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PAPERS

# Modelling, analysis and control design of hybrid dynamical systems

Dominik Vošček, Anna Jadlovská, Dominik Grigľák*

This paper introduces a methodology for one of the challenges regarding cyber-physical systems, ie modelling and control design them as hybrid systems. The proposed methodology comprises modules with specific steps to accomplish the tasks. Specifically, the paper aims to utilize hybrid systems framework onto the chosen hydraulic hybrid system with complex dynamics to showcase different aspects of hybrid systems. The mathematical model was derived using hybrid automata framework and then transformed into the linear form either using Jacobi matrices or using linear approximations without Jacobi matrices. After that the system was validated and analysed and the control design utilizing piecewise linear-quadratic regulator optimal control was proposed. Furthermore, parameters of control algorithm were tuned using particle swarm optimization algorithm. The whole logic, system dynamics and constraints are implemented within MATLAB/Simulink simulation environment using s-functions. The proposed methodology can be implemented on the various types of cyber-physical systems as far as they can be described as hybrid systems.

K e y w o r d s: cyber-physical system, hydraulic hybrid system, methodology, particle swarm optimization, piecewise affine system, piecewise LQR optimal control

## 1 Introduction

Cyber-physical systems (CPS), defined as an integration of physical processes with computation platforms, are an integral part of the phenomenon Industry 4.0. One of their complexity challenges stated in [1, 2] can be formulated as to model and control CPS within hybrid systems framework [3].

This paper focusses specifically on this challenge of CPS from modelling up to the control design as hybrid systems (HS) [4, 5]. The most convenient hybrid systems framework for such a task is hybrid automata (HA) which naturally deals with a continuous and discrete dynamics of hybrid systems [6]. However, such a mathematical representation is not appropriate for analysis and control design of CPS. For these tasks, different but equivalent mathematical representations were introduced, eg piecewise affine (PWA) systems [7].

There have been proposed several approaches to unify the procedure to model, analyse and design control algorithms for hybrid systems. Within mentioned procedures belong one published in [8], however, this approach does not utilize analysis of the system in the open loop and during control synthesis no metaheuristic algorithms to tune control parameters were used. Another approach, published in [9], utilizes supervisory control of hybrid systems but omits the analysis part. Methodology utilizing modelling and diagnosis of hybrid systems was proposed in [10].

Goal of this article is to propose and introduce the unified methodology for the whole process from modelling up to the control design and therefore cover all the steps to ensure proper design and analysis of CPS as a hybrid system. This process was partially introduced in [2, 11] and will be completed with regards to other research challenges. The methodology consists of several steps, namely determination of HA elements such as possible discrete modes and transitions between them, followed by assigning continuous dynamics to these modes. At this point it is possible to simulate and analyse the hybrid system.

After validation of the system, design control utilizing appropriate control algorithms can be implemented onto the hybrid system. Between the most used control algorithms for hybrid systems belong model predictive control based on multiparametric optimization [12] and piecewise optimal linear quadratic (LQR) optimal control [13]. These methods were chosen as representatives of control algorithms for hybrid systems. However, there are many others such as semi-Markov mode switching for linear parameter-varying systems [14] or supervisory control [15].

While designing control law, a metaheuristic method for tuning control law parameters can be utilized. Between these metaheuristic methods belong eg particle swarm optimization (PSO) [16], artificial bee colony [17], ant colony optimization [18] or grey wolf optimization approach [19]. We have chosen PSO algorithm as a representative example for tuning control algorithm parameters. This algorithm was then applied onto all controllable discrete modes of the HS.

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# Modelling Analysis And Design Of Hybrid Systems

Peipei Pang

**Modelling Analysis And Design Of Hybrid Systems:**

*Modelling, Analysis and Design of Hybrid Systems* S. Engell,G. Frehse,E. Schnieder,2003-07-01 In 1995 the Deutsche Forschungsgemeinschaft DFG the largest public research funding organization in Germany decided to launch a priority program Schw punktprogramm in German calledKondisk Dynamics and Control of Systems with Mixed Continuous and Discrete Dynamics Such a priority program is usually sponsored for six years and supports about twenty scientists at a time in engineering andcomputersciencemostlyyoungresearchersworkingforadoctoraldegree There is a yearly competition across all disciplines of arts and sciences for the funding of such programs and the group of proposers was the happy winner of a slot in that year The program started in 1996 after an open call for proposals the successful projects were presented and re evaluated periodically and new projects could be submitted simultaneously During the course of the focused research program 25 different projects were funded in 19 participating university institutes some of the projects were collaborative efforts of two groups with different backgrounds mostly one from engineering and one from computer science There were two main motivations for establishingKondisk The rst was the fact that technical systems nowadays are composed of physical components with mostly continuous dynamics and computerized control systems where the reaction to discrete events plays a major role implemented in Programmable Logic Contr lers PLCs Distributed Control Systems DCSs or real time computer systems **Modelling, Analysis and Design of Hybrid Systems** S. Engell,G. Frehse,E. Schnieder,2002-07-10 In 1995 the Deutsche Forschungsgemeinschaft DFG the largest public research funding organization in Germany decided to launch a priority program Schw punktprogramm in German calledKondisk Dynamics and Control of Systems with Mixed Continuous and Discrete Dynamics Such a priority program is usually sponsored for six years and supports about twenty scientists at a time in engineering andcomputersciencemostlyyoungresearchersworkingforadoctoraldegree There is a yearly competition across all disciplines of arts and sciences for the funding of such programs and the group of proposers was the happy winner of a slot in that year The program started in 1996 after an open call for proposals the successful projects were presented and re evaluated periodically and new projects could be submitted simultaneously During the course of the focused research program 25 different projects were funded in 19 participating university institutes some of the projects were collaborative efforts of two groups with different backgrounds mostly one from engineering and one from computer science There were two main motivations for establishingKondisk The rst was the fact that technical systems nowadays are composed of physical components with mostly continuous dynamics and computerized control systems where the reaction to discrete events plays a major role implemented in Programmable Logic Contr lers PLCs Distributed Control Systems DCSs or real time computer systems **Modelling, Analysis and Design of Hybrid Systems** S. Engell,G. Frehse,E. Schnieder,2014-03-12 In 1995 the Deutsche Forschungsgemeinschaft DFG the largest public research funding organization in Germany decided to launch a priority program Schw punktprogramm in German calledKondisk Dynamics and Control of Systems with Mixed Continuous

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a major role implemented in Programmable Logic Contr lers PLCs Distributed Control Systems DCSs or real time computer systems **Bond Graph Model-based Fault Diagnosis of Hybrid Systems** Wolfgang Borutzky,2014-11-04 This book presents bond graph model based fault detection with a focus on hybrid system models The book addresses model design simulation control and model based fault diagnosis of multidisciplinary engineering systems The text beings with a brief survey of the state of the art then focuses on hybrid systems The author then uses different bond graph approaches throughout the text and provides case studies *Predictive Approaches to Control of Complex Systems* Gorazd Karer,Igor Škrjanc,2012-09-20 A predictive control algorithm uses a model of the controlled system to predict the system behavior for various input scenarios and determines the most appropriate inputs accordingly Predictive controllers are suitable for a wide range of systems therefore their advantages are especially evident when dealing with relatively complex systems such as nonlinear constrained hybrid multivariate systems etc However designing a predictive control strategy for a complex system is generally a difficult task because all relevant dynamical phenomena have to be considered Establishing a suitable model of the system is an essential part of predictive control design Classic modeling and identification approaches based on linear systems theory are generally inappropriate for complex systems hence models that are able to appropriately consider complex dynamical properties have to be employed in a predictive control algorithm This book first introduces some modeling frameworks which can encompass the most frequently encountered complex dynamical phenomena and are practically applicable in the proposed predictive control approaches Furthermore unsupervised learning methods that can be used for complex system identification are treated Finally several useful predictive control algorithms for complex systems are proposed and their particular advantages and drawbacks are discussed The presented modeling identification and control approaches are complemented by illustrative examples The book is aimed towards researches and postgraduate students interested in modeling identification and control as well as towards control engineers needing practically usable advanced control methods for complex systems *Assurances for Self-Adaptive Systems* Javier Cámara,Rogério de Lemos,Carlo Ghezzi,Antonia Lopes,2013-01-16 The increasing complexity of systems and the growing uncertainty in their operational environments have created a critical need to develop systems able to improve their operation adapt to change and recover from failures autonomously This situation has led to recent advances in self adaptive systems able to reconfigure their structure and modify their behavior at run time to adapt to environmental changes Despite these advances one key aspect of self adaptive systems that remains to be tackled in depth is assurances the provision of evidence that the system satisfies its stated functional and non functional requirements during its operation in the presence of self adaptation This book is one of the outcomes of the ESEC FSE 2011 Workshop on Assurances for Self Adaptive Systems ASAS held in Szeged Hungary in September 2011 It contains extended versions of some of the papers presented during the workshop as well as invited papers from recognized experts The 12 refereed papers were thoroughly reviewed and selected The book consists of four parts

formal verification models and middleware failure prediction and assurance techniques Leveraging Applications of Formal Methods, Verification and Validation Tiziana Margaria,Bernhard Steffen,2012-09-25 The two volume set LNCS 7609 and 7610 constitutes the thoroughly refereed proceedings of the 5th International Symposium on Leveraging Applications of Formal Methods Verification and Validation held in Heraklion Crete Greece in October 2012 The two volumes contain papers presented in the topical sections on adaptable and evolving software for eternal systems approaches for mastering change runtime verification the application perspective model based testing and model inference learning techniques for software verification and validation LearnLib tutorial from finite automata to register interface programs RERS grey box challenge 2012 Linux driver verification bioscientific data processing and modeling process and data integration in the networked healthcare timing constraints theory meets practice formal methods for the developent and certification of X by wire control systems quantitative modelling and analysis software aspects of robotic systems process oriented geoinformation systems and applications handling heterogeneity in formal development of HW and SW Systems Graph Transformations and Model-Driven Engineering Gregor Engels,Claus Lewerentz,Wilhelm Schäfer,Andy Schürr,Bernhard Westfechtel,2010-11-08 This festschrift volume published in honor of Manfred Nagl on the occasion of his 65th birthday contains 30 refereed contributions that cover graph transformations software architectures and reengineering embedded systems engineering and more *Control Systems, Robotics and AutomatioN – Volume XVI* Heinz D. Unbehauen,2009-10-11 This Encyclopedia of Control Systems Robotics and Automation is a component of the global Encyclopedia of Life Support Systems EOLSS which is an integrated compendium of twenty one Encyclopedias This 22 volume set contains 240 chapters each of size 5000 30000 words with perspectives applications and extensive illustrations It is the only publication of its kind carrying state of the art knowledge in the fields of Control Systems Robotics and Automation and is aimed by virtue of the several applications at the following five major target audiences University and College Students Educators Professional Practitioners Research Personnel and Policy Analysts Managers and Decision Makers and NGOs *Discrete-Event Modeling and Simulation* Gabriel A. Wainer,Pieter J. Mosterman,2018-09-03 Collecting the work of the foremost scientists in the field Discrete Event Modeling and Simulation Theory and Applications presents the state of the art in modeling discrete event systems using the discrete event system specification DEVS approach It introduces the latest advances recent extensions of formal techniques and real world examples of various applications The book covers many topics that pertain to several layers of the modeling and simulation architecture It discusses DEVS model development support and the interaction of DEVS with other methodologies It describes different forms of simulation supported by DEVS the use of real time DEVS simulation the relationship between DEVS and graph transformation the influence of DEVS variants on simulation performance and interoperability and composability with emphasis on DEVS standardization The text also examines extensions to DEVS new formalisms and abstractions of DEVS models as well as the theory and analysis behind real world system identification and control To

support the generation and search of optimal models of a system a framework is developed based on the system entity structure and its transformation to DEVS simulation models In addition the book explores numerous interesting examples that illustrate the use of DEVS to build successful applications including optical network on chip construction building design process control workflow systems and environmental models A one stop resource on advances in DEVS theory applications and methodology this volume offers a sampling of the best research in the area a broad picture of the DEVS landscape and trend setting applications enabled by the DEVS approach It provides the basis for future research discoveries and encourages the development of new applications Robot Intelligence Technology and Applications Jong-Hwan Kim,Hyung Myung,Seung-Mok Lee,2019-04-12 This book constitutes revised selected papers from the 6th International Conference on Robot Intelligence Technology and Applications RiTA 2018 held in Putrajaya Malaysia in December 2018 The 20 full papers presented in this volume were carefully reviewed and selected from 80 submissions The papers present studies on machine learning optimization modelling and simulation path planning neural networks landmark recognition and reinforcement learning **Logic, Computation and Rigorous Methods** Alexander Raschke,Elvinia Riccobene,Klaus-Dieter Schewe,2021-06-04 This Festschrift was published in honor of Egon B rger on the occasion of his 75th birthday It acknowledges Prof B rger s inspiration as a scientist author mentor and community organizer Dedicated to a pioneer in the fields of logic and computer science Egon B rger s research interests are unusual in scope from programming languages to hardware architectures software architectures control systems workflow and interaction patterns business processes web applications and concurrent systems The 18 invited contributions in this volume are by leading researchers in the areas of software engineering programming languages business information systems and computer science logic **Computational Mathematics, Modelling and Algorithms** J. C. Misra,2003 This comprehensive volume introduces educational units dealing with important topics in Mathematics Modelling and Algorithms Key Features Illustrative examples and exercises Comprehensive bibliography **Model Engineering for Simulation** Lin Zhang,Bernard P. Zeigler,Yuanjun LaiLi,2019-02-27 Model Engineering for Simulation provides a systematic introduction to the implementation of generic normalized and quantifiable modeling and simulation using DEVS formalism It describes key technologies relating to model lifecycle management including model description languages complexity analysis model management service oriented model composition quantitative measurement of model credibility and model validation and verification The book clearly demonstrates how to construct computationally efficient object oriented simulations of DEVS models on parallel and distributed environments Guides systems and control engineers in the practical creation and delivery of simulation models using DEVS formalism Provides practical methods to improve credibility of models and manage the model lifecycle Helps readers gain an overall understanding of model lifecycle management and analysis Supported by an online ancillary package that includes an instructors and student solutions manual **Formal Methods in Manufacturing** Javier Campos,Carla

Seatzu,Xiaolan Xie,2014-02-25 Illustrated with real life manufacturing examples Formal Methods in Manufacturing provides state of the art solutions to common problems in manufacturing systems Assuming some knowledge of discrete event systems theory the book first delivers a detailed introduction to the most important formalisms used for the modeling analysis and control of manufacturing systems including Petri nets automata and max plus algebra explaining the advantages of each formal method It then employs the different formalisms to solve specific problems taken from today s industrial world such as modeling and simulation supervisory control including deadlock prevention in a distributed and or decentralized environment performance evaluation including scheduling and optimization fault diagnosis and diagnosability analysis and reconfiguration Containing chapters written by leading experts in their respective fields Formal Methods in Manufacturing helps researchers and application engineers handle fundamental principles and deal with typical quality goals in the design and operation of manufacturing systems Models and Analysis for Distributed Systems Serge Haddad,Fabrice Kordon,Laurent Pautet,Laure Petrucci,2013-02-07 Nowadays distributed systems are increasingly present for public software applications as well as critical systems software applications as well as critical systems This title and Distributed Systems Design and Algorithms from the same editors introduce the underlying concepts the associated design techniques and the related security issues The objective of this book is to describe the state of the art of the formal methods for the analysis of distributed systems Numerous issues remain open and are the topics of major research projects One current research trend consists of profoundly mixing the design modeling verification and implementation stages This prototyping based approach is centered around the concept of model refinement This book is more specifically intended for readers that wish to gain an overview of the application of formal methods in the design of distributed systems Master s and PhD students as well as engineers in industry will find a global understanding of the techniques as well as references to the most up to date works in this area

Applied Decision Support with Soft Computing Xinghuo Yu,2012-12-06 Soft computing has provided sophisticated methodologies for the development of intelligent decision support systems Fast advances in soft computing technologies such as fuzzy logic and systems artificial neural networks and evolutionary computation have made available powerful problem representation and modelling paradigms and learning and optimisation mechanisms for addressing modern decision making issues This book provides a comprehensive coverage of up to date conceptual frameworks in broadly perceived decision support systems and successful applications Different from other existing books this volume predominately focuses on applied decision support with soft computing Areas covered include planning management finance and administration in both the private and public sectors **Logical Analysis of Hybrid Systems** André Platzer,2010-09-02 Hybrid systems are models for complex physical systems and have become a widely used concept for understanding their behavior Many applications are safety critical including car railway and air traffic control robotics physical chemical process control and biomedical devices Hybrid systems analysis studies how we can build computerized controllers for physical systems which

are guaranteed to meet their design goals The author gives a unique logic based perspective on hybrid systems analysis It is the first book that leverages the power of logic for hybrid systems The author develops a coherent logical approach for systematic hybrid systems analysis covering its theory practice and applications It is further shown how the developed verification techniques can be used to study air traffic and railway control systems This book is intended for researchers postgraduates and professionals who are interested in hybrid systems analysis cyberphysical or embedded systems design logic and theorem proving or transportation and automation

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