RIGA TECHNICAL UNIVERSITY

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INCREASING ENERGY EFFICIENCY OF ROBOTIZED PRODUCTION SYSTEMS IN AUTOMOBILE MANUFACTURING

Summary of doctoral thesis

Riga 2013

RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Industrial Electronics and Electrical Engineering

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Doctoral Program "Computer Control of Electrical Technology"

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CONFIRMATION

Hereby I confirm that I have composed this Doctoral thesis by myself and that no other than the indicated aid and sources have been used. This thesis has not been submitted for the doctoral degree in any other university.

Dāvis Meike …………………………….(Signature)

Date: ………………………

The thesis is written in English, it contains 5 sections written on 214 pages, and 74 figures and 20 tables are included. There are 6 attachments and 176 references cited.

Abstract

Industrial robots are deployed in many manufacturing industries and are a key technology in implementing production on the desired scale, speed, quality and costs. This work proposes various methods for the energy efficient use of medium and high payload industrial robots and robotized production systems.

A new, complete robot system model is developed, applicable to various types of 6 degrees-of-freedom articulated manipulators, considering actuator drive systems and controller cabinet losses. In this thesis, methods for energy-efficient large-scale robotized production planning are proposed, such as idling strategies, strategic selection of the robot manipulator type and intelligent brake management. A cluster analysis of the robot trajectory planning algorithms and a case study of dynamic robot program optimization within a robot production cell in the automotive industry are given. The effective use of regenerative energy is evaluated and a novel power converter system for multi-robot cells is proposed to enable energy sharing between several robot actuator drive systems.

Experimental validation and a viability proof of the proposed optimization approaches are provided. It is estimated that complementary implementation of all proposed methods increases the energy efficiency of robot manufacturing systems of ca. 30% over the state of the art.

Contents

General description of the work

Problem description

Industrial robotics is a key technology in the automotive industry and has an increasing role in general industry. The automotive industry is a large energy consumer, whereas a significant part of total electrical energy is consumed by robotics. Up to one fifth of a vehicle's greenhouse-gas emissions during its life-cycle is accounted for in the production phase, whereas the energy requirement of robotics in production is 5-10% of the total consumed electrical energy. Therefore, it is self-evident that energy consumption (EC) minimization in both new and existing manufacturing systems impacts production costs and total emissions.

Despite the fact that production equipment, i.e. electrical machines, drives, even robot systems, is designed using the *leading-edge* available market technology, often an improvement of a particular component does not lead to a performance increase of the whole system. A metaphor may be used: A car's fuel consumption does not depend just on engine and vehicle type; it heavily depends on how it is driven and the actual path the driver chooses. Concerning energy efficiency in highly automated robot factories, a large optimization potential exists from the viewpoint of system integrators and end users. The problem this work is dealing with is the lack of methodology in production planning processes and robot system controls for energy consumption forecast and reduction.

Aim of the work

The general aim of this work is to contribute to reduction of the total ecological footprint of highly automated robotic factories by developing new methods for energy efficient use of industrial robotics. The work also aims to set a new baseline for the state of the art technology.

Methodology

An analysis and classification of robotized production types have been done. Mathematical modeling methods have been used to develop motion planning algorithms. There are new robot models developed and experimentally validated.

The problem field is limited to the automotive industry, large scale manufacturing multi-purpose robot manipulators with payloads over 100kg, integrated into highly automated production systems and operating with no human interaction.

Scientific novelty and main contributions

- There is proposed and developed a power electronics converter circuitry for energy exchange between robot controller drive DC buses, and the experimental validation.
- Detailed analysis of robot usage in the automotive industry has been done.
- There are developed and validated multi-robot and multi-domain robot system models.

- Case study on energy performance of various robot manipulator types has been done.
- Solutions for energy-efficient usage of holding brakes have been proposed.
- Case study results on dynamic robot program optimization within the robot workcell has been done.

Several work contributions may be directly transferred to other robot types, industries or production technologies.

Practical usage

Each of the simulated or experimentally validated optimization approaches is evaluated for implementation in the Mercedes-Benz production facility in Sindelfingen, Germany. The instantaneous energy savings potential per 1000 robots is given in text boxes throughout all sections.

The methods for intelligent holding brake usage are implemented in several *Mercedes-Benz* factories. Developed modeling concepts have been proposed for extension of the international RRS1 standard[1].

Structure of the work

The research work is structured rather thematically than chronologically. The thesis sets out five tasks, which are structured in their respective sections. Sec.1 gives the motivational background by reviewing the recent global policy on energy and trends in automation technology. An introduction to in-thesis relevant robot system properties is given and state of the art modeling tools are reviewed. In

Sec.2, a detailed robot modeling tool-chain for an energy consumption determination of the robotic applications is presented. Robot system enhancements and strategic production planning approaches for large scale manufacturing are presented in Sec.3. Detailed modeling and evaluation are performed on various industrial robot path generation and optimization algorithms that are described in Sec.4. In Sec.5, an analysis and various approaches for effective use of recuperative energy is presented. Finally, conclusions and insight to future work is given. Besides the state of the art described in Sec.1 more specific literature review is given at the beginning of each section. A short summary is provided at the end of each section.

The thesis contains 214 pages, and 74 figures and 20 tables are included.

Approbation

The core parts of this thesis have been published in 14 international conferences, one scientific journal and 7 patent applications, from which four have been approved by 2013.

Selected publications

1. Davis Meike, Giovanni Berselli, Marcello Pellicciari "Energy Efficient Use of Multi-Robot Production Lines in the Automotive Industry: Detailed System Modeling and Novel Optimization Approaches" in *IEEE Transactions on Automation Science and Engineering*, 2013.
2. Davis Meike, Armands Senfelds, Leonids Ribickis "Power

Converter For DC Bus Sharing To Increase The Energy Efficiency In Drive Systems" in *The 39th Annual Conference of the IEEE Industrial Electronics Society (IECON)*, pp.7197-7202, 2013.

3. Davis Meike, Marcello Pellicciari, Giovanni Berselli, Alberto Vergnano, Leonids Ribickis, "Increasing the energy efficiency of multi-robot production lines in the automotive industry," in *The IEEE 8th International Conference on Automation Science and Engineering (CASE)*, pp. 299-303, 2012.
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5. Davis Meike, Leonids Ribickis, "Energy Efficient Use Of Robotics In The Automobile Industry," in *The IEEE 15th International Conference on Advanced Robotics (ICAR)*, pp. 507-511, 2011.

Other publications[1]

6. Armands Senfelds, Davis Meike, "Utilization of Regeneration Energy in Industrial Robots System," in *Proceedings of the 54th Annual International Scientific Conference of Riga Technical University*, pp. 95-100, 2013.
7. Marcello Pellicciari, Giovanni Berselli, Federico Balugani, Davis Meike, Francesco Leali, "On Designing Optimal Trajectories for Servo-Actuated Mechanisms Through Highly Detailed Virtual Prototypes" in *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp.1780-1785, 2013.
8. Ivars Rankis, Davis Meike, Armands Senfelds, "Utilization of

[1] In chronological order.

Regeneration Energy in Industrial Robots System" in *11th International Symposium "Topical Problems in the Field of Electrical and Power Engineering"*, 2013.

9. Davis Meike, "Multi-domain model for the evaluation of large scale robotic applications within production," in *Proceedings of the 53rd Annual International Scientific Conference of Riga Technical University*, p.113, 2012.
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11. Davis Meike, "Development of the Energy Efficiency Improvement Methods for Industrial Robots," in *International Symposium and Doctoral School of Electrical Engineering*, pp.96-99, 2012.
12. Davis Meike, "A study of time-energy optimal trajectory planning algorithms of robot manipulators," in *Proceedings of the 52nd Annual International Scientific Conference of Riga Technical University*, pp.100-105, 2011.
13. Davis Meike and Leonids Ribickis, "Recuperated energy savings potential and approaches in industrial robo-tics," in *The IEEE 7th International Conference on Automation Science and Engineering (CASE)*, pp. 299-303, 2011.
14. Davis Meike and Leonids Ribickis, "Industrial robot path optimization approach with asynchronous fly-by in joint space," in *IEEE International Symposium on Industrial Electronics*, pp. 911-915, 2011.
15. Davis Meike, Leonids Ribickis, "Analysis of the Energy Efficient Usage Methods of Medium and High Payload Industrial Robots in the Automobile Industry" in *10th International*

Symposium "Topical Problems in the Field of Electrical and Power Engineering", pp.1-5, 2011.

Patents[2]

1. Davis Meike, Michael Lebrecht, Armands Senfelds, Ivars Rankis, "Produktionsanordnung mit wenigstens zwei Antriebssystemen", P826268/DE/1, 24.06.2013, Note: submission.
2. Davis Meike, Michael Lebrecht, Thomas Schneider, "Verfahren zum Betreiben einer Mehrzahl von Robotern" P826274/DE/1, 24.06.2013, Note: submission.
3. Davis Meike, Michael Lebrecht, "Verfahren zum Auswählen von Robotervarianten", P826273/DE/1, 24.06.2013, Note: submission.
4. Michael Lebrecht, Davis Meike, Ivars Rankis, Thomas Schneider, "Fertigungs- und/oder Transportanordnung," DE 10 2011 122 427 A1, 28.06.2012.
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7. Michael Lebrecht, Thomas Schneider, Davis Meike, "Verfahren zur Steuerung und/oder Regelung von Antriebsmotoren eines Roboters," DE 10 2011 008 170 A1, 27.10.2011.

[2] In chronological order.

1 Motivation and State of the Art

Energy costs have grown steadily in recent decades[17, 18]. Ecologic footprint of products and manufacturing processes must be considered by current legislation. Energy efficiency is recognized as a key solution to reduce ecologic footprint and operation costs in factories with high robot density. Energy management and environmental responsibility are defined by standards ISO 50001 and ISO 14001, respectively[19, 20]. The focus of the thesis is the reduction of electrical energy consumption in highly automated robotized factories such as in automobile production. In particular, the focus lies on the high-payload industrial robot manipulators, since they are the most widespread robot types.

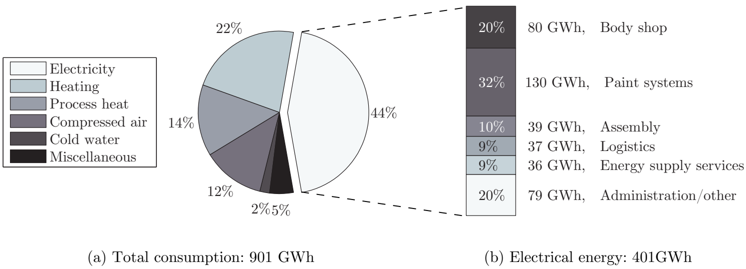


Figure 1.1: Energy consumption in Daimler AG Plant Sindelfingen. Data broken down by type of energy (a); by production centers (b). [21]

According to [22], the specific energy per vehicle was 3.3MWh in *Mercedes-Benz Cars* division, whereas the specific energy per vehicle in the body shop is ca. 320kWh. As shown in Fig.1.1 the total plant consumption was 901GWh in 2011, whereas the electrical energy counts for 44%. In this work, the target area is the body shop, since that is where 95% of all industrial robots are installed and it accounts for 20% of the consumed electricity.

An industrial manipulator KUKA KR2210 is selected as a reference manipulator. Fig.1.2 depicts its position in $\boldsymbol{q}_h = {}^{\pi}/_{180}[0,\ -90,\ 90,\ 0,\ 0,\ 0]^T$ with numerical values for axes given in degrees.

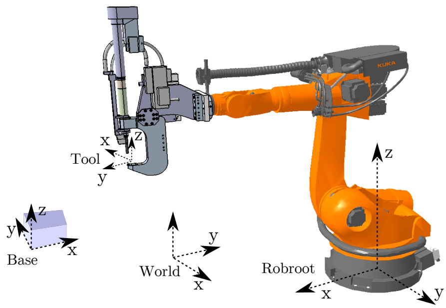


Figure 1.2: 6DOF industrial robot manipulator with a welding tool, overview of coordinate systems.

Intelligent power networks, smart grids, and energy efficiency are categorized among the top positive impulses for sustainable and profitable technology development, according to survey of "VDE-Trendreport 2013"[23]. Industry has the highest expectations on networked production equipment, efficient use of resources, and energy. The automotive industry will benefit the most from the realization of cooperative and flexible systems or simply *smart facto-*

ries, which are predicted to be implemented in 12 years.

A survey on previous work of the overall production optimization strategies, mostly reveal managerial methods. Less are those case studies written in a technical manner to optimize the high level controls in robotic factories. A survey on recent work on energy efficient industrial robotics shows that the research focus has mainly been on the optimization of robot trajectories. Most of the research efforts, however, only have a theoretical significance, since they are often based on academic robot manipulator types and not all robot system losses are considered in their models. None of the sources examined in this research provide an evaluation of any of the optimization approaches in respect to the actual robot usage in the automotive industry.

2 Robot System Modeling

Due to robot structure complexity, an intuitive estimation of EC is difficult, and software tools to model simulate the energy consumption of commercial robots to date are not available. Therefore, a novel multi-domain model for electrical consumption determination of robot applications is presented in this section. As shown in Fig.2.1, the model considers a variety of power losses in whole robot systems, such as manipulator friction, electrical losses in actuators, and their drives. An energy exchange between robot axes within the electrical drive model is considered, and furthermore, a DC bus voltage fluctuation due to recuperation is modeled. Model validation results on a KUKA KR2210 industrial robot show an absolute error below 3.7% for dynamics and the electrical drive model.

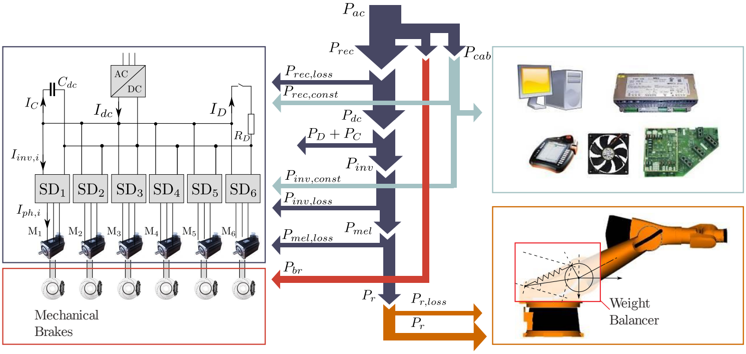
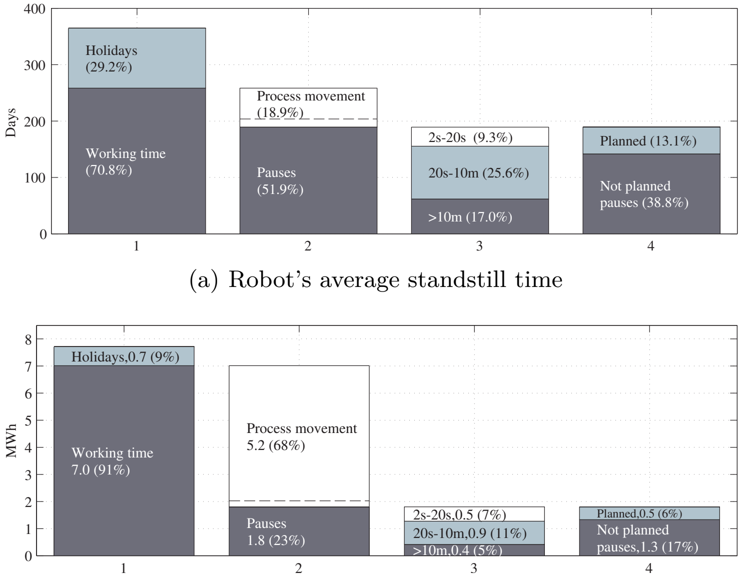


Figure 2.1: Block diagram of a drive system and power components

The developed software covers a complete tool-chain from original robot programs that can be copied directly from physical robot controllers to electrical consumption of the robot system. Modeling tools can use robot controller simulator for realistic trajectory generation, or its own path planner for development processes. The model allows estimating the electrical consumption in robotic production lines, determining power peaks, and providing data as a basis for dimensioning parameters in the drive system's DC bus.

3 Production Analysis and Robot System Enhancements

A statistical evaluation of actual robot usage in automobile production as shown in Fig.3.1 is an important basis for EC savings estimation of various strategic robot system optimization approaches in real factories. The consideration of these concepts distinguishes theoretical assumptions from economical feasibility.



(a) Robot's average standstill time

(b) Robot's average energy consumption

Figure 3.1: A numerically average robot energy consumption comparison in an automobile body-shop Assumed values: $P_{mov} = 3150W$, $P_{stand} = 650W$, $P_{cab} = 275W$

Many strategic improvements may be realized in early production planning phases or by means of controller configuration. The methods for system enhancements are grouped as follows:

- The use of low power modes;

- Intelligent brake management;
- Energy efficient TCP positioning in a workcell and load adaptation;
- Manipulator selection.

A *reference application* has been selected according to standstill/movement analysis. It has the duration $t_{appl} = 34.2s$, including standstill duration $t_{stand} = 11.3s$ and process standstill duration $t_{wld} = 4.7s$ for process execution (welding, grasping, screwing, etc.). Fig.3.2 shows the robot system's losses during this application with two excelled items. P_D is the power of brake resistance on DC bus, but P_{br} is the power to keep the holding brakes opened- system domains, where optimization potential is recognized.

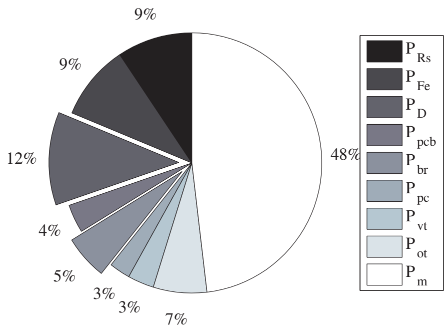


Figure 3.2: Power distribution during a reference application, $\overline{P}_{ac} = 2293W$

In this section, nine approaches are considered as implementation close and their respective EC minimization potential was estimated in compliance with the production analysis. It includes methods for intelligent holding brake management: brake power adaptation and brake release on demand, evaluation of energy efficient TCP positioning in the workspace, reduction of load mass and gravity shift of tool load and manipulator selection by energy efficiency criteria. A complementary implementation of the discussed strategic improvements delivers over 17% EC reduction.

4 Movement Optimization

An evaluation of various trajectory generation algorithms shows that a trade-off between movement execution time and EC must be met. There are 13 various movement profile generation algorithms analyzed and practically implemented for 6-DOF manipulators. Some general conclusions can be listed:

- Energy losses in the robot system are mainly caused due to rapid accelerations/decelerations. Fig.4.1 shows a crucial difference in system's losses between two movement profiles: full speed and at half velocity/acceleration.
- Typically, full-synchronous trajectories have smaller peak accelerations, which lead to less EC than other axes synchronization types.
- Movement profile change requires significant modifications in commercial robot controllers, therefore, implementation is not possible by end-user.
- An adaption of the appropriate amplitude of maximal acceleration, maximal velocity or scaling the whole position profile of the IR are implementation-close alter-

natives.

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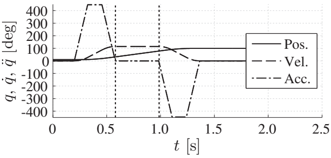
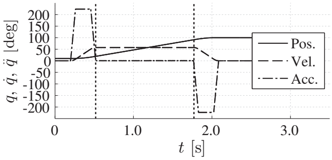
4. An adaptation of the appropriate amplitude of maximal acceleration, maximal velocity or scaling the whole position profile of the IR are the implementation-close alternatives.

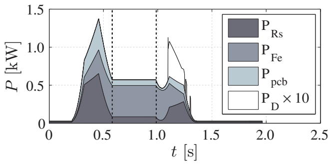
A *trajectory scaling* approach has been applied to a state-of-the-art workcell with 4 IRs. Modeling results confirm possible savings of up to 7.3% of the total EC. Results show that considering realistic production interlock signals, a complete robot system model and various robot controller-state static losses have significant impact on cost function and deliver more precise results over current theoretical research in this field. The method is implementation-close, since it requires no modification of the programs of the robot, instead a chosen scaling factor β, brake release delay time T_b are the standard variables of the robot controller. A control system for real-time computation of the optimal β factors is proposed.



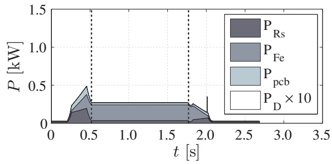
(a) Kinematic profile, $\dot{q}_{i,max}$, $\ddot{q}_{i,max}$



(b) Kinematic profile, $1/2\dot{q}_{i,max}$, $1/2\ddot{q}_{i,max}$



(c) Power losses in robot controller, $\dot{q}_{i,max}$, $\ddot{q}_{i,max}$



(d) Power losses in robot controller, $1/2\dot{q}_{i,max}$, $1/2\ddot{q}_{i,max}$

Figure 4.1: Acceleration-dependent losses in robot system

5 Use of Recuperative Energy

Today, a remarkable proportion of energy consumption industrial robots dissipate on balancing resistors of DC bus due to the required dynamic performance of the robot actuators. Analysis shows that per cycle time as much as 10-20% of the total consumption is dissipated in heat. This section distinguishes and proposes three alternatives to reuse the regenerative energy:

- The use of passive capacitive energy storage,
- The increase a DC bus voltage fluctuation range, and
- Drive DC bus sharing.

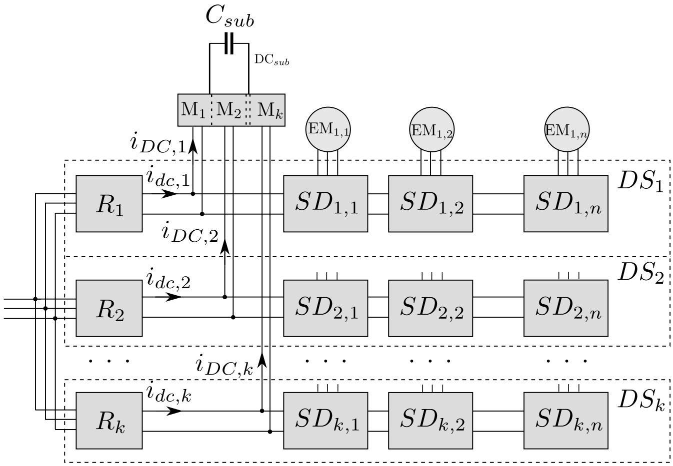
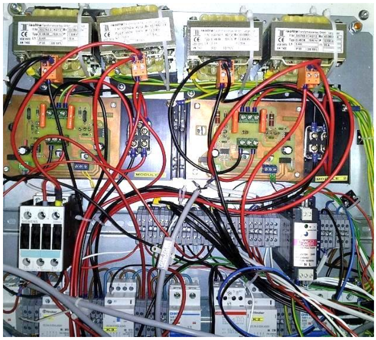


Figure 5.1: Block schematic of a DC subgrid for energy exchange

The savings are mostly dependent on such influential factors as tool weight, application type and actual total pause length between cycle times. Although the passive energy storage systems have proven to be effective, often the investment cost is the crucial factor for a manufacturer's management decision about retrofitting any existing production facilities.

In this section, there is a power converter proposed, which deploys an external DC-subgrid for energy exchange with only one optional storage element in the network. As shown in Fig.5.1 k drive systems $DS_1, \ldots, DS_k$ are used so that each supplies n servo drives $SD_{i,1}, \ldots, SD_{i,n}$. Each of the DC buses $DC_1, \ldots, DC_k$ are connected to the power converter modules $M_1, \ldots, M_k$. Each module is connected to a subgrid DC_{sub}, so that any module M_i is parallel to

(a) Robot test cell and measuring equipment



(b) Power converter modules

Figure 5.2: Developed energy-exchange system for two industrial robots

any other M_{i+1}. The capacitor C_{sub} determines the size of the energy exchange buffer. Thus, all drive systems can work both as stand-alone machinery and connected elements in a shared DC-subgrid. No hardware modification or synchronization of original equipment is required. Eventually, the proposed energy savings device may eliminate the necessity for a brake-chopper.

The prototype power converter system and the robot laboratory is shown in Fig.5.2. Experimental results with industrial robots show energy savings up to 22% for specific robot handling programs. A reference application, considering production standstills, results in 639kWh savings or 8.3% of total consumption *per annum*.

Conclusions and Future Work

This thesis deals with energy efficiency in large scale automated production facilities that employ industrial robot manipulators. The following is a summary of the main conclusions of this thesis. There are four distinguished types of optimization approaches:

- State control in both robot system and high-level controls;
- Workcell design in early production planning stages;
- Robot movement and path optimization;
- Efficient use of regenerative energy.

Accordingly, 14 specific methods are analyzed for increasing energy efficiency of industrial robots.

Theoretical results

The main theoretical results and conclusions of the thesis are[1]:

- Analysis of robot usage in automobile production. Detailed results show what type of pauses and standstills occur statistically in automobile body shops.
- Many of the production standstills can be used to improve the EC by setting the robot system in low power mode or turning it off automatically. The challenge is to forecast such standstills.
- A detailed power loss analysis has been done for an average robot application, which provides an overview of

[1] In order of occurrence in thesis.

which components are the most *energy-sensitive*.

- An evaluation has been done to identify energy efficient workspace areas. A comparison with a typically occupied workspace shows that they do not overlap, i.e. an optimization potential exists.
- An evaluation has been done to identify how the change of tool load and COG shift influence the EC. Generally, load reduction and COG shift towards the flange have a positive impact, however it strongly depends on the particular workspace area in which the robot is working.
- An analysis of the relationship between holding brake release time delay and annual energy savings has been done.
- A discussion on standardized robot comparison by means of energy efficiency has been started. Preliminary results show that it has little practical usefulness due to the high diversity of robot applications.
- Experimental and modeling results show that energy losses in robot systems are mainly due to rapid accelerations/decelerations, whereas during deceleration energy loss on the brake chopper has the most significance.
- General velocity reduction is beneficial in terms of EC reduction to a specific minimum value; at lower values EC increases due to static losses and gravity forces. Dynamic adaptations of the appropriate amplitude of maximal acceleration and/or velocity are practical methods for reducing EC, if implementation is done considering interlocks in the workcell context. A case study and

modeling results on related approach *trajectory scaling* show significant energy savings.

- Various movement profile generation algorithms have been analyzed showing that in some cases it can be beneficial in terms of EC reduction. However, it is not technically possible on most commercial robot controllers.
- Modeling results show that an increase of DC bus voltage of robot controllers is beneficial in terms of EC reduction.
- Modeling results show that an extended passive capacitive energy storage system on the drive DC bus of a robot controller is beneficial in terms of EC reduction. However, every additional increment of storage size always has a higher cost.
- Modeling results of drive DC bus sharing of multiple robots show that regenerative energy is being exchanged with much smaller sizes of intermediate energy storage being necessary. Furthermore, as more robots are coupled, less intermediate energy storage (per robot) is required.

Practical results

The main practical results and conclusions of the thesis are[2]:

- Three power converter circuitries for regenerative energy exchange between robots have been proposed, applicable to any robot controller with an actuator drive

[2] In order of importance in author's view.

DC bus. Experimental results demonstrate the expected functionality and high energy savings. No modification of robot controllers is required.

- A method for brake release on demand is proposed which has been implemented on type KR C2 controllers, and which is proposed for implementation in KR C4 controllers (both KUKA robots).
- A robot system model for EC determination has been developed. Experimental validation results prove high accuracy for dynamic and electrical drive domains.
- Developed model for multiple robot comparison. Multi-robot/multi-domain models have been implemented in a software tool.
- Developed modeling concepts have been proposed for extension of the international RRS1 standard[1].
- Experimental results of an appropriate size of passive extended capacitive energy storage on the DC bus of the robot controller show significant EC savings for both typical handling and welding robot applications.
- A method for EC reduction of holding brakes during the movement (brake power adaptation) is proposed.

A case study of a production body shop shows that complementary implementation of all methods can reach 30% annual energy savings over the state of the art.

Future Work

A *factory of the future* should be based on novel architecture of the power supply system with fewer hardware components, fewer energy losses due to multiple power transformations, easier integration of renewable power sources and improved power network quality. Intelligent controls should additionally manage energy consumption, allow exchange with (hybrid) energy storage of subordinate equipment in real time, dependent on actual energy requirements, costs and manufacturing targets. Since most of today's robot actuators and welding equipment convert alternating-current to direct-current (DC) at some point of their power supply systems, a direct DC supply is an implementation alternative for such architecture.

The exact impact of any of the proposed energy efficiency optimization methods is strongly dependent on the specific application. Therefore, any expected impact calculated in this thesis has only an illustrative purpose. Energy models of various items of equipment (also robots) and optimization methodologies must be integrated into virtual production planning and/or commissioning tools. Since robot dynamic data is proprietary for commercial robots, it is suggested that robot energy consumption modeling is based on the extended RRS1 standard using an RCS module. Methods that deal with controls optimization should be implemented in offline commissioning tools.

Future work in the form of the EU-supported research project "Automation and Robotics for European Sustainable Manufacturing" [24] (AREUS) has been launched in 2013.

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