Informatik

Sebastian G. Mechs

Model-based Engineering for Energy-efficient Operation of Factory Automation Systems within Non-productive Phases

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Berichte aus der Informatik

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D 104 (Diss. TU Clausthal)

Shaker Verlag
Aachen 2014

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.: Clausthal, Techn. Univ., Diss., 2013

Printed in Germany.

ISBN 978-3-8440-2721-1
ISSN 0945-0807

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

TU Clausthal
Clausthal University of Technology

Model-based Engineering for Energy-efficient Operation of Factory Automation Systems within Non-productive Phases

Doctoral Thesis
(Dissertation)

to be awarded the degree
Doctor rerum naturalium (Dr. rer. nat.)

submitted by
Dipl.-Wirtsch.-Ing. Sebastian Gabriel Mechs
from Schweinfurt

approved by the Faculty of
Mathematics/Computer Science and Mechanical Engineering
Clausthal University of Technology

Dissertation TU Clausthal 2013

Date of submission: 2013/05/08
Date of oral examination: 2013/09/24

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Abstract

In the face of a future rise in energy prices, energy-efficient operation of industrial automation systems has strategic impact for manufacturing companies. The reduction of energy demand during non-productive phases helps to contribute to the overall energy efficiency of automated production systems.

Up to now, there is no general scientific concept which addresses energy-efficient operation of factory automation systems within non-productive phases technically and economically on a multi-subsystem level. However, proposing detailed instructions and strategies for multiple interacting subsystems is crucial in order to realize energy savings technically.

On this account, the proposed automaton-based system model enables the analytical description of structural and behavioral aspects of industrial automation systems. This kind of mathematical modeling serves as basis for identifying optimal strategies analytically relying on a structure-exploiting procedure which enables efficient strategy computation. Those strategies quantify the energy savings potentials and give support for technical realization.

Since the computation of optimal strategies for industrial automation systems is complex, a novel approach is developed to calculate those strategies efficiently incorporating the problem structure provided by the model. Using models of real-world automation systems, the approach of this thesis is evaluated regarding further objectives. First, the feasibility of strategy execution is ensured which enables the evaluation of design decisions. Computed strategies are verified in the target system regarding correct execution. The prediction of energy demands by strategies is sensitive to model-to-system deviations, so that tests are applied to check the system model for accuracy of predictions. Economic considerations complete the assessment of the approach.

Using the general concepts and methods of this thesis, the energy demand for industrial automation systems can be substantially reduced within non-productive phases. The chosen approach supports the model generation, the computation and evaluation of strategies, and the technical realization for industrial automation systems.

Keywords:

Energy efficiency, energy-optimal, industrial automation, non-productive phase, model-based engineering, priced timed automaton, networked automata, symbolic reachability analysis, constraint optimization problem, combinatorial optimization, optimal strategy, feasible strategy

Zusammenfassung

Zukünftig steigende Energiepreise stellen die automatisierte, industrielle Produktion vor die Herausforderung, benötigte Energie effizient einzusetzen. Die Reduzierung des Energiebedarfs in Nicht-Produktivphasen ermöglicht dabei einen wesentlichen Beitrag zur Gesamtenergieeffizienz von automatisierten Produktionssystemen zu leisten.
Forschungsansätze liefern bisher keine analytischen Ansätze zur Berechnung von detaillierten Strategien, um das Energieeinsparpotenzial von Nicht-Produktivphasen in modularen Automatisierungssystemen einzuschätzen. Es werden jedoch detaillierte Anweisungen und Strategien für interagierende Subsysteme benötigt, um Energieeinsparungen technisch realisieren zu können.
Die vorliegende Arbeit bietet daher ein automatenbasiertes Systemmodell zur Beschreibung von strukturellen und verhaltensspezifischen Aspekten von Automatisierungssystemen an. Dieses Modell dient als formale Basis zur Entwicklung eines Strategieoptimierungsmodells. Strategien liefern neben der Quantifizierung des Energieeinsparpotenzials eine Spezifikation zur Ausführung im Zielsystem.
Da die Berechnung einer optimalen Strategie für industrielle Automatisierungsanlagen komplex ist, kann auf Basis der gewählten strukturellen Problembeschreibung ein Berechnungsverfahren vorgeschlagen werden, um optimale Strategien zielgerichtet zu berechnen. Anhand von Modellen realer Fertigungsautomatisierungssysteme wird der Ansatz dieser Arbeit nach weiteren praxisrelevanten Fragestellungen evaluiert. Zum Einen muss bereits zur Designzeit des Automatisierungssystems hardwarenah die Ausführbarkeit von Strategien sichergestellt werden, um Designentscheidungen und deren Auswirkungen zu bewerten. Zum Anderen unterliegt die Vorhersage des Einsparpotenzials aufgrund von Unterschieden zwischen Modell und System einer bestimmten Abweichung. Mittels Tests wird die Auswirkung auf die Aussage des Einsparpotenzials untersucht. Eine Schlussbetrachtung zeigt das ökonomische Energieeinsparpotenzial auf, das mit dem in dieser Arbeit vorgestellten, modellbasierten Ansatz realisiert werden kann.
Der generische Ansatz dieser Arbeit erlaubt den Energiebedarf von industriellen Automatisierungssystemen in Nicht-Produktivphasen in beträchtlichem Maße zu reduzieren. Dabei wird sowohl die Modellerstellung sowie die Strategieberechnung und Strategiebewertung als auch die technische Umsetzung unterstützt.

Schlagwörter:

Energieeffizienz, energieoptimal, industrielle Automatisierung, Nicht-Produktivphase, modellbasierte Planung, zeit- und kostenattributierter Automat, Automatennetzwerk, zeitliche Erreichbarkeitsanalyse, kombinatorisches Optimierungsproblem, optimale Betriebs- und Schaltstrategien, Strategierealisierung

Acknowledgment

As in every challenging project that creates something new, this doctoral thesis would not have been possible without the inspiring advice of many parties. The outcomes of this thesis are in many ways based on interdisciplinary work during my doctoral period at Siemens Corporate Technology in Munich and Clausthal University of Technology from 2010 to 2013. The detailed work in the field of energy efficiency in industrial automation has been enabled by my former supervisor Mr. Volker Albrecht who established the contact to Mr. Frank Konopka responsible for researching energy efficiency aspects in industrial automation that time. Mr. Konopka provided the confidence on which I based my work resulting in this thesis. Additionally, Mr. Jörn Peschke, Mr. Rainer Förtsch, and Mr. Patrick Volkmann enabled the discussion of my concepts and ideas benefiting from their profound and comprehensive knowledge of energetical aspects in industrial automation systems. The discussions resulted in a detailed screening of my work and perpetually reminded me of the technical feasibility. I have obtained a deep understanding of the problem context by these lively debates over weeks and months.

Besides discussing the technical requirements, Dr. Steffen Lamparter and Dr. Stephan Grimm provided advice to improve conceptual and scientific aspects. My doctoral thesis adviser Prof. Dr. Jörg P. Müller backed my scientific approach in an open and cordial way from the computer science point of view. His perception of the problem context and his scientific experience have considerably contributed to the scientific solidity of this thesis. I also express gratitude to Prof. Dr.-Ing. Dr. h. c. Peter Göhner for reviewing the approach, the contents, and results of this doctoral thesis based on his expertise with automation systems.

To the same degree as the technical and scientific parties made possible this work, my wife Kathrin has contributed essentially to this thesis with her permanent encouragement and incontrovertible affection.

Sebastian Mechs, Munich, May 2013

Acronyms

BB	Bounded investigation of the set of strategies
CE	Complete enumeration of the set of strategies
CNC	Computer Numerical Control
COP	Constraint Optimization Problem
CSP	Constraint Satisfaction Problem
CU	Control Unit
DB	Data Block
DBM	Difference Bound Matrix
DES	Discrete-Event System
DEVS	Discrete Event System Specification
DPM	Dynamic Power Management
EM	Energy Management
EMS	Energy Management System
ERP	Enterprise Resource Planning
FB	Function Block
FMS	Flexible Manufacturing System
I/O	Input/Output
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
ILP	Integer Linear Programming
IPC	Industrial Personal Computer
MES	Manufacturing Execution System

NC	Numerical Control
PCS	Process Control System
PI	Profibus International
PLC	Programmable Logic Controller
PPC	Production Planning and Control
SCL	Structured Control Language
SP	Complete enumeration of solutions without the use of strategies
SPN	Stochastic Petri Net
TA	Timed Automaton
TBA	Timed (Büchi) Automaton
TPN	Time Petri Net
UML	Unified Modeling Language

Symbols and variables

Sgn^{in}	Set of input signals
Sgn^{out}	Set of output signals
Σ	Set of timed events
V	Set of interval variables
SV	Set of shared variables
St	Set of states
St^{symb}	Set of symbolic states
T	Set of time points, time sequence
L	Set of related strategies
$L_{unrelated}$	Set of unrelated strategies
Sub	Set of subsystems
Seq^i	Set of alternative switching sequences of a Subsystem sub_i
Z	Set of zones
$Z^{\uparrow}$	Projection
$\{r\}Z$	Reset
mod	Number of modes in a subsystem
tra	Number of transitions in a subsystem
dev_{energy}	Model-to-system overestimation/underestimation of energy demand [%]
dev_{power}	Average model-to-system deviation regarding input power [%]
dev_{delay}	Average model-to-system deviation regarding mode delays [%]
eni_{idl}	Energy input without strategy (system idling)

eni_{str}	Energy input with applied strategy
$\text{ens}_{\text{pau}}^{\text{abs}}$	Absolute energy savings within a pause interval = eni_{idl} - eni_{str}
$\text{ens}_{\text{pau}}^{\text{rel}}$	Relative energy savings within a pause interval [%]
pc	Input power
sv_i	Shared variable sv of subsystem sub_i
sd_{ik}	Subsystem dependency between Subsystem sub_i and Subsystem sub_k
sub_i	Subsystem i
sys	System
$\text{obj}_{\text{energy}}$	Objective function *energy minimizing*
obj_{time}	Objective function *time minimizing*
$\text{v}_i(\text{seq}_k^j)$	Interval variable i of a switching sequence seq_k in Subsystem sub_j
mem	Maximum computational memory consumption [MB]
run	Computational runtime [s]
ev_i	Event i
sgn^{in}	Input signal
sgn^{out}	Output signal
st_k	State k
$\text{st}_k^{\text{symb}}$	Symbolic state k
deg	Average number of subsystem dependencies
clu	Clustering coefficient
dep	Dependency density
m_k^i	Mode k in Subsystem sub_i
occ	Occurrence
$\text{e}(\text{l}_p)$	Minimum energy demand of a related strategy p
l_p	Related strategy p
l_{opt}	Energy-optimal, related strategy
$\text{e}(\text{l}_{p,unrel})$	Minimum energy demand of an unrelated strategy p

$l_{p,unrel}$	Unrelated strategy p
tb_M	Test bed for simulation-based experiments
tb_S	Test bed for direct experiments
d	Delay time in a mode
t_i	Time point i
α	Production mode of a subsystem
β	Ready-for-production mode of a subsystem
δ	Synchronization mode of a subsystem
ε	Off mode of a subsystem
γ_i	Standby mode i of a subsystem
$\zeta^{(n)}$	n subsystems in mode ζ
σ_i	Timed event i
•	Planned strategy is feasible
○	Planned strategy is not feasible