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Transformation of traditional assembly lines into interoperable CPPS for MES: an OPC UA enabled scenario

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Abstract

The exploitation of I4.0 paradigm requires the availability of adequate information across all engineering and production value chains, which is the result of aggregation and fusion of data from various heterogeneous sources, often under real-time conditions. On the one hand, this comprises a challenge for the provision of an efficient, secure and dependable information management infrastructure. On the other hand, system architects must find solutions to assure interoperability on both syntactical and semantic level with reasonable engineering costs. In this paper authors present the research outcomes related to the conceptualization of a generalized information model and a service architecture, for the transformation and integration of typical third-party, stand-alone industrial equipment - FESTO prolog-factory in the specific - into an OPC UA enhanced, Industry 4.0 interoperable CPPS for new generations of Manufacturing Execution Systems. Aim of the discussed approach is to define basic but general guidelines of applicability for the definition, modelling and provision of standardized, Industry 4.0 compliant, CPPS-based industrial services, starting off from a typical legacy industrial environment.

Keywords: Industry 4.0; Cyber-physical Production System; Interoperability; Standardization; OPC UA

1. Introduction

The transformation of real industrial equipment into service-oriented, semantically interoperable components is one of the major concerns of Industry 4.0 (I4.0). Legacy systems need to be “opened” and “adapted”, and this is particularly true for small and medium enterprises that want to access the new business opportunities evoked (or dictated) by the I4.0 [1].

Business motivation is not enough to access nor win the game: industrial digitalization, standardization of service oriented architectures, system interoperability and security are only some of the major aspects with crucial importance in this era of the “new” industrial revolution [2]. The implementation and/or adoption of technologies enabling industrial standardization at all level of information exploitation. In-line with argumentation reported in [3], I4.0 requires also a new style of MES for several reasons. Firstly, modern consumers are demanding customization. I4.0 offers an unprecedented opportunity for success but companies must have plant floor software that is ready to adapt to demand fluctuations. Secondly, I4.0 is a concept revolving around cyber-physical systems (CPS), the merging of virtual and real worlds and creating a platform of interoperability between IT and operations technology. The logic behind this is that products, materials, equipment, tooling, etc. will have embedded electronics which enables communication with each other and gives them computing power for new collaboration scenarios.

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In line with the previous considerations, the research work presented in this paper is part of a much wider development program, whose final goal is the realization of a next-generation Manufacturing Execution and Support System (MESS in the following). Aim of the MESS (which is object of a separate publication) is to realize a robust, reconfigurable and interoperable execution and information system that can be used for optimizing and/or improving production activities in a manufacturing facility, with the focus on quick response to changing production conditions. One of the fundamental functionality of the MESS is to orchestrate the distributed productions processes (routings) and support communication and integration among a variety of Cyber-physical Systems (CPS) inside the facility. In this paper authors target an OPC UA enabled integration methodology for the creation of the general conditions necessary for the conversion of a traditional assembly cell into a service interoperable CPPS (an I4.0 component in the previously mentioned MESS).

1.1. Motivation and contribution

The aim of the article is to show a procedure that even in the case of a legacy production systems - which do not meet the specifics of I4.0 - it is possible to make the production unit suitable for higher-level management through hardware and software development. Thus, it can be proven that I4.0 compatibility is not limited to specifically new devices.

Traditionally isolated industrial cells/workstations need to be converted into Cyber-physical production systems (CPPS) for the provision of their services and the creation of Manufacturing-as-a-Service (MaaS) conditions, the basis for next possible industrial revolution after I4.0. The *acatech* paper created the initial basis for a discussion in Europe about Cyber-physical Systems (CPS) in 2011 [4]. The main goal was to adapt the hardware manufacturer's Networked Embedded System (NES) based bottom-up CPS approach with the IT technology top-down IoT concept. This paper is based on those indications and is inspired by architectural outcomes presented in [5].

There are several initiatives world-wide toward the standardization of industrial reference architectures [6] (RAMI 4.0 [7] and IIRA [8], but de-facto no widely-accepted standards) and their enabling technology. One of these is the OPC UA [9], which is a standard for modelling, binding and exposing services but does not indicate guidelines on how this information should be modelled for a given domain. Like what happens with ontology, OPC UA is a context-independent modelling technology. To this end, authors of this paper:

- propose a service integration mechanism to be used as a model to convert a generic, usually isolated, industrial work-cell into an interoperable CPPS; and
- present a step-by-step method to assess, extend and publish the functionality of the legacy production cell according to the previously mention model
- provide a real implementation of the transformation use-case, which is based on OPC UA modelling technology, with the intent to publish the CPPS services to the much wider interoperable environment of the MESS.

1.2. Paper outline

After a brief introduction on industrial of I4.0 scenarios and the importance to migrate from legacy production systems to CPPS-based interoperable environments, motivation and contributions by the authors are presented. Section 2 gives a short overview of related works. In Section 3 the approach methodology is presented in detail, highlighting the basic concepts of the service integration model, the functionality of the targeted production cell and the system architecture. Section 4 is centred on the realization details of this work and particularly on the building blocks of the solution, the implementation of the OPC UA interface to the MESS. Discussion and conclusion close the manuscript.

2. Related works

Several attempts for converting traditional industrial systems into interoperable, digitalized components have been made during the last years [10]. Nevertheless, the main challenges for both I4.0 and IIoT (Industrial Internet of Things) including security, standard exchange of data and information between devices, machines and services (not only within an industry but also between different industries) still remain some of the open issues [11]. RAMI 4.0 (Reference Architectural Model Industry 4.0) provides a framework for developing products and business models for I4.0 scenarios, by means of a three-dimensional map that shows how to approach the deployment of I4.0. This reference model recommends OPC UA to implement the communication layer but lacks of a proposal for the unification and/or simplification of the information model underlying such industrial development (while targeting other interoperability scenarios through OPC UA [12,13]). In 2016, the I4.0 platform published a checklist based on which the implementation of I4.0 can be divided into 3 levels. Even in the lowest category, it is expected to consist of elements and products that can be addressed over a network via TCP / UDP or IP and integrate an OPC UA information model. The checklist also emphasizes the property requirements for the OPC UA information model.

3. Methodology

The approach presented in this paper is characterized by the activities summarized in the step-by-step list reported hereafter:

1. Exploit the MESS service integration common model (refer to Section 3.4 for details). MESS embodies an OPC-UA client, which has access to the equipment' information model. It can discover functionality and monitor the equipment state, as well as the manufacturing processes.
2. Assess the initial industrial equipment configuration.
3. Verify the applicability of standardized technology (both software and hardware).
4. Identify the implementation gap in the service model.
5. Develop the necessary bridging middleware.
6. Expose the CPPS services.
7. Connect to a OPC UA-enabled open MESS for validation

and demonstration.

8. Assess effectiveness of the approach and replicate it for other services and equipment.

3.1. Basic concepts of the service information model

Aim of this section is to recall the essential concepts which lay at the basis of the OPC UA information model developed. In order to realize the idea of a generally embeddable I4.0-compliant manufacturing service provider cell, a common service model has been built and a minimal set of these basic but mandatory core concepts has been defined. These concepts propose a generalization for both the actionable and the reporting capabilities of a cell. They were selected in order to guarantee: the core digital representation of the cell, the service interface to a collaborative environment, as well as the compliance of the cell with the NES definition of CPPS and I4.0 components in RAMI 4.0 (further details about the overall MESS information model will be published separately):

- *Command*: from the point of view of an external production environment, any consumable (micro or macro) service with a well-defined utility in the production process or environment. It represents a capability of the CPPS utilizable from the external world.
- *Task*: an instantiated operation with defined input parameters.
- *Report*: any status update in the advancement of the command and tasks execution.
- *Variable*: any observable physical signal or computed quantity produced by the CPSS and published to the external world.

3.2. System architecture

The workstations of the cell are controlled separately with a legacy Siemens PLC (S7-300), each workstation can operate independently. Orders can be managed with HMI. The possibility of central control as well as external communication is provided by a Siemens S7-1500 PLC. This device supports (up to firmware 2.0) the use of OPC UA as a client and server, which is thus also accessible to third party devices.

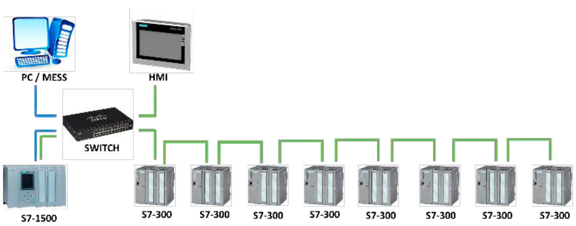

Fig. 1. Production cell topology

The network of PLCs forms a Daisy chain (Fig. 1.) type topology. There is a Profinet connection between the PLCs of the workstation based on several network protocols (HMI Connection, S7 Connection).

3.3. FESTO prolog-factory functionality

In terms of the function of the production cell, it is an automatic production cell that manufactures, assembles and pallets three types of cylindrical parts. The cell consists of eight workstations (Fig. 2.), the material flow between the workstations is linear. Cell orders are handled using an HMI interface, the system works on pull basis:

1. Triple distribution station: three parts are stored type dependent separately and dispensed depending on the order. The three cylindrical parts are as follows: red-plastic, black-plastic, gray-aluminum.
2. Testing station with colour sensor: using a colour sensor and a distance sensor, the dispensed part is controlled.

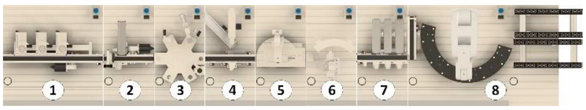

Fig. 2. FESTO prolog-factory layout seen from a ceiling camera

3. Processing station: using a turning table, the part is moved to the machining and inspection positions.
4. Pick and place station: from a slider feeder the clock plates are installed into the cylinder by aid of a pneumatic manipulator.
5. Fluid muscle station: joining the cylinder and the clock plate using a pneumatic press.
6. Warehouse station: three-level warehouse with six storage spaces on each level, where the loading and unloading is provided by an electro-pneumatic manipulator.
7. Separating station: inspection of products unloaded from warehouse, and if necessary order dependent separation of them.
8. Commissioning station: order dependent commissioning of products onto pallets and forwarding the pallets in a dedicated manner (AGV or TRIPOD).

3.4. Service integration model

As illustrated on Fig. 3. the MESS core connects to the CPPS as an OPC-UA client. It requires a predefined model structure from the server to explore the facilities of the equipment (Section 3.1).

The most important information is the list of functionalities (services) and system state variables that the cell provides to the external world. Services are represented as OPC-UA methods. In order to execute a specific task the MESS core calls the appropriate method and waits for the incoming reports on the task status.

These reports are specified through special OPC-UA variables. The MESS core monitors these variables and reacts depending on the level of the notification (information/ack, warning, failure and error), as well as for all the other system related state variables.

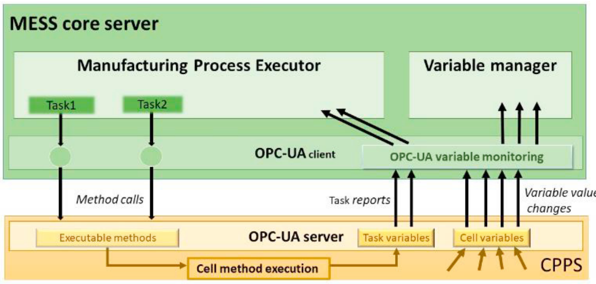

Fig. 3. MESS-CPPS communication via OPC-UA

4. Realization

The purpose of converting a production cell into an OPC UA based CPPS was the connection to a distributed production control system, condition for working with additional tools in the lab. Integration is based on OPC UA information technology, whose main leveraged features can be summarized as follows: faster and more efficient communication, continued support to traditional query data update, conventional communication protocol in a unified architecture, platform independence, increased security (no configuration of security features were required), cost-effectiveness, shorter lead-in times, and a simplified configuration of remote connections.

4.1. Building blocks of the solution

The first and most important element of this integration is the hardware capability, so a PLC that is capable of handling OPC-UA must be added. Another condition for a MESS system-controlled production line is the creation of an OPC-UA based communication and information model between the PLCs and the control system. The information model was developed in close cooperation with the development team of Centre of Excellence in Production Informatics and Control, based on the requirements set by them. The information model can be used to ensure the flow of data between different systems. The information model was created using by Siemens SiOME - OPC UA Modeling Editor software, this information model is actually an .xml file. Steps for creating an information model and interfaces between softwares are depicted on Fig. 4.:

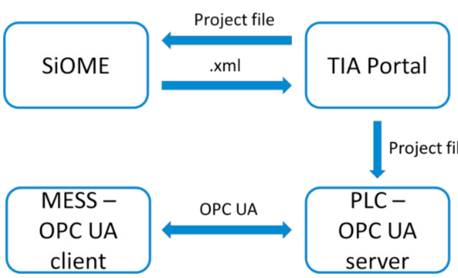

Fig. 4. Information model application method

1. TIA Portal: PLC code creation, project file.
2. SiOME: Building an information model according to MESS requirements. Development of methods, objects, variables, arguments definition for important operations.
3. SiOME: Load a project file created in the TIA Portal and link the appropriate data structures, export information model (.xml).
4. Load TIA Portal: .xml as the OPC UA server interface.
5. MESS-based system management: Calling methods, setting necessary parameters.

4.2. Scope and preconditions for integration

Considering the specifications of the production cell, the integration provides full supervision, but the possibility of external intervention is limited to the management of orders. The manual initialization phase is essential for starting, which is also required for security reasons. During manual start-up, the air and power supply to the production cell must first be ensured. The next step is to visually check the condition of the physical devices in the production cell and eliminate any abnormalities. Then, with the help of the HMI interface, the MESS operating state must be enabled. After enabling MESS mode, manual production start is not possible, only the central controller can start the production.

4.3. Implementation of the OPC UA interface to the MESS

The environment and software configuration comprised the following components: Siemens S7-1516-3 PN/DP PLC, as hardware, and Siemens TIA Portal and Siemens SiOME - OPC UA Modeling Editor – as software.

The information model follows the prescribed structure (Section 3.1) and includes the administration methods as well as the file structure required for the server. Methods, intended ass the micro services of a cell, have been developed to enable cell operation in specific elements of the file structure. In the current operating state, the central control can call four methods. The condition for executing the methods depends on the statuses of the cell, as listed:

- *Starting* – the cell is in MESS operation status, orders not accepted
- *Working* – the cell is in MESS operation status, orders accepted
- *Stopped* – the cell is stopped, orders not accepted
- *Off* – the cell is in Manual operation status, orders not accepted
- *Error* – Failure operation status, manual intervention is required, orders not accepted

4.3.1. Commands

There are currently four types of service command that the production cell can offer (description/input parameters/output parameters):

1. Palette Order (Production start-up, Palette and Workpiece order/Destination, Workpiece type and number/Order ID).
2. Delete Order (Delete order based on order ID/Order ID/Command accept/reject);

3. AGV workplace request (Shared workplace use/Workplace request or return/Command accept/reject).
4. Move (Deflector vane movement/Movement interval (s)/Command accept/reject).

4.3.2. Variables

Currently, nearly a hundred variables are monitored that include I / O signals from the entire production cell, as well as other parameters that support Plant Simulation-based Digital Twin operation.

4.3.3. Reporting

Based on the MESS architecture, the connected stations communicate with each other with status codes, different status codes indicate the task already started and in progress, and the already completed task. Within each status code, several stages of readiness are possible in terms of the processes of the production cell. These states appear in the form of comments, supplementing the individual statuses, this value is not relevant to the central control. The number of tasks for each method is fixed and cannot be changed dynamically, because the information model on the basis of which the system will operate must be prepared in advance and downloaded to the PLC. It is not possible to change the information model during operation due to the specifics of the PLC as an executive element (or there is, but it requires a system restart). Task return value can be the following for the Palette Order method:

- Production is progress (Workpiece production)
- Production is progress (Workpiece production, Palette released)
- Palette ready, waiting for release (TRIPOD)
- Palette released for TRIPOD
- Palette ready, waiting for release (AGV)
- Palette ready, waiting for AGV (in position 5)
- Palette released for AGV

4.3.4. Programming tools and other requirements

From the point of view of the MESS, the programming environment can be described as an OPC UA server or OPC UA client page (Fig. 5.).

Server: the device is the PLC, which can be programmed using the TIA Portal. TIA Portal version 15.1 can only be installed on a Windows 10 64-bit system. The information model providing the OPC UA protocol will also be implemented on the server side, and SiOME software, which also support the Windows 10 operating system is required for editing. The information model is loaded into the PLC via the TIA Portal. The control of the commands defined in the information model can be defined on the PLC using the OPC UA Method function blocks edited in the TIA Portal (this is closely related to the programming of the cell control). The PLC was programmed in LAD and SCL.

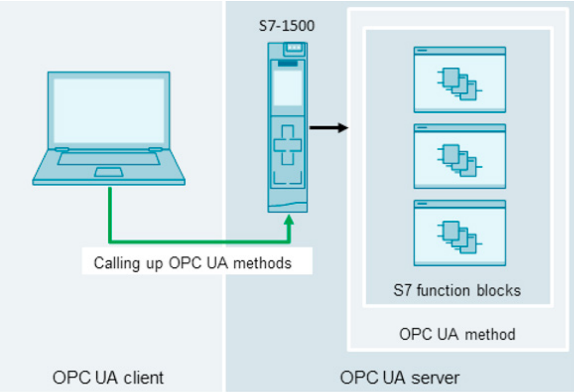

Fig. 5. OPC UA based system [14]

Client: The MESS system, or any other OPC UA compliant Client (Prosys in our case), used for testing where operational data can be queried in the structure of the information model defined on the server side, and commands can be executed.

4.3.5. Integration testing process

During the integration and testing process, a mandatory boot sequence was defined. During this process, the initialization steps take place on the HMI interface after the air and power supply have been provided. The production cell has a manual and automatic (MESS) mode, where the manual mode facilitates testing capabilities, and the automatic mode creates the conditions for working with the MESS. The testing phase was massively based on the execution and debugging of methods via Prosys, as after calling the method it was possible to enter the parameters and the return value could be identified. It can also be used to track the current status of tasks and to query the values of variables. An important criterion for specifying variables is that external access should be set to read-only during configuration for system security. Proven industry standard devices can be operated reliably during the test phase and as well as after the MESS implementation.

5. Discussion

The most important feature of the FESTO prolog-factory is that it consists of industry standard devices and integration with MESS takes place through these devices. The control as well as the communication with the MESS are also performed by the PLCs. The PLC, as a logic controller, performs reliable operation from pre-written programs and defined parameters. Any change to the PLC requires a restart of the production cell, therefore the sequence of integration with MESS must be designed accordingly.

Factors influencing the development of the information model, experiences can be summarized as follows:

i) it can only handle a predefined number of Tasks, the number of Tasks cannot be changed dynamically during operation.
ii) When parameterizing variables, they can have read-only

properties because of system security and to avoid unwanted intervention.

iii) By the protocol for writable variables, server-side and client-side writing are also allowed, which means serious security risks. To overcome this, it is necessary to create a cohesiveness between the field programmer level and the control programmer level. The establishing of the standardized synchronisation of these programming levels require further development and research work.

iv) When editing a SiOME information model, the project file cannot be opened in the TIA Portal at the same time.

v) When editing a SiOME information model, a custom namespace domain must be created, which can be freely edited, or other standard models can be imported. The basic namespace only provides the framework for operation and it is not allowed to be edited.

6. Conclusion

To scale I4.0, or in general next generation factory developments, into a practice that is predictable, reliable and efficient will require standardization. The intent of standardization is to maximize participation of many independent parties. It is a common language or a coordination mechanism for parties to accelerate and coordinate progress. Application scenarios for I4.0 systems are always characterized by a high degree of flexibility, adaptability and autonomy of the components involved in the operation. To do so, they need a common language based on interaction and service patterns. It is made up of a vocabulary and a defined grammar, the contents and effects of which must be clearly described semantically.

In this paper authors presented the outcomes related to the conceptualization of a generalized information model and a service architecture, for the transformation and integration of typical third-party, stand-alone industrial equipment - FESTO prolog-factory in the specific - into an OPC UA enhanced, I4.0 interoperable CPPS for new generations of Manufacturing Execution and Support Systems. The achieved aim of the discussed approach was mainly to define the basic, general information model for the provision of standardized, I4.0 compliant, CPPS-based industrial services, starting off from a typical legacy industrial environment.

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