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Systems within Non-productive Phases**

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

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(Dissertation)

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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

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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.

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