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Multi-paradigm modelling of Cyber-Physical Systems

Dmitry Morozov, Mario Lezoche, Hervé Panetto

Research Centre for Automatic Control of Nancy (CRAN), CNRS,
Université de Lorraine, UMR 7039, Boulevard des Aiguillettes
B.P.70239, 54506 Vandoeuvre-lès-Nancy, France.
e-mail: {dmitrii.morozov, mario.lezoche, herve.panetto}@univ-lorraine.fr

Abstract: Cyber-Physical Systems (CPS) lead to the 4-th Industrial Revolution (Industry 4.0) that will have benefits from high flexibility of production, easy and so more accessible participation of all involved parties of business processes. The Industry 4.0 production paradigm is characterized by autonomous behaviour and intercommunicating properties of its production elements across all levels of manufacturing processes so one of the key concept in this domain will be the semantic interoperability of systems. This goal can benefit from formal methods well known in various scientific domains such as artificial intelligence, and machine learning. So, the current research concerns the adaptation of the approach named Formal Concept Analysis (FCA) for structuring knowledge and for optimizing CPS interoperability.

Keywords: Formal Concept Analysis, Modelling, Cyber Physical System, Semantic Interoperability, Interoperability optimization, Industry 4.0, Meta Model representation.

1 INTRODUCTION

The CPS (Cyber-Physical System) is the term that describes a broad range of network connected, multi-disciplinary, physically-aware engineered systems that integrate embedded computing (cyber-) and technologies into the physical world (adapted from [1]). Inside this kind of network, each smart component (a sub-system of the CPS) is with sensing, data collection, transmission and actuation capabilities, and vast endpoints in the cloud, gathering and providing large amounts of heterogeneous data.

The CPSs will lead to the 4-th Industrial Revolution (Industry 4.0) that will have benefits from high flexibility of production, easy and so more accessible participation of all involved parties of business processes. Actually, the Industry 4.0 paradigm is characterized by autonomous behaviour and intercommunicating properties of its production elements across all levels of manufacturing processes.

In this regard the following research directions, related to the CPS and the Industry 4.0 paradigm, take an important place: optimization of sensor networks organization, handling big datasets, challenges about the information representation and processing. These research domains can benefit from scientific methods well known in the artificial intelligence domain, and machine learning. Basing our efforts on this motivation we are currently investigating application of a promising approach named Formal Concept Analysis (FCA) for modelling and thus analysing a large scale set of collaborative CPS.

The research addressed in this paper is related to the study of FCA-based patterns for optimizing CPS interoperability in the Industry 4.0. The cooperative manufacturing systems involve

large number of Information Systems distributed over large, complex networked architecture in relation to physical machines. Such cooperative enterprise information systems (CEIS) have access to a large amount of information and have to interoperate between them and with the machines to achieve their purpose. CEIS architects and developers have to face a hard problem: interoperability at a large scale. There is a growing demand for integrating such systems tightly with organizational and manufacturing work so that these information systems can be fully, directly and immediately exploited by the intra and inter-enterprise processes [2].

Interoperability can be defined as the ability for two or more systems to share, to understand and to consume information [22]. Some work [23] in the INTEROP NoE project has identified three different levels of barriers for interoperability: technical, conceptual and organisational. Organisational barriers are still an important issue but out of scope of this paper. The technological barriers are strongly studied by researchers in computer science and the solution is generally based on model transformation [24].

Our, past and actual, research [25] focuses on the conceptual level of interoperability that is the ability to understand the exchanged information. A concept is a cognition unit of meaning [26], an abstract idea, a mental symbol. It is created through the action of conceptualisation, that is, a general and abstract mental representation of an object. During the history of human effort to model knowledge, different conceptualisation approaches regarding different application domains were developed [27].

When trying to assess the understanding of an expression coming from a system to another system, there are several possible levels of interoperability [28]:

- encoding: being able to segment the representation in characters;
- lexical: being able to segment the representation in words (or symbols);
- syntactic: being able to structure the representation in structured sentences (or formulas or assertions);
- semantic: being able to construct the propositional meaning of the representation;
- semiotic: being able to construct the pragmatic meaning of the representation (or its meaning in context).

This structure is coherent, each level cannot be achieved if the previous levels have not been completed [28]. The encoding, lexical and syntactic levels are the most effective solutions for removing technical barriers for interoperability, but not sufficient, to achieve a practical interoperability between computerized systems. Dealing with trying to enable a seamless data and model exchange at the semantic level is still a big issue that needs conceptual representation of the intended exchanged information and the definition of the pragmatic meaning of that exchanged information in the context of the source and destination applications.

The main prerequisite for achieving the interoperability of information systems (and thus a set of collaborative CPSs, noted by the authors) is to maximize the amount of semantics that can be used and to enact it by making it increasingly explicit [3]. There are different approaches in conceptual modelling and these differences are reflected in the conceptual languages used for the modelling action. Entity-Relationship approaches (E-R) have been widely used and extended. They led to the development of different languages for data modelling [4,5,6]

Object-Oriented Modelling (OOM) [7] approach addresses the complexity of a problem domain by considering the problem as a set of related, interacting Objects. However, the abstract semantics inherent to these approaches imposes the modeller to make subjective choices between entities, attributes and relationships artefacts for modelling a universe-of-discourse [8]. In order to cope with such heterogeneous modelling patterns, we focus our interest on approaches that enable their normalization to a fine-grained semantic model by fragmenting the represented knowledge into atoms called formal concepts.

1.1 Cooperative Enterprise Information Systems

Information Systems are systems whose activities are devoted to capture and to store data, to process them and produce knowledge, used by any stakeholders within an enterprise or among different networked enterprises. It is commonly agreed that Cooperative Information Systems provide a backbone for the Integrated Information Infrastructure [29].

Although the progress made in information technology considerably improved the efficiency of applications development, its drawbacks and limitations are obvious and serious. The components technologies are heterogeneous, platform- and machine-dependent. The above-mentioned

limitations and barriers measurably hinder the development and the maintenance process.

There is a growing demand to integrate such systems tightly with organizational work so that these information systems can be directly and immediately used by the business activity.

Here, the need of interoperation clearly appears. In fact, to achieve the purpose of the cooperation between the different Information Systems, information must be physically exchanged (technical interoperability), must be understood (conceptual interoperability) and must be used for the purpose that they have been produced (conceptual and organizational interoperability).

Classifying interoperability problems [30] and [31] may help in understanding the degree of development needed to solve, at least partially, these problems but conceptualization and semantics extraction is still an important issue because of the various contextual understanding of tacit knowledge embedded into those applications. The main prerequisite for achievement of interoperability of information systems is to maximize the amount of semantics which can be used and make it increasingly explicit [31], and consequently, to make the systems semantically interoperable.

2 A META-MODEL OF A CYBER-PHYSICAL SYSTEM

Components of a CPS: lets denote as P_i and C_i respectively the set of physical and cyber components of a system CPS_j . CPS_j is a structural agglomerate of these elements P_i and C_i which can also include other subsystems CPS_k into a composite cyber-physical system.

2.1 Towards a meta-model for CPSs

There are two relations of different nature between these components:

- R^P - the relation between subsystems to be physically connected (e.g. in a production line) and signifies transmission of any kind of physical object between systems.
- R^C - the relation of the connection between cyber components which signifies presence of an information/control channel between the components..

The components of a system perform certain functions depending on their role in the system, and according to that they have input I_i and output O_i , that capture the flows between this element and the elements that it is related to by R^P and R^C . As an example, for a sensor, input and output reflects transformation of mechanical or physical alterations of the physical world into quantitative measurements of a particular property. The source and destination of the exchange can be either other components of the system or the environment or some external source. To cover the latter case, we introduce into the sets of all physical and all cyber elements of CPSs model two elements e_p and e_c to stand for these environmental or external sources or destinations.

We define a system of CPSs as a tuple $CPSs = \langle \mathcal{P}, \mathcal{C}, \mathcal{CPS}, R^P, R^C \rangle$, where $\mathcal{P} = e_p \cup \cup_i P_i$ is a set uniting physical components of individual CPS, $\mathcal{C} = e_c \cup \cup_i C_i$ is a set of cyber components, and \mathcal{CPS} which is set of CPSs. Each individual CPS of the set \mathcal{CPS} , as was defined before, is a tuple of subset of cyber components, physical components and other CPS that it consolidates. Here we assume that every element of \mathcal{P}, \mathcal{C} , and \mathcal{CPS} has its corresponding input I_i and output O_i . The details of exchange do not have special interest for our research in this paper, in general I_i and O_i can be of any type and have any values.

Compositionally, different CPSs $c_1, c_2 \in \mathcal{CPS}$ could share some of their components: $c_1 \cap c_2 \neq \emptyset$. For example, as in systems utilizing the same computational node to supervise physical production activities, or as an actuator such as light switch which can be considered as a part of two systems: one is local electrical circuit of an apartment, and the other is a smart-home system for automating and controlling the household electronics. Following figure is an example of two simple CPSs consisting of one physical and one cyber component each forming a composite CPS. Where the communication between CPS_1 and CPS_2 is done through the C_1 and C_2 ; and the composite CPS_3 has its own actuator components P_3 and C_3 .

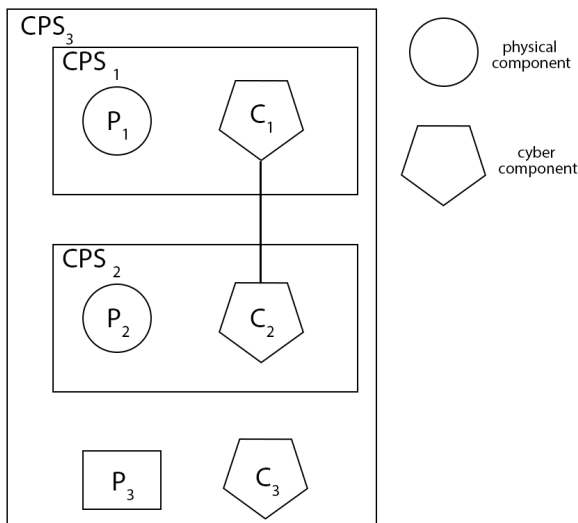


Figure 1, Composite CPS₃ consisting of two subordinate systems CPS₁ and CPS₂, and providing its proper functionality through components P₃ and C₃

2.2 Extending

The proposed meta-model $CPSs = \langle \mathcal{P}, \mathcal{C}, \mathcal{CPS}, R^P, R^C \rangle$ that we have elaborated is presented in UML notation on Fig. 2. Our formal meta-model concretizes broad definition of cyber-physical systems, taking into accounts key properties that these systems are envisaged to have.

Accordingly, each atomic CPS is given a single physical component, which models its mechanical behaviour, and a single cyber component, which naturally stands for the

computational functionality. This representation, on the UML diagram, is represented by the relationship 'form a single CPS' between the classes 'Cyber Component' and 'Physical Component' with multiplicity 1 to 1. An atomic CPS is the one that does not have any subsystems, but his own functional elements. This definition is created to show, with the best detail possible, the relationships between the two different parts of the entire CPS system. It stops at the presented "atomic" level because of the scope of this scientific paper that focuses on the relationships of the CPSs and the possibility to improve their interoperability.

As stated in the meta-model the 'Cyber Component' and 'Physical Component' classes are subclasses of the general class 'CPS Component', which models the common properties of these classes. Each of them can communicate with any other component and be the object of a communication, this is accomplished through their Input and Output interfaces. We also note that we do not make difference between physical and cyber types of communication and corresponding types of input and output interfaces, although it could be a worthwhile extension for a future model.

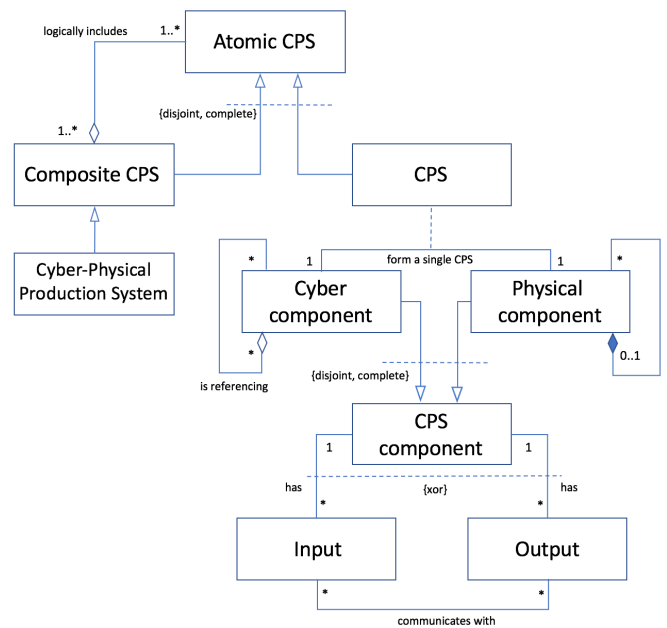


Figure 2 Meta-model of CPS

The relation 'is part of' (physically) is introduced into the model to represent physical structure of systems and their inclusion into one another on the physical level. As an extension to this type of composition of complex CPS we also introduce the aggregation relation 'logically includes'. Together with inheritance relation between classes Composite CPS and Atomic CPS it complies to the structural Composite pattern. With help of this aggregation relation, we model the property of CPS of dynamical reconfiguration and adaptation. Any system can lend its functionality to many super-systems (we borrow the utilisation of sub- and super- prefixes from mathematics, by analogy with subsets and supersets), although probably not at the same time. Inversely, any system can accommodate multiple subsystems. The class of Cyber-

Physical Production Systems can be viewed in the proposed model as a subclass of Composite CPS.

There is tight connection between these two relations ‘*is physically part of*’ and ‘*logically includes*’, in the sense that whenever a system is in the relation ‘*is physically part of*’ this also entails that it is being ‘*logically included*’ in that system, but not in the other direction.

2.3 Hierarchical structures of the meta-model and corresponding algebraic lattice representation

Unlike our previous approach [18] where we modelled CPS using Formal Concept Analysis in a standard object-attribute fashion, currently we extend modelling approach to also account for links that exist between components and also for hierarchical inclusion of systems one into another according to their composite structure.

In this way CPSs can be modelled independently in the physical and cyber perspectives using corresponding relations, each one defining an algebraic lattice. The hierarchical structure gives rise to the third lattice that can be used for tacit knowledge recognition and further explicitation. The relations between the two Lattices are related to the context. The merging of the two Lattices is computationally expensive.

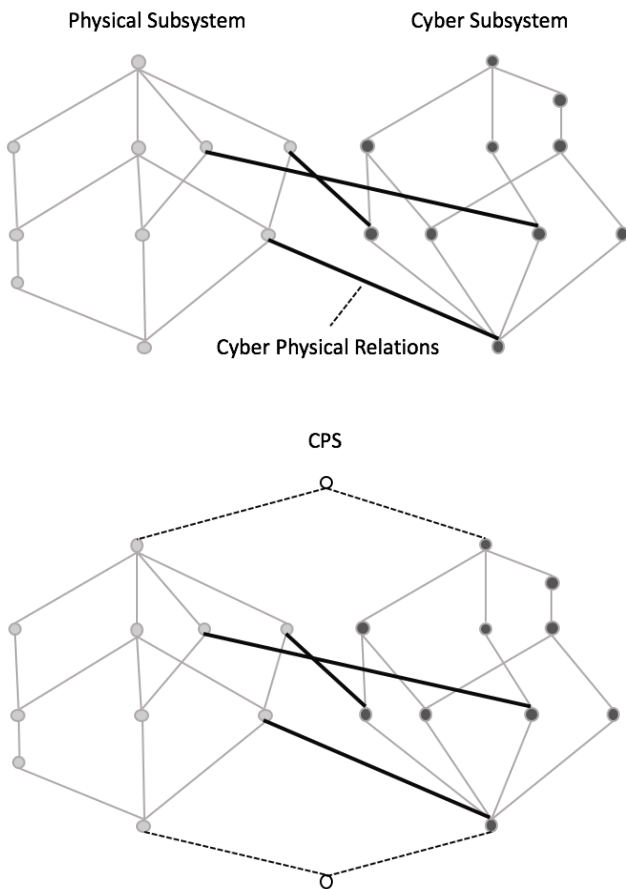


Figure 3 CPS Functional Model Decomposition and Relations discovery and representation.

3 CASE STUDY

In our case-study we show how our meta-model can be applied to an example CPS to obtain a compact model, which then can be used for further analysis.

3.1 Painting and varnishing of a car — process model

Let us consider an abstract process of painting a car (see Fig. 4), that can take place, for example, as a step of auto-mobile industrial production or as a part of vehicle post-reparation process.

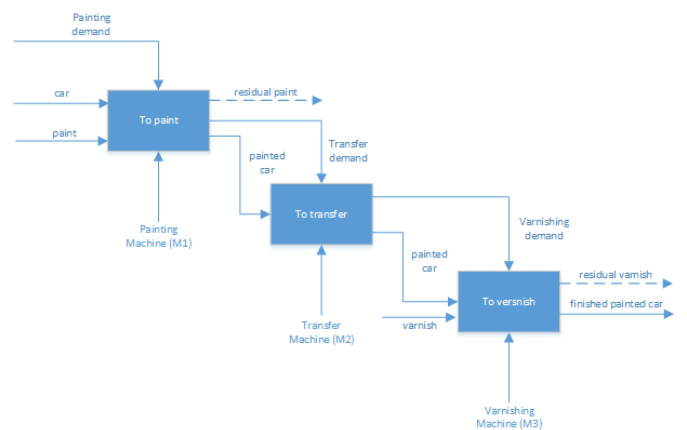


Figure 4 Painting of a car — Business Process Model

There are two main actions constituting the process: to paint and to varnish. Both of these actions are performed by specialized equipment, we call them Painting Machine M1 and Varnishing Machine M3. Another action concerns transporting the object between two machines and is performed by Transfer Machine M2. In the real world, the production which instantiates this abstract model may use all types of appliances implementing these functions.

As a simplest version of this scenario one can think of a personal use painting and varnishing machines, where the transportation of the painted object is not needed, and thus a garage can be used to stand for Transfer Machine M2, which does nothing but keeps a car in the same place. As an example of more complex realisations of the model one could envision a sophisticated Cyber-Physical Production System (CPPS) in a real plant, where the benefit of production optimization is proportional to the scale of the production.

As a physical input for painting and varnishing process the CPS is supplied from outside an object (a car) and consumables such as paint and varnish. From cyber perspective, information signals — painting demand, transfer demand and varnishing demand — initiate corresponding stages of the process.

Lastly, the machines have their outputs that transfer physical objects — the car or residuals of the process, or issue a signal to launch the next step.

3.2 Graphical notation for modelling CPSs

Let us introduce graphical notation for the proposed meta-model (see Fig. 5). An instance of the class CPS is denoted as a two-coloured ellipse, with the dark half standing for the physical component, and light-coloured half standing for the cyber component. Accordingly, the relation ‘*form a single CPS*’ is represented by union of halves of ellipses into a whole ellipse. The property of the two classes to be disjoint and complete is manifested by absence of a fully coloured ellipses (entirely dark or entirely light) in the model notation. The exchange with external environment is modelled with help of the environment $\mathcal{E} = \langle e_p; e_c \rangle$ which is coloured in green, in contrast to blue for ordinary CPS.

The output and input classes of components are not represented in the notation, because their impact can be completely deduced from the relations ‘*communicates with*’, that they realize. The relation ‘*communicates with*’ takes place between components of CPSs in one of the two dimensions: physical or cyber. The relation ‘*communicates with*’ in the physical dimension is represented as a line connecting two dark-halves of ellipses and in cyber dimension as a line connecting two light-halves of ellipses.

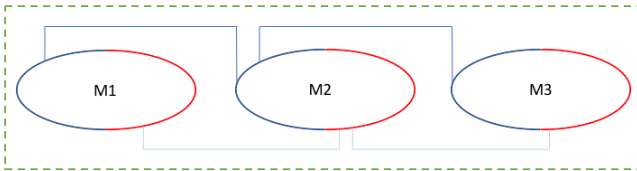


Figure 5 Graphical notation

The relation ‘*is part of*’ between an atomic CPS and a composite CPS (more precisely between their physical counterparts) is represented as an inclusion of ellipses into a rectangle with a dashed perimeter. Specifically, a CPS is a part of a composite CPS if it is depicted inside of a rectangle. The relation ‘*is part of*’ of two composite CPSs is similarly represented as inclusion of corresponding rectangles.

Finally, the relations ‘*is referencing*’ and ‘*logically includes*’ are omitted in the graphical notation to not clutter the model. Nevertheless, in the mathematical model introduced later in the text, the relations are present.

Certain properties of CPS can be directly deduced from this notation. For example, based on type of connection with other CPSs one can try to classify CPSs. For example, a CPS that does not have any physical input and output, and communicates only in cyber dimension is definitely can be considered as a computational node. In addition, a CPS receiving only physical input and providing only a cyber output can be claimed a sensor. Or an actuator is a CPS that does have only physical output but no cyber outputs.

4 ASSISTING MODELLING PROCESS OF CYBER-PHYSICAL SYSTEMS

Guided by the perspective proposed in the literature [10] we define our generalized model of CPS as a system of components that can be unambiguously divided into two groups: a control decision and sensor part, that will represent cyber layer of the system, and to a physical counterpart, i.e. all actuators that communicate all the actions into real world. This explicit division between two abstract cyber and physical parts of a system in some sense imposes a limitation on the

modelling approach. Nevertheless, as a guiding tool in design process its application does not lead to any restrictions on how the system will be later specified or implemented.

In our modelling approach, we understand the division onto physical and cyber layers as a separation between the functional roles of the system components. We consider physical nodes as terminal execution nodes which materialize the behaviour of the system. In contrast sensor and computation nodes from the cyber layer provide data and decisions. The special cases where a cyber-node itself realizes tail end functions can be deduced to the above case by dividing its modelling element into two elements: a physical one which takes over these tail end duties and the cyber one which serves for computations.

Our research sets the goal to investigate combinatorial and statistical properties of concept lattices, in particular those properties which express and reflect the interoperability of systems. Although current paper does not go beyond basic FCA analysis, it proposes an illustrative case study of its application to CPS.

Understanding of a system is a gradual and iterative process, involving many levels of abstractions of the system, varying from a general outlook to focalization on details of specific subsystems. In FCA toolset, which is built around a complete lattice, this issue is naturally addressed by arising structure of classes which covers all levels of generalization. Readily available lattice diagram helps in visual navigation, implication base outlines the axiomatic of the domain.

Another important subject in the context of CPSs concerns dealing with big scale systems, and situations when a lot of data being produced. Literature on FCA suggests number of techniques addressing this issue: iceberg concept lattices [11], projections of pattern structures [12], and conventionally used feature selection methods.

5 CONCLUSIONS

Two results are achieved in this scientific work. The first one is the presentation of a CPS meta model and its graphical notation that represents a first step towards the knowledge formalisation needed to structure the use of formal tools, and the second is the FCA adaptation to this domain.

Formal Concept Analysis have been applied in many domains as a knowledge representation and discovery tool. Current paper takes a step into adaptation of the approach and its evaluation for the needs of Cyber-physical systems modelling and analysis. We have demonstrated employment of the basics of FCA on a simple example, and outlined the major interest in its application in the interoperability context.

It is worthwhile to note the distinction of modelling control-flow of a system with FCA. Taking into account that FCA is a bottom-up approach in the sense that it starts with particularities of the domain and builds upon them a structure to allow to capture general dependencies. Traditional graphs-based formalisms (such as Petri-nets for Process modelling or Feature model in Software development) on the other hand are conceived specifically for modelling and appear to be more expressive. The research studying relation between FCA and graph modelling methods [17], [18] indicates necessity of utilization of additional filtering after lattice is constructed.

This basically signifies doubling of the cost of construction of the model.

Further research will aim at answering questions: How relationships between concepts of a lattice can be interpreted in terms of interoperability of the corresponding parts of the system. How can one benefit from establishing links between concepts of the lattices of two or more collaborating cyber-physical systems in terms of improving their interoperability? As further development of the approach we plan to study utilisation of the resulting lattice-models to answer the proponent questions of Industry 4.0 such as identification of redundancies in functionality or data-storage and improvement of flexibility of systems and self-adaptation.

In the future work, we will focus on interpretation of the models, through some extra knowledge derived from formal (example Ontologies) or informal (expert experiences) knowledge, and definition of correspondences between lattices that could be used for improvement of interoperability between the systems.

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