The Two-Hemisphere Modelling Approach to the Composition of Cyber-Physical Systems

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Abstract: The Two-hemisphere model-driven (2HMD) approach assumes modelling and use of procedural and conceptual knowledge on an equal and related basis. This differentiates 2HMD approach from pure procedural, pure conceptual, and object oriented approaches. The approach may be applied in the context of modelling of a particular business domain as well as in the context of modelling the knowledge about the domain. Cyber-physical systems are heterogeneous systems, which require multi-disciplinary approach to their modelling. Modelling of cyber-physical systems by 2HMD approach gives an opportunity to transparently compose and analyse system components to be provided and components actually provided, and, thus, to identify and fill the gaps between desirable and actual system content.

1 INTRODUCTION

Cyber-Physical Systems (CPS) have never been more central to the corporate strategy today. The features they offer, reliability, performance and robustness are the queens qualities that allow companies to be competitive. To cope with the complexity of the execution of such heterogeneous systems, it is necessary to define an approach to tame its complexity. This approach should be flexible and generic in order to adapt to any type of component of such system and thus, should offer an ability to manage system composition.

The two-hemisphere model driven (2HMD) approach has been successfully applied for domain modelling and software design (Nikiforova and Kirikova, 2004). One of the most distinguished features of this model is its applicability for both human understanding and automatic transformation. In this paper we illustrate the way how 2HMD approach may be applied to the task of modelling and composition of CPS.

The goal of the paper is to show the way how the problem of complex system composition from smaller parts can be solved by using 2HMD approach for modelling of CPS components. From the point of view of 2HMD approach, each component of a CPS may be considered as a conceptual class, which preforms the particular operations and meet the defined requirements. The requirements are derived from the model that consists of functional and conceptual "hemispheres".

Thus 2HMD approach is applicable for both modelling of components and modelling of the process of to be supported by that component at the same level of abstraction. Moreover, the 2HMD approach can help to identify conflict situations, where the additional analysis is required for sharing responsibilities between system components.

Features of Cyber Physical Systems and the necessity to model and compose them are discussed

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in Section 2. The essence of the two-hemisphere model driven approach is clarified in Section 3. Application of 2HMD approach for composition and modelling of components of CPS are outlined in Section 4. Conclusions are given in Section 5.

2 CYBER-PHYSICAL SYSTEMS IN THE CONTEXT OF SYSTEM COMPOSITION

A cyber-physical system (CPS) is a mechanism controlled or monitored by computer-based algorithms. In CPS, physical and software components are deeply intertwined, each operating on different spatial and temporal scales, exhibiting multiple and distinct behavioural modalities, and interacting with each other in a myriad of ways that change with context (Khaitan, et al., 2014).

Being CPS inherently complex, any significant analysis is a challenge. The behaviour results from the different scales of the effect of the emerging or fundamental phenomena, the different nature of the components, the interactions and the drawbacks of the internal compositions. A comparable domain is System of systems (SoS), in which analysis exploits decomposition (or, equivalently, design exploits composition), and the system additionally exhibits emerging behaviours or features that have to be modelled at a higher level. While both for CPS or SOS an holistic approach is viable for a general understanding of the system from the point of view of an external observer, in order to design or assess in detail its behaviours the heterogeneity of the problems that have to be analysed require that every aspect and every component, and every scale and every hierarchical subsystem, need a proper model and a proper modelling technique. This is also a natural consequence of the wide set of expertise that has to be involved in the design, the maintenance and the management of a CPS: every professional takes care of a different aspect of a subsystem, using a specialized view on it that privileges his responsibilities and the modus operandi typical of his field. Building up a comprehensive model of the system could then benefit from the application of an approach that allows model composition and use of different modelling approaches together in a coordinated framework, such as multiformalism (Gribaudo and Iacono, 2014) or multiparadigm (Vangheluwe, Lara and Mosterman, 2002) modelling. For what is related to the design and the analysis of non-functional specifications of system components, some frameworks exist that allow multiformalism modelling for non-functional specifications by providing, by means of metamodeling, the ability of designing new modelling languages that can be naturally integrated with existing ones and support modularity and multiformalism: e.g., the SIMTHESys approach (Barbierato, Gribaudo and Iacono, 2011) explores these possibilities and is being extended to include also support for a domain, hybrid systems (Barbierato, Gribaudo and Iacono, 2016), that includes CPS. The main directions behind this approach aim to decouple whenever possible the state spaces of the various components (with significant results in favourable cases (Barbierato, et al., 2013)), build natural interactions between models written in different modelling languages, and representing emerging properties of the overall model. Leveraging this experience, it is possible to abstract the main ideas and take inspiration for implementing ideally similar compositional and modular features in modelling approaches that focus on aspects that are different from non-functional specification. In this paper we want to discuss the applicability of some of the concepts here presented about non-functional specifications to a more abstract modelling domain, specially focusing of the perspective that allows the application of the 2HMD approach. CPS involves transdisciplinary approaches, merging theory of cybernetics, mechatronics, design and process science (Hancu, et al., 2007), (Lee and Seshia, 2011), (Suh, Carbone and Eroglu, 2014). The process control is often referred to as embedded systems. In embedded systems the emphasis tends to be more on the computational elements, and less on an intense link between the computational and physical elements. CPS is also similar to the Internet of Things (IoT) domain, sharing the same basic architecture; nevertheless, CPS presents a higher combination and coordination between physical and computational elements (Rad, et al., 2015). As far as CPS are multidisciplinary heterogeneous systems, their implementation requires a strategy for modelling and decomposition into smaller components. The components of such systems then should be detailed at the same level of abstraction.

One of those systems is Ensemble Component-Based Systems (Bureš, et al., 2013), (Keznikl, et al., 2012), where components are autonomous and the communication is implicit. Needless to say that emergent systems as an up-and-coming systems introduce new concepts for design (Bureš, et al., 2013), (Hennicker and Klarl, 2014) as well as for whole system development process (Carloni, et al., 2005). Working with such distributed systems require dynamicity and scalability with reserving to the autonomous behaviour in each component. This allows designers to have their focus on individual components and to work on developing each of the following separately: 1) the component structure and behaviour, 2) the implicit connector called ensemble, and 3) the link between computational and physical elements for each individual alone.

ECBSs are dynamic systems, which require composition and decomposition of its components and ensembles depending on the context. These systems offer a combination of both architectural and behavioural models to represent such decomposition in their structure, providing by that the ability to analyse and verify satisfaction of their requirements. Moreover, the methodology in this modelling approach considers each component in the system as a black box. More specifically, each component features a set of roles where each one serves as an interface in the communication. Each role consists of a set of data fields called knowledge and mode-switch table (Bureš, et al., 2016). In the knowledge section, an enumeration of component modes is presented as a data field. Hence, the behaviour of the component is held in the mode-switch table that has all the context constraints and their corresponding modes.

It is worth mentioning that each mode is associated to a set of processes in the component that is executed when the mode is active. Furthermore, the component has sub-components that are captured in the structure as data fields. By setting this data field, it is possible to build a hierarchical component (i.e. the data field could hold a null value). Although the structure of the components represents (de)composition structure, it does not capture the (de)composition process; it is only describing the flow of activities in an autonomic component of the system using mode-switch table for each role that the component features. Simply put, the role activity diagram will have the knowledge on the transitions and the modes as activities. Therefore, a mode-switch table in the architecture is a representation of the behaviour of the component role. Regarding the (de)composition process, ensembles are responsible for it, since they form between the components that have specific modes and exchange the knowledge between them. The ensembles have three basic structures: 1) the roles and their current modes of the components, 2) the context as a membership condition, and 3) the knowledge exchange. Hence, the ensemble behaviour is held in the knowledge exchange part, which is guarded by corresponding constraints (i.e. roles or mode in the roles, and membership condition). Ultimately, ensembles have a hierarchical structure due to hierarchical structure of their components (Bureš, et al., 2015).

Finally, in those terms, (Al Ali, et al., 2014) and (Bureš, et al., 2016) introduce approaches to capture the internal and external uncertainty in the system, and to handle it during the adaptation process by linking the physical elements in the same abstraction level as computational ones. In (Al Ali, et al., 2014), this is applied to Ordinary Differential Equations (ODE) for physical objects at the process level. The goal is to capture the impact of delays, which are caused by networks or computational parts, on physical elements (i.e. actuators). The method enhances the prediction of the real state boundaries of each physical object.

About the same problem, (Bureš, et al., 2016) targets the uncertainty caused by sensor readings, where the precision of sensed data is the main concern. The effect of data precision is represented in a self-adaptation process, where the authors extend mode-switch logic to involve statistical testing. The extended logic applies hypothesis testing over historical data to evaluate the condition in mode-switching with a certain confidence level. It is worth mentioning that mode-switch conditions deal with short time prediction as well as the current situation. At the end, both kinds of uncertainty are captured explicitly in the architectural view, making it possible to apply traditional analysis and transformations with a minimum amount of modification on the existing tools. Similarly, we can discuss the issue of composition in the context of multiagent systems. Sometimes, the complex interactions between the individual agents give rise to an emergent behaviour of the system as a whole, e.g. in modelling social systems, traffic simulations etc. However, other applications can benefit from system composition, e.g. agent-based business process modelling. A tool that is often used in this situation is the visual notation of Role-Activity Diagrams (Ould, 2005). They contain roles, which describe the behaviour of a set of role instances. Roles have states, similarly to dynamic systems. A business process may contain one or more active instances of the same role. An actor is an agent that enacts a role instance. Activities are the basic building blocks of a role. Carrying out the activities of a role can be interpreted as transferring the process control from a state to another state. An activity may be carried out in isolation or may require coordination with activities in other roles, and in this case it is an interaction. Some studies showed that this class of workflows can be formalized and modelled by a concise set of distinct rules in a generic knowledge-based business agent architecture (Badica, et al., 2016) and can be implemented using both agent-oriented languages, such as Jason, and general-purpose functional languages, such as F# (Leon and Badica, 2016).

3 TWO-HEMISPHERE MODEL-DRIVEN APPROACH

The variety of modelling capabilities and the ability to express links traceability are decisive assets to manage system's complexity. The transformation tool takes one model as input and produces a second model as its output. The two hemisphere model driven approach (Nikiforova and Kirikova, 2004) proposes the use of business process and concept modelling to represent systems in a platform independent manner and describes how to transform them models into UML models, shown in Figure 1. The choice and design of these diagrams is not only based on the previously mentioned analogy with the human brain, but also due to the fact that information shown in these diagrams helps to describe the system from the two different points of view that we believe to be able to capture the most relevant aspects in system development. Business process modelling, as (Polak, 2013) mentioned, developed as a result of solutions made by Management Science and Computer Science in the 1970s, and keeps showing its importance in supporting process modelling and analysis. The importance of business process modelling is confirmed by (Harmon and Wolf, 2014) regular researches about the usefulness and usability of these processes. Results confirm that management of business processes is valuable for companies and that firms progressively adopt existing business process modelling notations and methodologies.

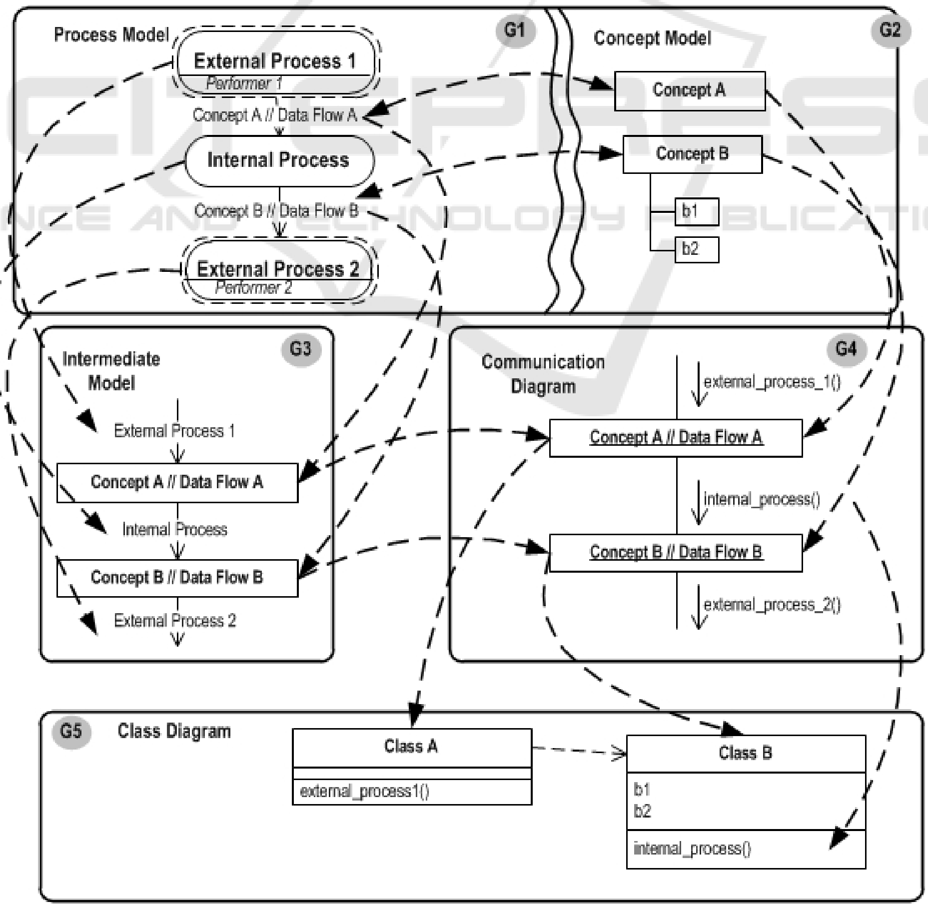

Figure 1: The essence of the two-hemisphere model transformation.

Consequently, the two-hemisphere model benefits from the incorporation of well-known business process tools and lowers, at the same time, the gap between existing and needed internal knowledge and procedures. As the two-hemisphere model serves as a bridge between problem domain and software design phase, business model is understandable to both sides - business people and developers. The inclusion of a conceptual model in the approach is motivated by the principles of the object-oriented paradigm and general context of data analysis. In many widely accepted software design approaches, in the first phases of the development cycle a data dictionary is created or an analogous document defines a shared agreement about terminology used in software development and documentation. (Johnason and Henderson, 2011) describes conceptual modelling as the basis of software development, absolutely needed to produce a quality design. Conceptual models are high-level software description, which contains concepts. Any kind of things, events and living beings that are important to given problem domain can be considered as concepts. Concepts are described with attributes, but methods shows actions specific to these concepts. An early and consolidate example of conceptual models is Peter Chen's (Chen, 1976) Entity-Relationship (ER) diagrams, used in database design (Hesse, 2007), and, later, in software system design. Consequently, a natural choice for the other part of the two-hemisphere model is a conceptual model, consisting of concepts and related attributes, with a model notation similar to ER diagrams.

4 THE TWO-HEMISPHERE MODEL-DRIVEN APPROACH FOR SOLVING COMPOSITION PROBLEMS

The strategy of the two-hemisphere model-driven approach supports gradual model transformation from problem domain models into program components, where problem domain models reflect two fundamental things: system functioning mechanisms (processes) and structure (concepts and their relations). Several two-hemisphere models presenting different aspects of CPS and its components structure and behavior have been marked as input with mapping rules, the class diagram and transformation trace has been received on output (see Figure 2). Transformation trace shows how an element of the two hemisphere model is transformed into the corresponding element of the class diagram, and which parts of the mapping are used for transformation of every part of the two hemisphere model (Nikiforova, 2009).

The model decomposition into small components and composition of them as an integrated system is a new research topic for two-hemisphere model-driven approach, originally introduced in (El Marzouki, et al., 2016). The work is under ongoing development and evolution, consequently, there is still no mature foundation to date for this. Our goal through the research on the composition of CPS is to study existing models of composition approaches by analysing and identifying: 1) what are the elements involved in the composition process, and 2) how the model composition is made in these approaches.

The ultimate goal is to arrive at an understanding of what is done for model composition in these approaches. "Model composition is an operation that combines two or more models into a single one." (Cavallaro et al., 2010) "Model composition in its simplest form refers to the mechanism of combining two models into a new one." (Dubre and Dixit, 2012) According to this, it can be said that the composition model is a process that takes two or more input models, integrates them through an operation and composition to produce a composite output model. However, this scheme is very abstract. No assumptions about the input models, output, or on the compositing operation is expressed. In practice, each approach must specify these assumptions for its work context. These also include the differences to classify approaches:

- Mechanism of composition: melting, replacing the union, weaving etc.
- Element composition: what are the additional elements involved in the composition. There are two classification axes: the type and formality of these.
- Language of composition: The composition of elements need formalisms to express them.

These formalisms are very diverse because each approach has its own elements of composition. They can be a weaving language, a metamodel of composition rules, a UML profile for model composition, etc (Dubre and Dixit, 2012). Despite their diversity, they can usually assess a compositional formalism on two points: the composition that provides abstractions and scalability.

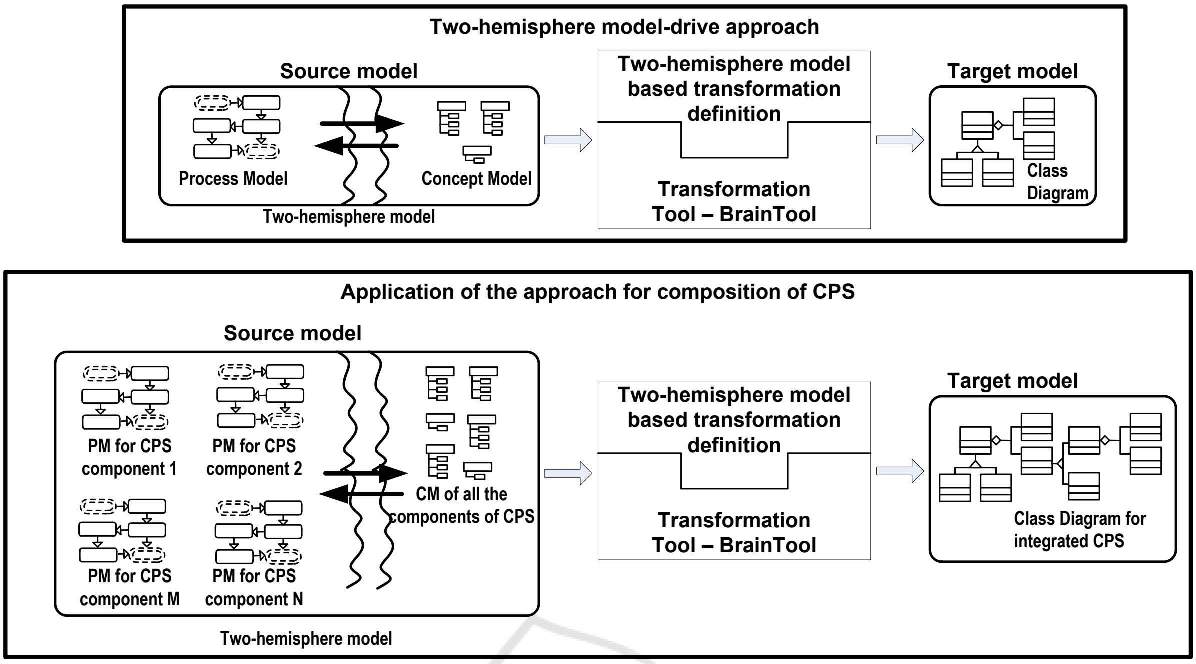

Figure 2: Adoption of the two-hemisphere model-driven approach to composition of CSP.

To synthesize, we can define the composition as a model management operation, which generates a single model by the combination of the contents of at least two models:

- Syntactic level: Expression model compound from input models;
- Semantics level: Assigning a semantic model compound, depending on the semantics of the associated source models;
- Methodical level: Using the model compound, derived from the composition process in a software development process.

Therefore, the composition process cannot be considered as an atomic operation. Before triggering the composition process itself, it is necessary to identify the links between the elements composing; hence the emergence of the pre-match phase followed by a composition operation that aims at the creation of the model "global" by combining elements using input patterns of relationships defined in the matching pattern.

So, considering all these all these criteria, it is clear that making a survey on composition techniques and identify their gaps seems an interesting path to build a new composition models operations based on two hemisphere model approach. In other words, we suggest using this taxonomy to create a novel composer framework to resolve composition conflicts for a given problem.

So now, we are also studying the made to take into account the semantic properties of models. If we take the example of two operations in two models that appear with the same signature (name, type, parameters), so to remedy this problem, we must either include a step of reconciliation between the separate designs or strengthen semantics associated with the input metamodel, so that we can implement finer comparison strategies that address the behaviours described by the methods.

5 CONCLUSIONS

The evolutionary nature of CPS aims at building cross-domain intelligence, in heterogeneous and dynamic contexts (Khaitan and McCalley, 2015) (Wu, Kao and Tseng, 2011). For this reason, CPS composition should focus on the interactions between the control logic and the physical systems, contemplating the possibility of limited information, e.g., stability, safety, performance, timeliness, etc.

CPS composition can be performed according to different criteria, from the CPS itself which is a schema of CPS as systems of systems (Nazari, Sonntag and Engell, 2015), to a hierarchy of components at the architectural level (Bhave, et al., 2011). The common feature among the different composition approaches is how they encapsulate the cyber and physical aspects through an infrastructure.

The latter should allow the integration of CPS concerns and, also provide support for the orchestration of a larger system architecture. In turn to manage the process of CPS integration the strategy of CPS components' composition became the important task for CPS modelling. The model composition is the central concept also in model driven architecture for maximizing return on investment, dealing with complexity and maintainability. This paper discusses abilities on adopting a new methodology presented in the form of a conceptual prototype to automatically compose models defined in terms of class diagrams in order to build a global view of the system under construction. We have presented the progress process on model composition based on the two hemisphere model driven approach introduced in (Nikiforova and Kirikova, 2004). The idea is focusing on model composition paradigm as a crucial activity. The composition of CPS is applied based on two-hemisphere model driven approach, which is an approach that aims to automate the process of class diagram development from correct and precise two-hemisphere model and enables knowledge representation in a form understandable for both business users and system analyst. As far as the two-hemisphere model-driven approach allow to share responsibilities among object classes and to define the relationships between them, we can consider that for CPS we can define: 1) the general schema of their components (the same as classes for object-oriented system), 2) how to share responsibilities between them, i.e., to define which processes will be performed by which components, and 3) structural relationships among CPS components (as well as dependencies) within the task of their implementation.

The central hypothesis of two-hemisphere model-driven approach is to apply many transformations for composition of the complex system from small parts, where each of them presented as the source model is defined in terms of a business process model, associated with a concept model, and the target model is defined in terms of class diagram, which is generated for the whole system. When the models are small enough and developed by a single or a couple of designers, they can be composed manually. However, in the case of cyber-physical system, the models are too large to be composed manually and it’s necessary to develop an automatic composition method to ensure that all the elements in the model are handled. In this paper we have only taken into account the conceptual part of our methodology, thereby the authors try at the moment to investigate the possibility to implement the proposed technique as an open source tool using ATL Language. The idea of conceptual composition prototype described in this paper currently can handle not only homogeneous models, those that share the same meta-model, it would be interesting to extend this approach to handle heterogeneous input models as well.

As a future work to what is presented in this paper we are currently investigating a finer-grained redefinition of every module of CPS separately, the first one will be a repository dedicated to the resolution of potential composition conflicts. This allows focusing on any type of conflicts that requires special treatment, thereby it will facilitate the generic implementation of the other modules.

Another line of future investigations concerns the model comprehension aspects of our model composition technique. The benefits for model comprehension address in particular the reverse process of building model hierarchies. We hope you find the information in this template useful in the preparation of your submission.

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