling data flow between the shop floor and the two ICT applications domains. The first application domain is production monitoring and synchronization, aiming to provide simple but effective dashboards in the manufacturing line, enabling a real time view on the current status of the line to enable the manager of the line to track the allocation of work and promptly react to the conditions detected and to the daily demand. The second application domain is diagnostic and predictive maintenance and aims to decrease the downtime of the internal logistic system, increasing the effective usage of the available equipment on the line and ensuring the good behavior of the logistic system, by detecting on real time, possible anomalies in the shop floor. Additionally, the application aims to avoid those problems by estimating and signaling the occurrence of future anomalies in the logistic system.

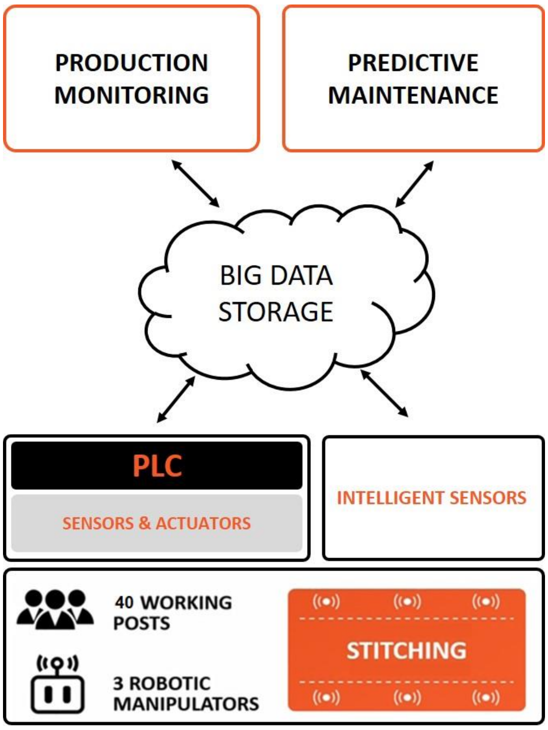

Figure 2 - BEinCPPS architecture - abstract view

Major elements supporting this solution are the existing sensors, actuators and the PLC devices responsible for controlling the manufacturing lines. Data generated at the shop floor has to be propagated to a big data repository and published in an information bus (Happ et al., 2017), providing any factory and enterprise level application the possibility to receive this data on "near real-time". The information bus also has the aim to support any bidirectional communication among high level applications in order to support the Cyber-Physical Production System and the consequent creation of any needed service. The exploitation of intelligent sensors in the shop floor is foreseen in order to enrich maintenance diagnostic activities with specific data concerning electricity consumption, temperature behavior and vibrations of the mechanical structure supporting the logistic system.

Four application experiments were conceived in the development of the CPPS system: "Access sensors on footwear production lines", "Diagnostic and predictive maintenance", "Production monitoring" and "Intelligent sensing on the shop floor". These application experiments are described in the following sections.

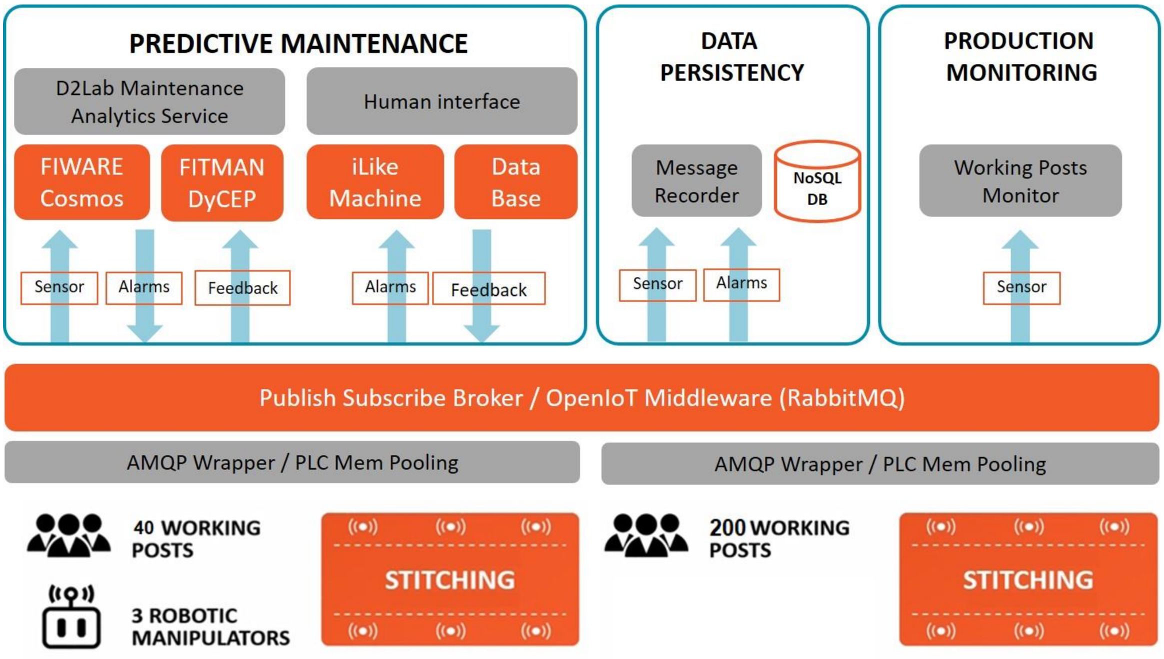

Figure 3 – Architecture of the CPPS components (selected components from the Open Source market in orange, own developments in gray)

2.1. Access Sensors on footwear production lines

The aim of this application experiment is to allow sensor-based and actuator-based data to be accessed in manufacturing plants, to store the correspondent data streams on a persistent NoSQL data repository and to propagate them on near real time to factory and enterprise level applications. Two different internal logistic systems were targeted, one with around 40 working posts and 3 robotic manipulators and another one with around 200 working posts. As shown in the Figure 3, the data provided by sensors and actuators available on the controlling PLC were gathered, filtered, wrapped in messages and published on a publish subscribe broker (Happ et al., 2017). From this point on, received data is stored on a NoSQL database (http://cassandra.apache.org/) and made available to any ICT applications.

2.2. Diagnostic and predictive maintenance

The aim of the application experiment is to analyze historical and near real-time sensor-based and actuator-based data related to the critical physical elements of the internal logistic system, in order to detect the actual occurrence of physical problems and to estimate their possible occurrence in the near/medium term future. As depicted in Figure 3, data published on the message broker is continuously analyzed by the D2Lab Maintenance Analytics Service. Non expected patterns in the data streams are identified and alarms message are generated, this are then sent to a mobile human interface enabling the maintenance technician to react in the field.

2.3. Production monitoring

This application experiments aims to address the real time view on the current status of the production system. The experiment was initiated on a manufacturing plant with around 200 working posts and then extended to another plant (40 working posts). As shown on Figure 3, data available on the controlling PLC are published on the publish subscribe broker and processed by the Working Posts Monitor. The allocation of work is graphically presented to the line manager which by acting on the SmartSL system can change the way the manufacturing operation are assigned to each working post and thus optimize the production.

2.4. Intelligent sensing on the shop floor

This application experiment aims to complement the diagnostic and predictive maintenance domain by detecting the occurrence of physical problems on the internal logistic system. The application experiment conducted on the manufacturing plant with around 40 working posts where were installed intelligent sensing devices, built with BeagleBone technology (Nayyar & Puri, 2015), able to gather new events from the shop floor. The data provided by intelligent sensors has to be published in the message broker providing any factory and enterprise level application with the possibility to receive this data on "near real-time". These data streams are then analyzed and alarms are generated if unexpected values and trends are detected. This is then signaled on the mobile human interface enabling the maintenance technician to react in the field.

Each manufacturing line is equipped with two BeagleBone Green Wireless (BBGW) witch fulfills requirements like low cost, wireless connectivity ability, physical size and versatility. One BBGW device comprises a temperature sensor (used to measure the temperature of the main electric motor of each robotic manipulator) and an electricity sensor for measuring the energy consumption of the motor. The other BBGW device is equipped with a vibration sensor for measuring the vibration in the whole mechanical structure.

Two different approaches were followed in the development: one using the "Framework for Distributed Industrial Automation and Control" (4DIAC) that comprises the 4DIAC-IDE (Integrated Development Environment) and the 4DIAC-RTE also known as FORTE, and other approach using the Node-RED that is an open source graphical-browser-based tool for wiring Internet of Things (IOT) developed by IBM Emerging Technologies (Olsson & Asante, 2016).

The 4DIAC-IDE is based on the Eclipse framework and provides the environment for modeling applications. The FORTE is the runtime environment, which supports the execution of distributed control programs on small embedded devices (Zoitl, Strasser & Valentini, 2010). FORTE runs above the BBGW devices and can be configured with our own Function Blocks and external libraries.

The Figure 4 illustrates the architecture of the solution, the 4DIAC platform supports programming of the applications designed with Function Blocks, the devices configuration and also the applications deployment on the devices running FORTE.

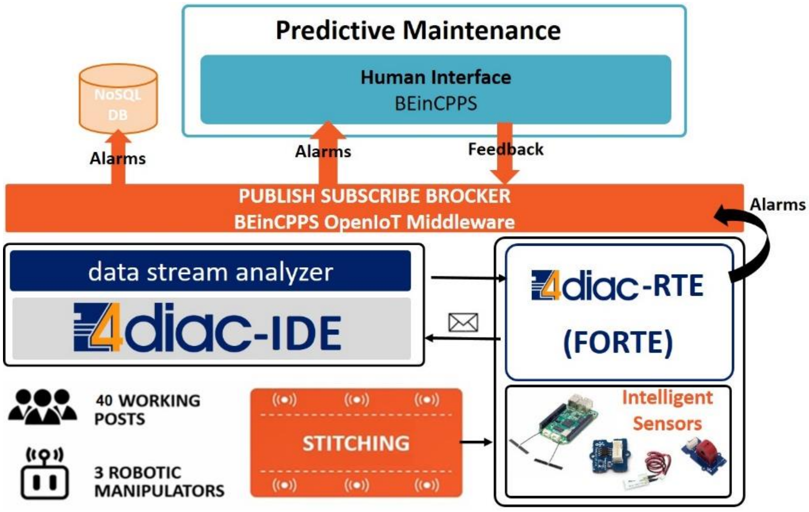

Figure 4 - Intelligent sensing : 4DIAC approach

The data read from the sensors is continuously analyzed in the 4DIAC platform. Non expected values in the data streams are identified and alarms are generated, this are then sent to a mobile human interface and the alarms are also stored in a NoSQL database.

The following Figure 5 identifies the architecture of the solution using Node-RED. Python scripts running in the BBGW device are responsible for gathering data from the grove sensors and publish events on the message broker.

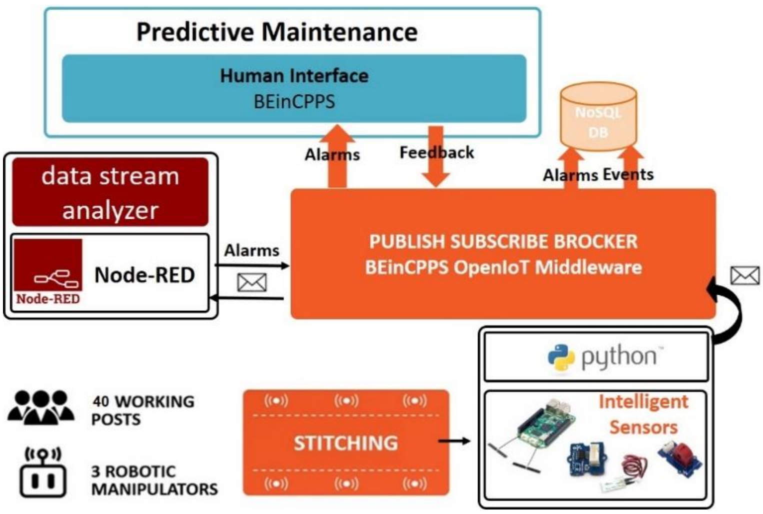

Figure 5 - Intelligent sensing : Node-RED approach

The Node-RED platform connects to the message broker and subscribes the events from the Intelligent Sensors, these data streams are then analyzed and alarms are generated if unexpected values and trends are detected this is then signaled on the mobile human interface. These alarms are also stored in a database in order to maintain the historical record and to make statistical analyses. In parallel are being stored the instantaneous electricity consumption of the robotic manipulator motor for later analysis about electricity costs.

3. Experiment Results and Business Assessment

The business objectives witch the large footwear producer expect to achieve in the project were to decrease production lead time and to improve the efficiency of production and the flexibility of production. To achieve the business objectives were identified the requirements and the target Key Performance Indicators that are directly related with specific application experiments. The four application experiments were initiated in two distinct phases, the first three experiments started on the first application experiments phase and implemented successfully all the planned requirements.

The approach to technical assessment of the performed experiments can be framed into the context of qualitative research, focusing more on human phenomena and less on quantitative data, with a case study approach based on exploratory point of view. The assessment methodology adopted for this work is based on questionnaires with open ended questions, for gathering feedbacks and lessons learned at experiment level, and Likert scale based indicators to get quantitative data about user satisfaction for the experiments performance. The qualitative data analysis performed in this work is based on content coding (Strauss & Corbin, 1990), whereas quantitative data are not analyzed in a statistical manner, also because there are no statistically relevant numbers to analyze. The following Table 1 summarizes the user satisfaction, showing the highlights of the three experiments performed in the first iteration. Seven out of twelve business requirements have been addressed, those mainly related to monitoring and visualization of the working posts status and events in the Stitching Logistic System. The five business requirements not addressed are mainly related to robotic manipulator monitoring, development postponed to second iteration.

Number of experiments evaluated	3
Total number of business requirements	12
Number of business requirements addressed	7
Percentage of critical business requirements addressed	56 %
User satisfaction (from 1 = N/A to 5 = Best)	4.0

Table 1 - experiment technical assessment summary at end of the first application experiments phase

It can be noted that, in the first iteration, the experiments address most of the identified business requirements. Furthermore, the coverage of critical (high priority) business requirements addressed in the first iteration just completed is quite satisfactory, being 56%.

The user satisfaction has been measured with a set of five indicators (“User requirements fulfillment”, “Learnability”, “Understandability”, “User attraction” and “Efficiency”), which depict characteristics important for SMEs as well. The Table 2 summarizes the experiment assessment, with an average technical assessment grade in the amount of 4.0 in the chosen Likert scale (from 1 = N/A to 5 = Best), meaning an overall quite good level of user satisfaction.

Experiment tech indicators	**Average grade**
Fulfillment of user requirements: "The solution fulfils the business requirements, that is, at least 90% of business requirements have been met at the current date"	4.0 (I agree)
Learnability: "It is easy to start to use the solution and learn functionalities"	4.3 (I agree)
Understandability: "The solution is easy and self-clear to understand and the concepts and terminology are understandable	4.0 (I agree)
User attraction level: "The solution is attractive to the user. I feel satisfied and comfortable when using it"	4.0 (I agree)
Efficiency: "The time and resources required to achieve the objectives of the solution are reasonable, the solution is fast enough and does not require too many steps"	3.7 (I agree)

Table 2 - Experiment technical assessment

To accomplish all the requirements, the second and third application experiments were extended to a second iteration together with the fourth experiment, “intelligent sensing on the shop floor”. These new requirements will be analyzed at the end of the second experiments phase. The Table 3 shows the targeted Key Performance Indicators, at the end of the first application experiments iteration and the KPIs addressed to the second phase.

Key Performance Indicators	**“As is”**	**”To be”**	**Actual value**
Downtime of Working Posts	15 min/day	5 min/day	10 min/day
Downtime of Manipulator	60 min/week	2nd phase	2nd phase
Nr. produced shoe pairs	X (private data)	+2.5%	+5.5%
Production costs / shoe pair	X (private data)	-5%	-10%
Data from Working Posts	No	Yes	Yes
Data from Manipulators	No	Yes	Yes

Real time anomaly detection (Working Post)	No	Yes	Yes
Real time anomaly detection (Manipulator)	No	2nd phase	2nd phase
Predictive anomaly occurrence (Manipulator)	No	2nd phase	2nd phase
Maintenance knowledgebase	No	Yes	Yes

Table 3 - Targeted Key Performance Indicators

4. CONCLUSION

The selected industrial context was the footwear industry, one of the strongest sectors in the Portuguese industry, registering a strong performance over the last five years, with exports growing by 43% while imports have risen by only 4%. The studied large footwear producer represents all the manufacturing companies employing similar logistic systems, has a long history of innovation both in the footwear manufacturing and in its distribution and retail. Their two manufacturing plants constitute the industrial facility that are being used in the exploitation of the BEinCPPS ICT Platform, representing a very challenging experimenting environment that can be replicated in the Portuguese footwear sector.

In total, four application experiments have been planned and executed "Access Sensors on footwear production lines", "Diagnostic and predictive maintenance", "Production monitoring" and "Intelligent sensing on the shop floor". The first three application experiments were initiated in a first application experiments phase and implemented successfully all the planned requirements. The most important indicators measured a decrease on the subcontracted costs in both maintenance and production, together with a greater number of produced shoe pairs. The application experiments initiated in the first phase were extended to a second iteration together with the fourth experiment, "intelligent sensing on the shop floor". At this moment the developments in the context of the second iteration are concluded and are being analyzed the experiment results and business assessment.

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