Thesis:

System-level feature-based modeling of cyber-physical systems

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SUMMARY

BACKGROUND

The research reported in this thesis book has opened a new door towards modeling intricate technical systems. It focused on system-level feature-based architecting and modeling of cyber-physical systems (CPSs) in the pre-embodiment phase of design. The challenges have been addressed ambitiously in the conducted research by providing the required underpinning theories, implementation methodologies, and processes, as well as a conceptual framework for the toolbox and a unique strategy of validation. In the theoretical realm, two remarkable theories have been developed. With regards to implementation, the main contribution is in development of the concept of warehousing, the procedures of knowledge engineering, and the new pre-embodiment design approach of CPSs. The developed framework was benchmarked against those of the available commercial and experimental system development tools.

The main challenge of our research with regards to development of a supporting tool for architecting/designing CPSs was to achieve and maintain a balance between a comprehensive system-level view and the consideration of the operational and architectural attributes and performance of the lower-level components. This issue is crucial in designing complex, integrated, and heterogeneous CPSs. According to our assumption, system-level consideration is unquestionably necessary for pre-embodiment design (conceptualization and configuration) of CPSs, while designing of the components can even be delegated to other experts. This also helps address the compositionality and composability of CPSs simultaneously.

RESEARCH DOMAIN AND ADDRESSED RESEARCH PROBLEM

The emergence of the concept of CPSs shifts the attention from component to system, from fraction to the whole, from efficiency to effectiveness, from means to goals, and from product to service. In this new paradigm, “design” implies system-level conceptualization, architecting, and configuration. In the future, a part of design will even be delegated to self-aware and self-adaptive CPSs for run-time execution. Presently, components are mostly considered as black boxes, and composability issues are the main challenges of the CPS designers. The discipline-oriented view had a dominant influence on developing conventional design and modeling tools. Consequently, the problem of system-level design of CPSs remained ill-solved - nevertheless it has been recognized and emphasized that system-level design needs a holistic and interdisciplinary view.

The available system design and modeling tools suffer from the lack of a parallel consideration of the innate details of components and the system as a whole, and ignore physicality of CPSs in

interaction with other systems and the embedding operational environments. Though widely used for designing CPSs, these modeling tools are mostly based on logical, analytical, and mathematical formulation. In order to model CPSs they typically apply some sorts of abstraction and simplification, which ignore a huge amount of attributes, constraints, and contracts. In fact, system designers are being pushed to formulate the relationship between components in an abstract level. Moreover, the available system-level modeling tools consider operations and architecture of a system as two separate aspects. Although this approach simplifies the inherent complexity of CPSs, ignoring mutual relations between architecture and operations is the side effect.

In our research, we assumed that by targeting three main characteristics of CPS, namely complexity, heterogeneity, and integrity, a novel tool would be able to sufficiently support CPS designers. However, the common solutions of applying excessive abstraction and simplification, and neglecting physicality of components should be avoided. Consequently, system-level feature-based modeling of CPSs was chosen as the focus of our research. The required high-level semantic is supported by strong ontological resources. The theoretical fundamentals, the conceptual framework and the computational methodological approach have all been elaborated. However, the development of the supporting ontology and fully-fledged implementation of the conceptual modeling toolbox were excluded in our research due to the time limitation.

OVERALL RESEARCH APPROACH

The research started with studying the state-of-the-art in the domain of CPS conceptualization and design supporting tools. The explorative studies in five domains resulted in obtaining sufficient insight about the knowledge gap and helped narrowing down the phenomenon to system-level feature-based modeling of CPSs. In the second research cycle, our investigations were centered on developing the required underpinning theories. As a result, based on integration and enhancement of several classic theories, the mereo-operandi theory (MOT) was proposed to underpin our ideas and logical argumentation. It provided the required theoretical framework for development of the system manifestation feature (SMF) theory in the third research cycle. The SMF theory was meant as a complementary to MOT and explained how it could be methodologically applied. The SMF theory specified foundational information structures required for creation of the building blocks (named as SMFs) for system modeling.

In the fourth research cycle, the required information structures, the methodology of implementation, the computational constructs, and the procedures of processing information have been created in order to move towards a computational implementation. Finally, the developed conceptual framework of our modeling toolbox was benchmarked against those of a number of leading commercial and experimental tools. The results revealed that there are gaps between the functionalities provided by the available modeling tools and the requirements of pre-embodiment design of CPSs. Moreover, it has been evidenced that the novelties introduced by the proposed SMFs-based modeling framework in properly and effectively addresses the identified challenges. It has also been revealed that the proposed conceptual framework provides a higher potential in supporting multi-disciplinary pre-embodiment design of CPSs, and can be the basis of a knowledge-intensive smart system design application of the future.

RESULTS AND NOVELTIES

The conceptual, computational, and methodological elements of our SMFs-based modeling framework are comprehensively discussed in the thesis book. The following text briefly mentions the novelties of the proposed modeling framework from both computational application and implementation perspectives:

N1 **Imposing strictly physical view:** The imposed physical view supports aggregation of all components (i.e. hardware, software and cyberware) without the need for applying abstraction. Subsequently, all parameters of lower level components directly determine and affect the features of the higher level components.

N2 **Enforced concurrent consideration of architecture and operation:** It results in a simultaneous creation of both architectural and operational models of a system in interaction. This is in contrast with most of the logically- and mathematically-based modeling tools, which put emphasis on the functional aspects of components.

N3 **Amalgamating of architectural and operational aspects:** All information sets that define relations among architectural and operational aspects are captured within SMFs. This results in a robust approach of modeling, in which the changes due to the operation of the components are directly reflected on their architectural attributes, and vice versa.

N4 **Using uniform information structures for heterogeneous components:** The knowledge frames and accordingly the database schema for accommodating pieces of information are the same for all types of constituents. Consequently, the relations among them are being uniformly processed, and the various constituents are differentiated semantically, not structurally.

N5 **Multi-level multi-granularity:** It offers the possibility of moving from coarse-grained to fine-grained elaboration in a system model, and vice versa. In the SMFs-based modeling framework, SMFs have the same information structure on all aggregation levels. Accordingly, containment and connectivity relations are captured likewise on all levels, without applying abstraction and simplification.

N6 **Multi-aspects coupling among SMFs:** Both containment and connectivity relations of SMFs are supported through interfaces of SMFs, neglecting types of components. Consequently, the integration is supported by several aspects of multiple coupling. The dynamic integrity is also captured through utilizing concept of spatiotemporal mereotopology.

N7 **Multi-stage model composition:** In the proposed framework, building blocks of system models are not created in one go. Generating genotypes, deriving phenotypes, instantiation of phenotypes, and model composition are the stages that an SMF should go through to eventually end up in a model. As a result the manual information input is minimized by selection and mostly excluded in the conceptual design phase.

N8 **Multi-purpose system-level features:** Trans-disciplinary fusion of knowledge, reasoning with higher level semantics, and harmonization of pre-embodiment design and computational methodologies are the multiple purposes that are fulfilled with SMFs.

N9 **Multiple application contexts:** SMFs as semantically rich and self-contained system-level building blocks support both system-level conceptualization and system-level engineering (analyzing and optimization). They can also be used as means of communication among experts. SMFs are reusable and modifiable modeling entities that are suitable for various design and engineering approaches.

N10 **Multi-component warehouses:** Warehouses of the SMF-based toolbox benefit from three interconnected components to support SMF creation and model composition. In this way, the tracks of model composition and modification can be captured.

N11 **Benefiting from active ontologies:** Semantic-richness of the SMF-based toolbox is supported by active ontologies. Continuous updating of the ontological records is seen however necessary due to emergence of new technologies, materials, attributes, protocols, and so forth. Although, effort-intensiveness of this task can be considered as a drawback, the usefulness of the results cannot be disregarded.

VALIDATION AND CONCLUSIONS

The theoretical results of our research have been validated through benchmarking against five commercial and academic modelling tools and languages. The aspects of comparison were chosen according to the characteristics of CPSs and the requirements of pre-embodiment design. Since the modeling framework introduced by this research is not fully implemented as a prototype toolbox, many of its functionalities could not be measured definitely. Consequently, it was compared with the characteristics of the frameworks of the available modeling tools, which were derived by a kind of reversed engineering. To reduce the uncertainty caused by the reasoning, we used literature study and relied on the opinion of CPS modeling experts who participated in our survey. The comparison of strengths and weaknesses of the modeling tools and the analyses of the findings of the conducted study approved the uniqueness of the proposed solution, as well as its sufficiency to support pre-embodiment design of CPSs.

The analysis of the findings of our research confirmed the expectable advantages of using system-level features in modeling complex systems. Putting together everything, our impression has been that though the research concerning system-level features is in general still in its infancy, a rapid and wholescale proliferation may be expected in the near future. Based on the findings, we propagate this scientific phenomenon and knowledge exploitation context as a novel topic for future scientific efforts. Though our research has introduced and elaborated on many merits of system-level feature-based modeling, it cannot be used, tested, and validated in practical application until a full-fledged implementation of the proposed modeling approach is available.

Publications

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