Hybrid Cloud Environment for Manufacturing Control System

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Abstract

Today the concepts of Smart factory, Internet of Things and Industrial Internet play a significant role in innovation process and new engineering design architectures. Using design thinking approach, university team of MSc and PhD students under the guidance of global IT company developed the cloud manufacturing control system based on the instructional flexible manufacturing line (FMS) equipment and production Internet-of-Things platform.

As a result, FMS consisting of several machine tools, manipulators, conveyor and storage is monitored and controlled under engineering cloud. The cloud-based in-memory database software being integrated part of the solution was provided by global IT company through industry – academia research initiative.

Physical devices have cloud representations connected with each other through the dependency model and communication channels. Presented framework allows to provide self-organization between cloud representations, scheduling of orders in the cloud and support of discrete event simulation process based on the real-time data from the devices (DEVS models simulation representation).

This cloud-manufacturing environment is fully functional and will allow to use this example for research and education of postgraduate students and industry clients and for understanding the important trends in future manufacturing.

Introduction

One of the most ambitious and distinctive international future manufacturing projects is the German Government program Industry 4.0 [4]. As a part of its long term strategy, the most important expected project achievement is the development of next generation cyber-physical systems, M2M communications based on real data analysis, cloud based engineering [1] and manufacturing environments. Despite the positive outcomes of the project so far, significant barriers remain, such as the technical complexity, soft (human) factors influence, inconsistency in business processes description and issues about integration with corporate information systems.

Indeed, the task of development a comprehensive framework for autonomous, intelligent production process for future product plants which plays an essential role in technological trends still remains an existing research area [9]. At the same time, topic importance is increasing due to growth of the requirements on product quality and customization, as well as dynamic competition imposing significant requirements on the ability of manufacturers to provide customers with products of required quality and quantity within competitive price boundaries.

At the presented investigation the reference framework for the IoT environment within production line (Industrial Internet framework) is proposed. The concept of our framework is based on the idea of different abstraction layers and responsibilities of software packages.

A main proposed result of this study is a new approach for student education. The project was developed by the group of students under the supervision of industry vendor. Practice based learning approaches are hard to overestimate and participation in such interdisciplinary, industry - academia initiatives provides students with a great industrial insights and is exceptionally useful for their future career development.

The paper is structured as follows. A brief history and reference framework are displayed, further cloud manufacturing planning and simulation level are proposed and learning outcomes are described.

History of the Automotive systems

Automation of different product life-cycle phases is being developed since 1970. The attention was usually focused on programs facilitating automated design (Computer Aided Design) and manufacturing (Manufacturing Execution Systems, MES) [2]. With significant help of information technologies, evolving since 1980, the new step was made, emerged a concept of FMS(Flexible Manufacturing System). In the end of 80th - beginning of 90th focus of attention shifted toward product design, manufacturing equipment configuration and new products management issues. At that time concepts of PDM (Product Data Management) and PLM (Product Lifecycle Management) were introduced. These concepts consider data exchange and integration with other enterprise services and provide through-life services [3] to support production process over the lifecycle.

Henceforth manufacturing automation have become strongly connected with Product Lifecycle Management concept, development of information technologies and the idea of unmanned plants. Nevertheless factory data started being integrated into a single

informational factory environment the links connecting subsystems were still weak.

The trend of united data space formation in manufacturing often employs approaches used in Internet of Things. Architecture of the common interactions between devices has been defined by Industrial Internet Consortium (IIC) [6]. Several of system characteristics which should be implemented according to IIC standard are reliability, scalability, usability, maintainability, portability and so on. There are also some critical characteristics that system should realize to ensure core system functionality: safety, security and resilience.

The cloud systems are commonly integrated in plant operation. Several research groups [5, 8] described system architectures of cloud robotics system based on Machine-to-Machine and Machine-to-Cloud communications. Despite of that development of a single architecture for manufacturing applications still represents a serious challenge [7]. Another important objective is creation of modeling and simulation cloud based tools, which will enable interoperability and self-organization of the manufacturing processes.

Below the idea of 4-layers conceptual framework for Industrial Internet is described.

Cloud manufacturing conceptual framework

On the Fig. 1 the framework overview is presented. The basic idea of conceptual framework consists in handling three main scientific problems in the field of IoT environment[13]:

- data exchange among network elements;
- effective integration of uncertain information;
- service adaptation of the dynamic system environment.

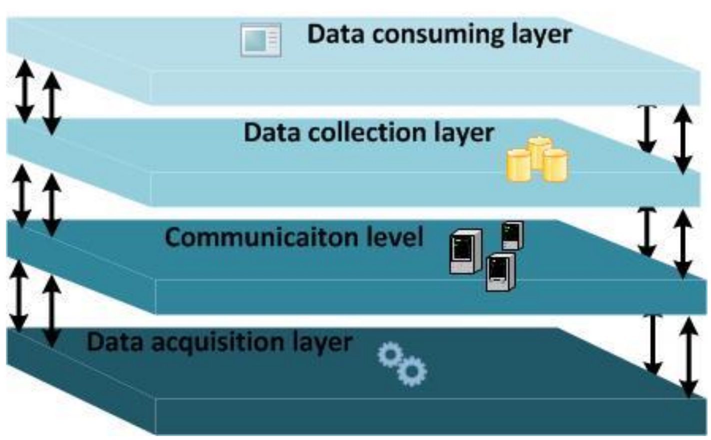

Fig. 1- Industrial Internet framework

A distinctive feature of legacy plants is a need of development new drivers and connections in order to meet the requirements of Industrial Internet. In this research it's called *instrumentation*. Any control system working with real equipment is based on device drivers providing interfaces to communication level. As a matter of fact expensiveness and inexpediency make supplementation of all the manufacturing plants with modern hardware unrealizable. Thus, we need to look for a solution dealing with legacy equipment and allowing to eliminate disadvantages of the ages. The newly developed framework solving the problem consists of 4 layers.

The first layer - Data Acquisition Layer masters with primary hardware issues similar for many plants. At this level the basic data is gathered from the different sources at shop floor. Process of instrumentation consists in connection with modern sensors and writing new drivers for the existing tools. It is important to deal with data describing parts (often acquired with help of RFID-chips). The main goal of automation here is carrying simple yet reliable real-time data verification and automatic activities, for example, closing the robot jaw.

Another challenge during building the hybrid cloud environment applicable for production line is integration of Information Technologies (IT) and Operation Technologies (OT). Information Technologies are responsible for representing all physical system characteristics in digital world domain. With traditional simulation approach we have models of the real word data in the computational modules. Symbol-grounding problem is the main issue of the information technology domain. Translation of symbols meaning to machine language is a complicated task. From the other side Operation Technology (OT) methods and real world "control" should be applied directly to the physical processes without addressing any models. In the IoT concept (especially in Industrial Internet domain) it is critical to use appropriate connections between IT-domain and OT-domain. Instrument facilitating minimization of the difference between OT-state and IT-model is our hybrid cloud control and simulation system. *Instrumentation* of this layer implies permission of local data storage for these perceptions.

Second layer represents a link between local parts and cloud solution. It is called a Communication Layer. *Instrumentation* here includes development of the drivers capable of sending information to the cloud (actually, writing service packages special for particular devices) and development of services in the cloud responsible for perceiving information. Another big challenge emerging on this layer is design of a comprehensive communication protocol allowing real-time data communication between devices. Nowadays the closest to hard requirements is an open Web Socket standard.

Third layer of the framework is Data Collection Layer. Data gathering and storage aspects influence a lot on the database architecture. Moreover, structured data storage and

organization cause correlations between the plant processes specifics and architecture and type of the database. In the further example of Data Collection Layer instrumentation we employ clone-based architecture of the storage. Typically, clone-based architecture usage is reasonable for meeting requirements for small flexible manufacturing systems.

The last layer of the framework is an Application Layer. Here data can be consumed by the customers. At this level user settings are applied and simple system customization is performed.

At the current paper the forth (Application) layer realization is emphasized. Simulation environment utilizes data received from previous layers. Discrete Event System Specification (DEVS) was applied as a basis for modeling.

Cloud Manufacturing simulation framework

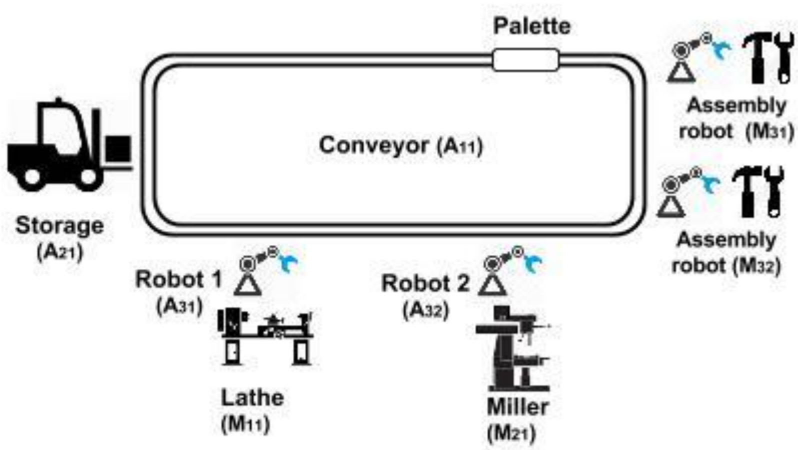

Fig. 2 – Schema of the manufacturing line

Firstly, defining all interaction in broad strokes, we ought to describe the main parts of the system. Presented manufacturing line consists of several devices: lathe and miller tools, assembly, storage and conveyor (Fig. 2). According to the framework described above we have four main areas of automation. The first one deals with the real-world device's interaction and data acquisition through drivers and additional sensors. Specific drivers and connectors allowing sensing and acquisition of data were developed. For the through-life engineering services and integration with other information flows in the factory the RFID tags were implemented. Hardly had data was acquired from devices, it was transferred through the second Communication Layer. Our goal was to equip existing production line as shown at the Fig. 2 with particular drivers and tag readers. Communication process was based on the Web-Socket protocol and included development of software connection servers

for device drivers and services working with them. Actual architecture of the system is shown at the Fig.2. The clone-based schema of the production line developed based on the cloud infrastructure represents Data Collection Layer implementation. Storage of messages received from devices was organized applying clone-based architecture [5] of the database. Data storage was located in the cloud system. One of the popular cloud solutions applicable for such case was chosen.

Information gathered from devices is the essential part of further simulation process.

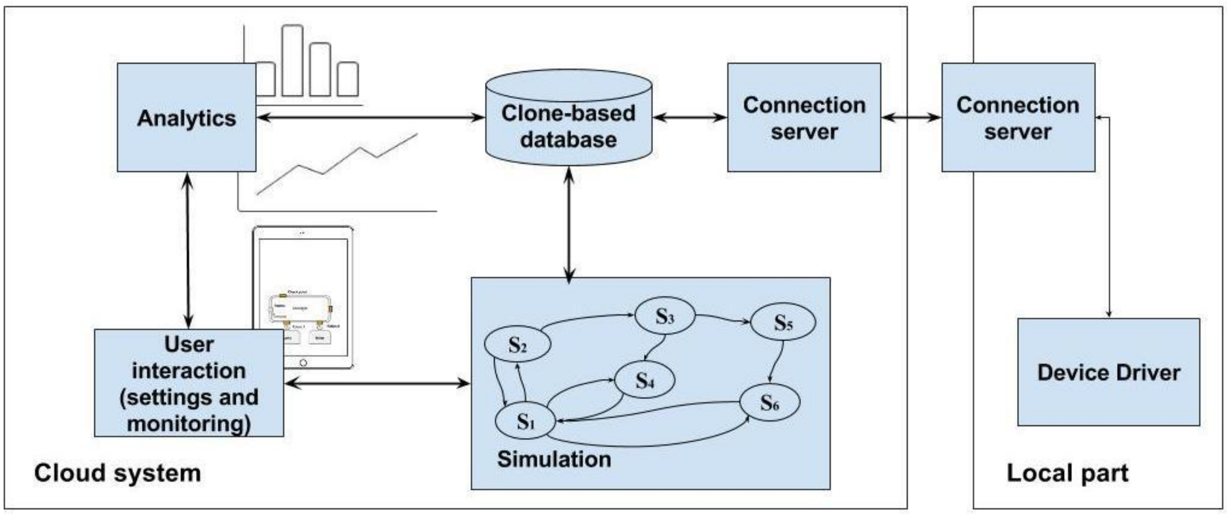

Fig. 3 – The Cloud Manufacturing framework

The system part responsible for modeling interaction includes simulation based on DEVS formalism. Data defines interaction between devices and produces predictive environment for the next steps of the process. Thus system holds information about physical devices and provides decision making support, analytics and prediction. Virtual clones of the environmental nodes on the previous level are modeled as atomic parts of the DEVS model [12]. The simulation process is described in details below.

Simulation

The cloud manufacturing framework reflects current system state in the cloud. Such representation allows to monitor and control the devices states. It is possible to report the problem and stop processing in case of the failure occurring during the workflow. This is the main reason why modeling and simulation in combination with the real data from the devices is vital. The control logic of the automated system can operate in real-time and be integrated in the both, simulation model and the real manufacturing system. Several simulation models can be

developed and engaged into the manufacturing stations.

The cloud-based manufacturing model consists of several parts: agents, presented devices and orders, computational model and the environment. Messages received from the associated orders and devices define current cloud agent's state and properties. Simulation is associated with the actual production process and commands generated in the model are translated to the devices (Fig. 4).

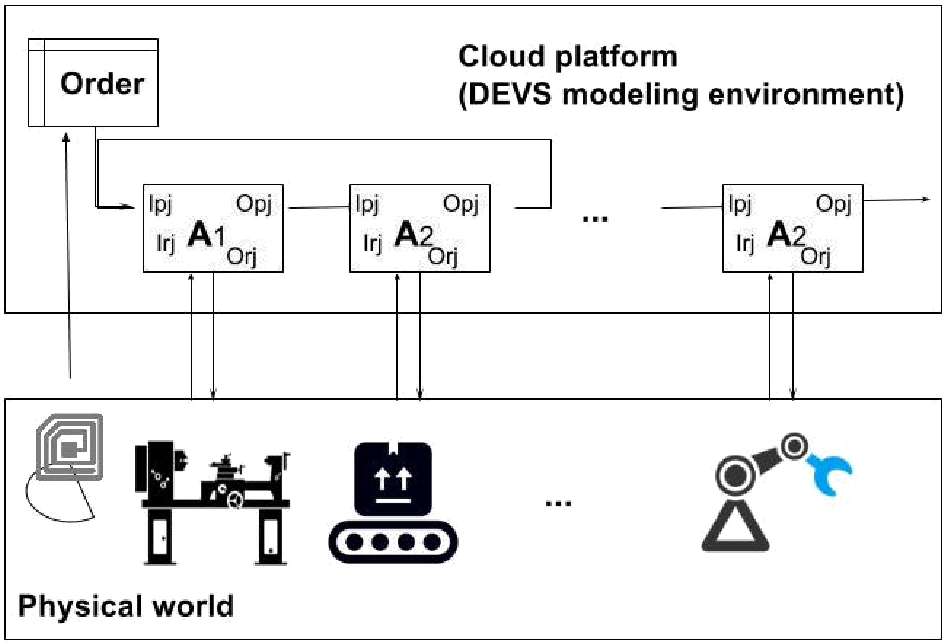

Fig. 4 – Schema of the Flexible manufacturing line.

DEVS framework [13] is used as a simulation part of the cloud environment. DEVS [10, 11] is a modular hierarchical system for modeling complex discrete event systems.

The basic DEVS formalism describes inputs, outputs, states of a model and relationships among them. Atomic DEVS models represent system behavior and couple DEVS model with structure of our system. Framework provides interoperability, supports hybrid systems and is widely used for engineering approach. Structure and atomic parts of the model defined by he DEVS formalism are formally named as follows:

$$M = \{X, Y, S, t_a, \delta_{ext}, \delta_{int}, \lambda\},$$

Where:

X - set of input events;

Y - set of output events;

S - *set of sequential states* (also called the *set of partial states*);

t_a - *time advance function* used to determine the lifespan of a state;

$\delta_{ext} : Q \times X \rightarrow S$ - *the external transition function* defining how an input event changes a state of the system

$\delta_{\text{int}} : S \rightarrow S$ - *the internal transition function* describing the way how system state changes internally

$\lambda : S \rightarrow Y^{\phi}$ - is *the output function* where $Y^{\phi} = Y \cup \{\varphi\}$ and $\varphi \notin Y$ is a "*silent*" or an "*unobserved*" event.

Our model consists of the several equipment units represented as atomic models. Units states are updated dynamically starting from the physical representation of the component in the beginning of the production process. During the simulation process state of the certain atomic model updates and simulation model is clarified. The structure of the system, devices interaction and messages are modeled as the *coupled model*. The example of coupled model in the context of interaction between robot and lathe tool is presented on the Fig. 5.

At the beginning of the simulation process we establish atomic models for each device clone. When the device clone is included to the system, atomic model with the particular configuration is created. The atomic model represents basic initial component of the modeling system and can be described as the diagram shown on the Fig.5

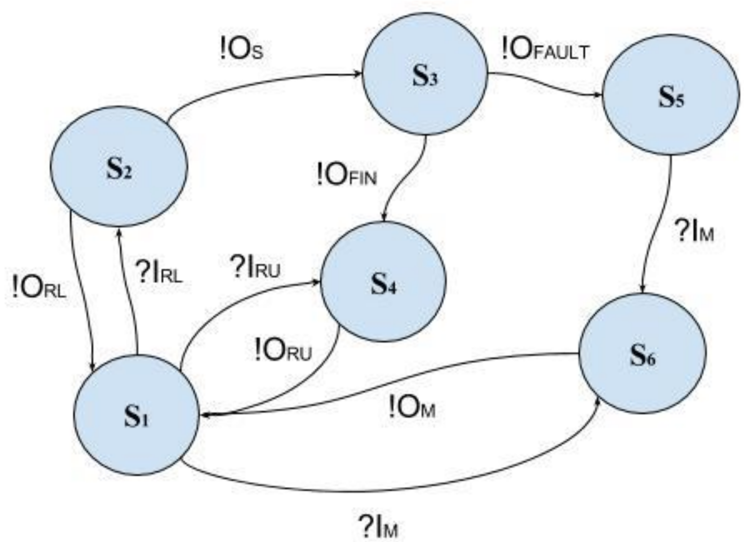

Fig. 5 – Atomic model of the lathe tool.

States and input/output messages of the machine tool are described as follows:

S1 - Machine tool is in the work state (ready for processing).

S2 - Raw part is loaded to the machine.

S3 - Machine tool is in the processing state.

S4 - Machine tool finished processing.
S5 - Machine tool is in the failure state.
S6 - Maintenance.
IRL- Robot loads raw part to the machine center.
ORL - Raw part was loaded but start processing command was not received.
OS - Lathe started processing.
OFIN - Lathe finished processing.
OFAULT - An accident occurs during the processing. Maintenance is required.
OM - Maintenance required.
ORU - Machine changed state to "ready".
O_M - Maintenance is finished.
OS - Lathe started processing.
IRU - Robot unloaded part from the machine.

Robot behavior depends on the lathe. Robot also sends information about its state and state of the tool. The coupled model (machine tool and robot) can be described as follows:

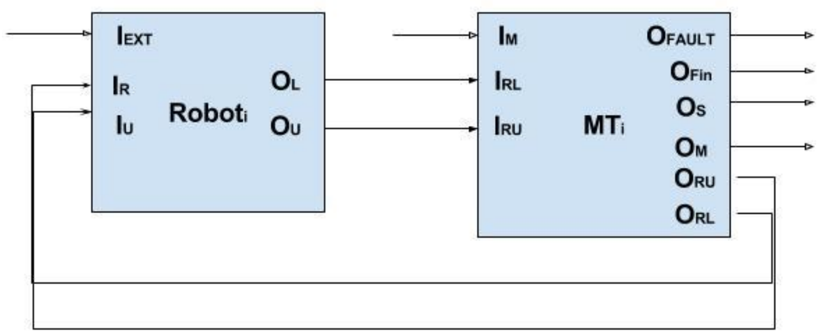

Fig. 6 – Coupled model of machine tool and robotic manipulator.

DEVS model of the system builds dynamically when the structure of the system is defined in the cloud environment. Cloud modeling system allows handle unexpected failures and dynamically re-configure the line.

Presented architecture reproduces modeling system state during several cycles of processing different parts. Predictive models on future machinery loading are built based on the modeling.

Modeling system fills the dependencies and restrictions on the database and defines inputs and outputs of the atomic models (device clones).

Framework development process and learning outcomes.

Industrial Internet framework implementing described four layer architecture and DEVS formalization and modeling was developed by a group of students as an independent learning project in context of industry - academia research initiative. The real manufacturing line equipped as shown on Fig. 2 was used. Practical experiments helped to proof advantages of the used approach.

There were two possible options for work tasks decomposition among students: "vertical" and "horizontal". The "vertical" approach implied that each team member should have fully automated one physical device, for example lathe or robot, writing drivers, services and application software specific for the chosen device himself. The "horizontal" approach consisted in tasks decomposition in correspondence with the four layer structure. Therefore each team member should write software implementing a particular abstraction layer.

The "horizontal" approach was chosen. Project results had shown correctness of this decision which, on the one hand, allowed everyone to learn specific technical domain in detail and share experience with others and, on another hand, to finish project within given time boundaries. One of the main learning outcomes includes extra team work practice as well.

Often theory about high-level abstraction concepts, such as any architectural issues cannot be understood in depth without having hands-on experience. Consequently, it was very important and useful for students to create the framework on their own.
There were three biggest challenges in the work process.

The first one was connected with machinery only supported with obsolete complimentary hardware which was not further produced. So, even an ordinary hardware part failure required by an order more efforts than was expected. The second challenge was studying of comprehensive and thus complex API of production cloud based Internet of Things platform. Finally, administrative access network issues slowed down the development process too.

Although these problems are neither new nor unique, given with such practice, students became aware of such systems "bottlenecks" and will be able to avoid, predict or manage similar problems in the future faster. That is very important for a good technical specialist to be familiarized with infrastructural issues since any ideal model needs to be implemented in real world circumstances which are far from the idealized ones, which the model was developed for.

Conclusion

A new integrated framework for the cloud-based manufacturing is introduced. Presented cloud environment employs approach enabling better design of future production systems as the subclass of learning and adaptive distributed systems. The method of continuous DEVS simulations is used for the cloud simulation model.

We hope that development of our framework will be a small step forward to a new generation of future production systems in the world of connected devices. We believe that cloud-based manufacturing lines are part of the future spatially distributed manufacturing infrastructure and we hope that contributed to development of the Factories of the Future.

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