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Viewpoints and views for the architecture description of cyber-physical manufacturing systems

Afifa Rahatulain\(^{a,b,*}\), Mauro Onori\(^{b}\)

\(^{a}\)SenseAir AB, Delso, 82060, Sweden
\(^{b}\)KTH Royal Institute of Technology, Department of Production Engineering, Stockholm, 10044, Sweden

* Corresponding author. Tel.: +46-73-461-2496; E-mail address: afifa.rahatulain@senseair.com

Abstract

A well-defined architecture covering all the views, viewpoints and related stakeholders’ concerns throughout the life cycle is vital for a good system design. This becomes even more crucial when designing Cyber Physical Manufacturing Systems (CPMS), one of the key elements in factories of the future. This paper identifies views and viewpoints necessary for defining architecture for CPMS. A mapping between system stakeholders, concerns and viewpoints is also presented. The results shall serve as a basis for an architecture-centric development methodology for CPMS as well as conventional manufacturing systems.

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1. Introduction

Cyber physical systems have a major role in defining the factories of the future in the fourth industrial revolution, i.e. Industry 4.0. However, several factors limit their wide-scale adoption by the existing industrial setups. System complexity, safety, network security, performance metrics, lack of a comprehensive architecture, non-availability of well-defined methodology, legislative requirements and support & integration tools are to name a few [1-3].

The main focus of this paper is to define a basis for the architectural descriptions of a cyber-physical manufacturing system, which can be used for a holistic development approach throughout the life cycle stages of the system [4,5]. The methodology adopted to achieve the objectives of this work is described in section 2. The main results discussed in this paper are:

- Identification of architectural viewpoints based on identified stakeholders (section 3.2).
- Classification of major views with respect to the identified viewpoints and relevant abstraction levels (section 3.3).
- A mapping between the stakeholders and their concerns with respect to the identified viewpoints is also presented (section 3.4).

This paper is concluded in section 4 with a brief summary and ideas for possible future work.

2. Methodology

The first step towards the objective of this work is to identify and define the architectural viewpoints [4] of the system. The description of the viewpoints discussed in this paper is based on the (i) system stakeholders as identified in [6], (ii) major system challenges & stakeholders’ concerns [7] and (iii) existing architecture definitions for manufacturing concepts based on cyber physical systems, such as Evolvable Production Systems (EPS) [1,8,9] and Holonic Manufacturing Systems (HMS) [10].

The next step after viewpoints identification, is the classification of major possible views and their characteristics, namely; function, behavior and structure, along with their relationships with the levels of abstraction (LoA) in a CPMS. The relationship between the views and different levels of abstraction has been derived from the Y-model as described in [11]. Depending on the system granularity level, each viewpoint can be instantiated into one or more views, each corresponding to a different level of abstraction.

The results are then summarized in the form of a matrix which provides a mapping between the stakeholders, concerns and the viewpoints. This work has major inspirations from the architecture descriptions and dependencies for cyber physical systems and in particular automotive systems [12-14].

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3. Architectural Viewpoints, Views and Levels of Abstraction in a CPMS

This section discusses the stakeholders, major concerns, viewpoints, and views with reference to cyber-physical manufacturing systems. The relationship of views with the levels of abstraction is also discussed. To ensure a common understanding of the terminologies used in this work, the basic definitions of the architecture-related aspects are also provided below:

- **Stakeholder**: A person, team or organization having an interest (concern) in a system is known as system stakeholder [4,5].
- **Views**: An architecture view addresses one or more concerns of the system stakeholders and is governed by a viewpoint [4].
- **Viewpoint**: The viewpoint provides conventions to construct, interpret and analyze the corresponding views using models, notations, design rules, languages, etc. [4].
- **Level of Abstraction**: The levels of a system hierarchy corresponding to different complexity and detail levels. The higher the level of abstraction, the less is the complexity of the details describing that particular level. In the context of this work, the levels of abstraction in a production system are classified as system, line, cell, device, component and control levels.

Fig. 2 shows an overview of the dependencies and relationships between different system elements and related architectural aspects. The stakeholders define their concerns for the system which are then framed by one or more viewpoints. Several views can be instantiated within a single viewpoint depending on the level of abstraction. Each level of abstraction can be defined under different view categories as having function, structure and behavior.

Several views and viewpoints have been proposed in the reference architectures for CPS in manufacturing (for example, Evolvable Production Systems (EPS) [9] and Holonic Manufacturing Systems (HMS) [10]). The work presented in this paper complements the existing viewpoints and further defines and categorizes them into distinct viewpoints and corresponding views. The classification is based on the stakeholder requirements and concerns with reference to the architecture descriptions provided in ISO/IEC/IEEE 42010 [4].

3.1. System Stakeholder and Concerns

Stakeholder identification is the first step towards the development of a well-defined methodology based on an holistic approach. Flood and Carson method [15] was used to identify the system stakeholders and to classify them according to the narrow and wider system of interests. Table 1 provides a list of the major stakeholders. Only the stakeholders under the narrow SOI domain are considered for this work.

The identification of the main requirements and concerns relevant to the system stakeholders is the next step towards the architecture development. The major concerns which are considered in this work are [7]: *system safety, robustness, flexibility, mobility, security, performance, functional safety, autonomy, cost, standardization, real-time compatibility, tool chain integration, information management, verification & valida-
Table 1: A list of major stakeholders involved in the development of a CPMS [6]

<table>
<thead>
<tr>
<th>Narrow System of Interest</th>
<th>Wider System of Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors provider</td>
<td>Product design</td>
</tr>
<tr>
<td>Equipment provider</td>
<td>Logistics</td>
</tr>
<tr>
<td>Controller provider</td>
<td>Operations planning</td>
</tr>
<tr>
<td>Software Engineer</td>
<td>Management / Decision-making</td>
</tr>
<tr>
<td>Programmer</td>
<td>Human resource</td>
</tr>
<tr>
<td>Network provider</td>
<td>Supply chain</td>
</tr>
<tr>
<td>Maintenance Support</td>
<td>Sales &amp; marketing</td>
</tr>
<tr>
<td>Operator</td>
<td>Administration</td>
</tr>
<tr>
<td>System Integrator</td>
<td>IT support</td>
</tr>
<tr>
<td>Customer (Industry)</td>
<td>Customer (Product)</td>
</tr>
</tbody>
</table>

tion, and traceability. Table 2 provides a summary of the identified concerns.

3.2. Classification of Viewpoints

Three major identified viewpoints for the architecture description of CPMS are; Implementation viewpoint, Functional viewpoint and Operational viewpoint. The implementation viewpoint is further categorized into hardware, software, and deployment viewpoints, while the operational viewpoint has two sub-categories, i.e. usability and communication viewpoints. The different viewpoints are shown in Fig. 3 and a brief description of each viewpoint is as follows:

1. **Implementation Viewpoint**: This viewpoint covers mainly the technical aspects related to the implementation and development of a system. It is further divided into three main categories:
   - Hardware viewpoint
   - Software viewpoint
   - Deployment viewpoint

2. **Functional Viewpoint**: The functional viewpoint covers the performance and functionality related aspects of a system. The focus is on what the system is supposed to do (e.g. process production orders, manufacture, self-configure, etc.) and how (e.g. KPIs, efficiency, etc.)

3. **Operational Viewpoint**: This viewpoint covers the operation related concerns of the system stakeholders, including how the system will be monitored, controlled and managed. It is further divided into the following categories:
   - Usability viewpoint
   - Communication viewpoint

The usability viewpoint covers the concerns related to operational details and management of the system, where as the communication strategies and information flow between the stakeholders, different abstraction levels and corresponding system elements is provided in the communication viewpoint.

Table 2: Major system challenges and stakeholders’ concerns [7]

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Stakeholders’ concern</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Flexibility</td>
<td>In terms of hardware (machines, equipment, controllers, etc.), software, and communication network</td>
</tr>
<tr>
<td>2.</td>
<td>Autonomy</td>
<td>The extent to which a system can have self-x properties</td>
</tr>
<tr>
<td>3.</td>
<td>Security</td>
<td>Connected networks, clouds, cyber attacks</td>
</tr>
<tr>
<td>4.</td>
<td>Performance</td>
<td>KPIs for system optimization, efficiency, effectiveness</td>
</tr>
<tr>
<td>5.</td>
<td>System safety</td>
<td>Advanced fail-safe mechanisms, synchronization issues, communication failures</td>
</tr>
<tr>
<td>6.</td>
<td>Functional safety</td>
<td>Safety critical systems, safety integrity levels, etc.</td>
</tr>
<tr>
<td>7.</td>
<td>Cost</td>
<td>Design, implementation, operational, functional costs, etc.</td>
</tr>
<tr>
<td>8.</td>
<td>Real-time compatibility</td>
<td>Real-time constraints for implementing a self-managed system</td>
</tr>
<tr>
<td>9.</td>
<td>Verification &amp; validation (V&amp;V)</td>
<td>Well-defined risk and change management strategies for V&amp;V activities throughout different life cycle stages</td>
</tr>
<tr>
<td>10.</td>
<td>Standardization</td>
<td>Compliance with existing standards related to safety, programming, distributed control and automation, etc.</td>
</tr>
<tr>
<td>11.</td>
<td>Tool-chain integration</td>
<td>Finding synergies between tools at different LoA, integrating discrete &amp; continuous times and events</td>
</tr>
<tr>
<td>12.</td>
<td>Information management</td>
<td>Multi-disciplinary information, completeness of knowledge models, common ontology, efficient information flow, etc.</td>
</tr>
<tr>
<td>13.</td>
<td>Traceability</td>
<td>Traceability of information, system design, testing, validation, etc. in all the life cycle phases</td>
</tr>
<tr>
<td>14.</td>
<td>Mobility</td>
<td>Particularly with reference to hardware flexibility</td>
</tr>
<tr>
<td>15.</td>
<td>Robustness</td>
<td>At different abstraction levels, e.g. system, device, control, etc.</td>
</tr>
</tbody>
</table>
3.3. Views And Their Relationship With Levels Of Abstraction

Depending on the level of abstraction, every viewpoint can be instantiated into one or more views, each corresponding to a different level of detail. The major possible views defined in this work are shown in Fig. 4. This work has inspirations from an automotive architecture description [12] as discussed earlier. Following is a brief description of each of the identified views:

- **Software view** provides a detailed representation of the software architecture of a system. The details about function blocks, software components, source code descriptions, etc. are often provided in the software view.

- **Hardware view** represents the mechanical, electrical and electronic characteristics of a system. It typically consists of sensors, actuators, manufacturing equipment, ECUs, communication interfaces, buses, etc.

- **Control view** covers the aspects related to the control system functionality.

- **Deployment view** covers the placement strategies and issues related to the deployment of software agents onto the physical controllers.

- **Use case view** represents the user interactions with the system.

- **Timing view** covers the timing related aspects of the system, including; message exchange delays, bus communication delays, response times, etc.

- **Network view** describes the connections between the system elements including the software and hardware topologies.

- **Information view** represents the information management strategies between different stakeholders and system elements. It covers the aspects related to the completeness of information and efficient communication flow in the system.

- **Allocation view** specifies the allocation of resources in the system as per the product requirements. Resource allocation algorithms and strategies are covered in this view.

Each of the view is further defined as having three basic aspects:

1. Function
2. Behavior
3. Structure

Each of the above views is governed by the modeling formalisms, tools and other conventions defined in the corresponding viewpoint. The basic relationship between the levels of abstraction and CPMS views inspired by the Y-model [11] is shown in Fig. 6.

3.4. Mapping of Viewpoints with Stakeholders and Concerns

The identified viewpoints are further mapped to the system stakeholders and concerns as shown in Fig. 5 in the form of a “viewpoint matrix” adapted from [13]. The concerns are plotted on the x-axis and the stakeholders are on the y-axis. The legend shows different viewpoints and their combinations represented by different colours, e.g., green, blue and orange colours represent the operational, functional and implementation viewpoints, respectively. Each stakeholder has several concerns in the system which can be framed by one or more viewpoints and are shown by the respective viewpoint colour for each x-y axis graph area. The mapping follows the correspondence rules defined in the ISO/IEC/IEEE 42010 standard [4], i.e., a concern can be framed by one or more viewpoints, whereas a viewpoint may also cover various concerns simultaneously.

For example, for an operator, all the concerns related to the system such as safety, robustness, traceability, autonomy, etc. comes under the operational viewpoint except the system performance which is related to functional viewpoint. Whereas, for a system integrator, the flexibility of the system is to be covered by all the three aspects, i.e., functional, operational and implementation. Similarly, cost may be a concern of implementation for an equipment provider, but comes under both functional and operational viewpoints for a customer.

4. Conclusion

Cyber-physical systems shall have a major role in manufacturing industry in shaping the factories of the future during the 4th industrial revolution. The increase in ICT dependency, connectivity and digitalization emphasizes the need for developing manufacturing systems on a standard architecture accepted by the industrial sector. The standard architecture shall be able to cover not only the technical viewpoints but should also incorporate other important factors such as business models, operational planning, knowledge management, tool-chain integration, etc. RAMI 4.0 [16], the reference architecture for Industry 4.0 is one of such approaches being developed by active collaboration between industrial and academic stakeholders.

The work presented in this paper provides a basis for developing the architecture framework and methodology for a holistic system development for CPMS. The viewpoints and views defined in this work are based on the stakeholders and their concerns relevant to the shop-floor level, i.e., the narrow System of interest (SOI) as shown in table [1,5,6]. This implies that the stakeholders related to the wider SOI, e.g., supply chain, operations management, planning, business model considerations, etc. are not in the scope of this work.

The inclusion of stakeholders from the wider SOI will further broaden the scope of this work and will contribute to the
addition of further viewpoints into the architecture framework. Another prospect for the future work includes finding synergies between manufacturing and other domains working with CPS, such as automotive industry. This can be further utilized in architectural descriptions for CPMS and incorporating them with the existing reference architectures, e.g. RAMI 4.0.

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