A Model-based Methodology for Tool Supported Design of Automated Systems

Zur Erlangung des akademischen Grades eines

Dr.-Ing.

von der Fakultät Bio- und Chemieingenieurwesen
der Technischen Universität Dortmund
genehmigte Dissertation

vorgelegt von

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aus

Gelsenkirchen

Tag der mündlichen Prüfung: 26.11.2014

1. Gutachter: Prof. Dr.-Ing. Sebastian Engell
2. Gutachter: Prof. Dr.-Ing. Alexander Fay

Dortmund 2014

Schriftenreihe des Lehrstuhls für
Systemdynamik und Prozessführung
herausgegeben von Prof. Dr.-Ing. Sebastian Engell

Band 2/2015

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A Model-based Methodology for Tool Supported Design of Automated Systems

D 290 (Diss. Technische Universität Dortmund)

Shaker Verlag
Aachen 2015

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Dortmund, Technische Univ., Diss., 2014

Printed in Germany.

ISBN 978-3-8440-3544-5
ISSN 1867-9498

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
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Foreword

Dear reader, before you start with the formal part of the thesis, let me use the opportunity of this single page to express some informal thoughts.

I spent some time thinking about what I would like to write in this preface. Just rattling out names of people I am thankful to seemed to be rather dull to me. (Take a look at http://www.dyn.bci.tu-dortmund.de, if you want to see some names, most of them are there.) Obviously, I would not be in the situation of writing these lines without my parents. I would not have been in the mood to finish this project without my girlfriend. And, of course, you would not have the chance to read this if Prof. Engell would not have hired me to work in his group. Needless to say, I am also thankful for the European research project MULTIFORM, which founded my research activities.

So, if not just listing names, what then? Well, perhaps a reason for being thankful! Let us have a look at it. Scientific research is not just a product that is ordered and then created. It is a process, which starts with a problem. Ideas are formed, tested, and then discarded or saved for further inspection. The process could be seen as a long series of refinements until a final solution is found. In my case, these refinements were influenced by my environment and especially by the people around me, those that I have met and discussed with. If you read this and remember our discussion or your input to this thesis, then be sure of my gratefulness for you!

Evidently, my interactions with my colleagues at the Process Dynamics and Operations Group were the most frequent. Thank you all for your input, your interest, your time, and your support during the production of the pipeless plant. Special thanks to the Hybride Gruppe sub-group and the one guy from the other chair! I would also like to express my gratitude to the people that worked with me on the MULTIFORM project and provided feedback on my work. Again, specials thanks to the people from Eindhoven, both TU and ESI, for their hospitality! My appreciation for all the interesting people I met during conferences, workshops, and PHD schools. And, of course, thanks to all the students I met that had a real interest in our work and research, which provided valuable input. This includes my three nice interns from Princeton University.

Let me end this by expressing my hope that this thesis, which is a gigantic leap for myself, may be a tiny but not needless step for research in general.

Martin Hüfner

Kurzfassung

Die industrielle, modellbasierte Entwicklung von Produktionsprozessen und zugehörigen Regelungs- und Steuersystemen erzeugt eine große Menge an Entwicklungsdaten mit komplexen Abhängigkeiten, was es schwer macht Inkonsistenzen in einer frühen Entwicklungsphase zu erkennen. Eine Vielzahl von Modellen unterschiedlichster Formalismen wird oft in den verschiedenen Stufen und Teilen des Entwicklungsprozesses genutzt. Die ausgewählten Modellformalismen schränken die Auswahl benutzbarer Softwarewerkzeuge in jeder Entwicklungsstufe erheblich ein oder erfordern die Neuentwicklung eines Modells in einem anderen Formalismus aufgrund fehlender Werkzeugintegration. Integriertes modellbasiertes Entwickeln verspricht den Entwicklungsaufwand und damit die verbundenen Kosten signifikant zu verringern und dabei die Qualität des entwickelten Systems zu verbessern, indem Fehler frühzeitig gefunden werden können. Je später Fehler entdeckt werden, umso teurer ist deren Behebung. Diese Dissertation stellt ein kürzlich entwickeltes Softwareunterstützungssystem für die modellbasierte Entwicklung von komplexen, automatisierten Systemen vor, unter Zuhilfenahme von zwei anspruchsvollen Fallbeispielen, die modellbasierte Entwicklung einer rohrlosen Anlage und die modellbasierte Entwicklung eines elektronischen Reglers für den Vergaser eines Verbrennungsmotors. Die innewohnende Komplexität dieser Fallbeispiele erfordert die besonderen Eigenschaften des Softwareunterstützungssystems, z.B. ein strukturiertes Daten- und Modellmanagement, Algorithmen um Entwicklungsprozess und -parameter konsistent zu halten, sowie die Integration modellbasierter Werkzeuge durch Modelltransformationen, um einen effizienten und qualitativ hochwertigen Entwicklungsprozess zu gewährleisten. Die Integration durch Modelltransformationen wird im Detail für die Verbindung der Modellierungssprache gPROMS mit dem Austauschformat CIF beschrieben. Eine Auswahl von Transformationsketten erläutert beispielhaft die Vorteile von Modelltransformationen. Diese Doktorarbeit zeigt, dass ein werkzeuggestützter, modellbasierter Entwicklungsprozess, insbesondere bei Unterstützung durch Werkzeugintegration mit Modelltransformationen, vorteilhafte Effekte auf die Effizienz und Qualität des Arbeitsprozesses hat.

Abstract

The industrial model-based design of production processes and corresponding control systems yields a large amount of design data with complex interdependencies, which makes it difficult to detect inconsistencies that may lead to design errors in an early stage of the overall design process. For different stages and parts of the design process, a variety of models in different formalisms is often used. The selected model formalisms restrict the choice of usable tools in each stage severely or require the new creation of a model in another formalism due to missing tool integration. Integrated model-based design promises to reduce the design effort significantly, and thus the cost, while improving the quality of the designed system by ensuring that errors are detected in an early stage, i.e. when it is relatively cheap to correct them. This dissertation illustrates a recently developed software support system for model-based integrated design of complex automated systems, using two challenging case studies, namely the model-based design of a miniature pipeless plant and the model-based design of the controller of a combustion engine carburetor. The inherent complexity of the case studies requires the features of the software support system, e.g. structured data and model management, algorithms for design consistency and design parameter propagation, and the integration of model-based tools by model transformations, to ensure an efficient and high-quality design process. The integration by model transformations is illustrated in detail for the connection of the modeling language *gPROMS* and the interchange format *CIF*. A selection of transformation tool chains exemplifies the benefit of model transformations. This thesis shows that tool supported model-based design, especially if aided by tool integration via model transformation, has beneficial effects on the efficiency and on the quality of the workflow.

Publications

This dissertation is based on the following publications and technical reports of the author Martin Hüfner. The author's parts of the presented publications are shown within braces after the references. This is followed by the occurrence of the publication in this dissertation.

Publications in Conference Proceedings

Hüfner, Martin; Grobosch, Sebastian; Sonntag, Christian; Engell, Sebastian: *A Customized Design Framework for the Model-based Development of Engine Control Systems.* Proc. 39th Annual Conference of the IEEE Industrial Electronics Society (IECON), Vienna, 2013.
(Adaption, customization, and application of the MULTIFORM *Design Framework* to the existing VEMAC design flow. Sections I, II, IV, V, and VI.)
This paper is the basis for the model-based design example of an electronic carburetor controller, shown in section 4.2.

Hüfner, Martin; Fischer, Stephan; Sonntag, Christian; Engell, Sebastian: *Integrated Model-Based Support for the Design of Complex Controlled Systems.* Proc. 11th International Symposium on Process Systems Engineering (PSE), Singapore, 2012.
(The model-based design flow of the *laboratory pipeless plant*, the customization of the MULTIFORM *Design Framework*, and the application of the *DF* on the *laboratory pipeless plant*. Sections I, II, III, IV, and V.)
This paper is the basis for the model-based design of the *laboratory pipeless plant*, described in section 4.1.

Schoppmeyer, Christian; Hüfner, Martin; Subbiah, Subanatarajan; Engell, Sebastian: *Timed Automata Based Scheduling for a Miniature Pipeless Plant with Mobile Robots.* Proc. IEEE Multiconference on System and Control, In: Zhang, Ji-Feng; Sauter, Dominique (Hrsg.): IEEE Conference on Control Applications (CCA), 2012.
(Timed automata model of the *laboratory pipeless plant* as an example to be used as a benchmark for the tools *TAOpt* and *UPPAAL*. Section III.)
This paper is referred in section 4.1.4 as a part of the model-based design of the *laboratory pipeless plant.*

Sonntag, Christian; Hüfner, Martin: *On the Connection of Equation- and Automata-based Languages: Transforming the Compositional Interchange Format to Modelica.* Proc. 18th IFAC World Congress, Milano, pp.12515-12520, 2011.
(Checking of the soundness of the provided transformation algorithm and applying the algorithm on the transformation tool chain example of the pilot plant, which is described in all three IFAC papers. Section 5.)
This paper is cited for the formal definition of the *CIF* automata in section 3.2 and section 3.7.1 as an example for a *CIF* to *Modelica* transformation.

Fischer, Stephan; Hüfner, Martin; Sonntag, Christian; Engell, Sebastian: *Systematic Generation of Logic Controllers in a Model-based Multi-formalism Design Environment.* Proc. 18th IFAC World Congress, Milano, pp.12490-12495, 2011.
(Connection of the shown pilot plant example to the other modeling languages in the transformation tool chain example that is shown in all three IFAC examples.)
The toolchain example of the Pilot Plant in section 3.8.2 is used from this paper.

Hendriks, Dennis; Schiffelers, Ramon; Hüfner, Martin; Sonntag, Christian: *A Transformation Framework for the Compositional Interchange Format for Hybrid Systems.* Proc. 18th IFAC World Congress, Milano, pp.12509-12514, 2011.
(The *gPROMS-CIF* transformations and the transformation tool chain example that is shown in all three IFAC papers mentioned here. Section 3.3.)
This paper is the basis for the transformation from the *CIF* to *gPROMS*, section 3.5.

Hüfner, Martin; Sonntag, Christian: *Werkzeugkopplung durch den algorithmischen Austausch hybrider dynamischer Modelle.* Proc. VDI Wissensforum, Automation 2010, Bd. 2092. VDI Verlag, Baden-Baden, ISBN 978-3-18-092092-4, 2011.
(The whole *gPROMS-CIF* transformation algorithm. Section 1 to 7, except the example of the two-tank model and the *SFC* controller in section 4 that is provided by Mr. Sonntag.)
This paper is the basis for the transformation from *gPROMS* to the *CIF*, which is described in section 3.4.

Technical Reports

Sonntag, Christian; Hüfner, Martin; Jabrayilov, Adalat: *Realisation of the model exchange with Modelica and gPROMS.* Technical Report D1.4.1, MULTIFORM, 2009.
(The *gPROMS* to *CIF* transformation and related sections. Sections 2.1, 3.2, 3.3, 3.4.1, 3.4.3, 4, 5, and 9.)
This report is also the basis for the transformation from *gPROMS* to the *CIF*, which is described in section 3.4.

Sonntag, Christian; Hüfner, Martin; Jabrayilov, Adalat: *Finalization of the model exchange with gPROMS and Modelica.* Technical Report D1.4.3, MULTIFORM, 2010.
(The *CIF* to *gPROMS* transformation and related examples. Sections 2, 3.1, and 4.)

This report is also the basis for the transformation from the *CIF* to *gPROMS*, section 3.5.

Sonntag, Christian; Hüfner, Martin: *Realisation of an interface to MUSCOD-II.* Technical Report D1.5.1, MULTIFORM, 2011.
(The whole tool chain. All sections except section 4.2.)
In section 3.7.2 as an example for the additional *CIF* to *MUSCOD-II* transformation.

Moneva, Hristina; Hamberg, Roelof; Punter Teade; Hüfner, Martin; Sonntag, Christian: *Final Description of Design framework.* Technical Report D5.1.2, MULTIFORM, 2010.
(Application of the MULTIFORM *Design Framework* on the *laboratory pipeless plant.* Section 6.2.)
This report is also the basis for the model-based design of the *laboratory pipeless plant*, described in section 4.1.

Moneva, Hristina; Hamberg, Roelof; Punter Teade; Hendriks, Dennis; Hüfner, Martin: *Report on the specification of the design task machine (Integrating the Design Framework and ToolDef tooling).* Technical Report D5.2.1, MULTIFORM, 2011.
(Adding *ToolDef* toolchain setups in the MULTIFORM *Design Framework* for the design of the *laboratory pipeless plant.* Section 3.2.)
This report is part of the model-based design of the *laboratory pipeless plant*, described in section 4.1.

Reke, Michael; Grobosch, Sebastian; Hamberg, Roelof; Hüfner, Martin; Kamin, Volker; Komareji, Mohammad; Sonntag, Christian: *Final description of the case studies.* Technical Report D6.1.2, MULTIFORM, 2010.
(Design of the *laboratory pipeless plant.* Section 3.)
This report is part of the model-based design of the *laboratory pipeless plant*, described in section 4.1.

Grobosch, Sebastian; Kamin, Volker; Hüfner, Martin; Hamberg, Roelof; Moneva, Hristina; Punter, Teade; Skou, Arne; Izadi-Zamanabadi, Roozbeh; Sonntag, Christian: *4 Reports on first results and experiences obtained for the case studies.* Technical Report D6.1.3, MULTIFORM, 2011.
(Results of the model-based design of the *laboratory pipeless plant.* Section 3.)
This report is part of the model-based design of the *laboratory pipeless plant*, described in section 4.1.

Punter, Teade; Hamberg, Roelof; Moneva, Hristina; Vink, Peter; Hüfner, Martin; Grobosch, Sebastian: *Report on the test of the tools and the tool integration platform functionalities.* Technical Report D6.2.1, MULTIFORM, 2012.
(A guideline for model-based design flows. Section 2.)
This report is part of the model-based design of the *laboratory pipeless plant*, described in section 4.1.

Contents