

Final Report

Computational Design

Optimization Techniques for Engineering Design Problems

Johan Ölvander, PhD
Division of Machine Design
Department of Management and Engineering, Linköping University
Phone: +46 13 281711, email: johan.olvander@liu.se

Background and motivation

Engineering design is a special form of problem solving where a set of frequently unclear objectives has to be balanced without violating any given constraints. Thus, it seems natural to look upon a design problem as multi-objective optimization problems. By employing modern modeling, simulation and optimization techniques, vast improvements could be achieved in design. However, there will always be parts of the design process that require human or inquantifiable judgment that is not suited for automation with any optimization strategy.

Computational design can be seen as the use of computers in the design process in order to formalise and automate it to a level that agrees with current technologies in computer sciences and applied mathematics in a broad sense. The project concentrates on the parts of the design process that can be formalised, as well as how formal methods affects the design process as a whole. This includes optimisation methods, sensitivity and robustness analysis, as well as formal methods for defining system requirements, and methods to ensure traceability in design. Since computational design methods operate on system models, modelling and simulation are central concepts in this research area.

Optimization as it is employed here is based on simulation results, possibly from a large number of different simulation environments. The problem is also characterized by the presence of both continuous parameters and discrete selections of individual components from catalogs or databases. Thus, the problem is non-linear and there are no derivatives of the objective functions available in a straightforward manner. These are reasons for applying non-gradient optimization methods such as the Complex method or Genetic Algorithms. Another reason is that these methods are robust in locating the global optima in multi-modal search spaces.

Industrial motivation

High quality, quick response to market needs, innovative products and low cost are decisive in order to stay competitive on an increasingly competitive global market. It also becomes more important to find and to express requirements more exactly in order to be able to emphasize the right ones. To beat the competition to the market it is also necessary with a rapid development process. Especially in the early conceptual phase of the design process, the designer needs efficient tools that make it possible to compare different design solutions and to analyze the whole system, and not just a part. Tools are also needed, that can relate design decisions at detail level to high-level requirements in order to ensure traceability in the design. In this project the above issues are addressed by introducing formal optimization methods together with comprehensive simulation models and integrate them in the development process in cooperation with industrial partners.

Main goals and achievements

The project aims at developing design methods and tools that improve the design process and the quality of designed systems. The design process paradigm uses decision-making models to describe design alternatives, and optimization methods that search the design space for the best design among all possible design options. Within the project a framework has been developed where simulation,

optimization and decision support tools are interconnected and integrated in the product development process. The framework includes multi-objective and multi-disciplinary optimization techniques, and tools for structuring optimization problems and formulate objective functions.

Different optimization algorithms have been developed within the projects, such as a multi-objective genetic algorithm for mixed continuous and discrete problems [12], [16], [38]. Additionally the Complex method has been improved by making it adaptive, [25], but also by making it capable of handling problems with mixed variables, [30], [31]. Furthermore, methods have been developed for comparing performances of different optimization algorithms, [29], [34], [40]. Techniques for balancing robustness and optimality and for taking uncertainties into account have also been developed in [10], [17] and [32]. Furthermore, matrix based design methods, such as OFD, DSM and the morphological matrix, have been formalized and implemented in a computational framework thus facilitating automation early in the development process. The results have been implemented at Saab and are reported in, [21], [27], [28] and [35].

A modular simulation and optimization framework for robot design has been developed, using the object oriented simulation package Dymola and the discrete Complex optimization method, which has been implemented in MATLAB, [24].

Industrial cooperation

Within the project the developed techniques have been applied to industrial problems in cooperation with the project partners. Thereby the validity of the developed methods has been assessed, and knowledge has been gained in order to improve and develop new methods that support engineering optimization. The Industrial cooperation is summarized below. Please note that many of the publications are co-authored with the industrial partners.

Volvo Car Corporation

Two projects have been conducted in cooperation with Volvo Cars. The first project aims at finding the optimal set of functions to implement in an automobile in order to maximize profit subjected to development budget constraints and safety issues. The project is carried out in cooperation with Christian Grante at Volvo Car Corporation, who is a former PhD student from the department. This project has resulted in publications [15] and [43]. The second project is the Evolve project, which was a student project run in collaboration with Volvo Cars, for which we received the TekIT-prize 2005. Papers [14], [46] and [42] present the results and some of the lessons learned from this project.

Parker Hannifin AB

There has been a close cooperation with Parker Hannifin to develop quieter hydraulic pumps by using advanced modeling, simulation and optimization techniques. In this project simulation and optimizations results have been verified using measurements of physical components that have been designed based on the outcome of the optimizations. During 2003 to 2006 the cooperation involved PhD student Andreas Johansson, which resulted in Andreas's PhD thesis [4] and publications [8] and [44]. The cooperation continued with PhD student Liselott Ericson, which has resulted in her licentiate thesis [1] and publications [20] and [22]. Andreas are now a Parker employee, and thereby the methods and tools developed in the project are transferred to the company.

Saab Aerospace AB

Together with Saab Aerospace, tools and methods are being developed for optimal design of aircraft fuel systems. Within this project optimization is used together with matrix based design methods in order to support conceptual design of aircraft fuel systems. Publications from this collaboration include [3], [9], [11], [21], [27], [28], [32], [35] and [37]. Furthermore, the methods developed within this project are now in use at the company.

ABB Robotics

Within the project, there has been a close collaboration with ABB Robotics involving PhD student Marcus Pettersson focusing on development of optimization algorithms and methods to support design optimization in industrial robots. Marcus has developed tools and methods at the university but also spent considerable time at ABB in order to integrate the methods with the software tools used in the development process at ABB. The techniques developed have been used to solve real engineering

problems at ABB Robotics, and the results show great potential. The project has resulted in Marcus' doctoral, [2], and licentiate, [5], and publications [25], [26], [30], [31] and [33]. Marcus is now employed at ABB Corporate research, so the techniques developed at the university could easily be transferred to ABB.

ABB Corporate Research

There is also collaboration with ABB Corporate Research in the field of robot design optimization. One focus area for this project is optimal design of product families, i.e. not to optimize a single robot but a family of different robots taking modularity issues into account. The first results from this research are presented in [18]. Ongoing efforts within this project include the work of PhD-student Mehdi Tarkian who develops highly flexible parametric CAD-models that are connected to other software programs such as Dymola, MATLAB and MS Excel, see [19].

Furthermore, the cooperation with the two ABB companies has also resulted in the project 'Integrated Framework for Optimal Design', financed by VINNOVA with 4.1 MSEK during 2005-2007.

Economic report

The majority of the financial support has been used to finance the project leader, Johan Ölvander. However, parts of the resources have been used to finance PhD students Marcus Pettersson and Mehdi Tarkian, as well as for travel expenses.

The project has contributed to the following promotions and dissertations

- **Johan Ölvander**, Docent appointment, 2005.
- **Marcus Pettersson**, *Design Optimization in Industrial Robotics – Methods and Algorithms for Drive Train Design*, Dissertation, 2008. (Licentiate dissertation in 2005)
- **Liselott Ericson**, *Flow Pulsations in Fluid Power Machines – a measurement and simulation study*, Licentiate dissertation, 2008.
- **Hampus Gavel**, *On Aircraft Fuel Systems – Conceptual Design and Modeling*, Dissertation, 23 February 2007.
- **Andreas Johansson**, *Design Principles for Noise Reduction in Hydraulic Piston Pumps – Simulation, Optimization and Experimental Verification*, Dissertation, October 2005.
- **Christian Grante**, *On Design of Safety Critical Automotive Systems – A Semi-automated approach for Balancing Profit and Safety*, Dissertation, June 2004.

Research group

Based on the financial support from CENIIT a research group has been established within the field of design optimization with an emphasis on industrial robot development. Currently one associate professor, one PhD student and two industrial post docs (employed 20% at the university) are associated with the research group.

Publications since project start 2003

The project has resulted in the following publications including theses supervised by the project leader. Please note that the project leader changed family name from Andersson to Ölvander in 2004.

Theses

- [1] Ericson L., *Flow Pulsations in Fluid Power Machines – a Measurement and Simulation Study*, Licentiate thesis no 1355, Department of Management and Engineering, Linköping University, 2008.
- [2] Pettersson M., *Design Optimization in Industrial Robotics – Methods and Algorithms for Drive Train Design*, Dissertation no 1170, Department of Management and Engineering, Linköping University, 2008.
- [3] Gavel H., *On Aircraft Fuel Systems – Conceptual Design and Modeling*, Dissertation no 1067, Department of Mechanical Engineering, Linköping University, 2007.
- [4] Johansson A., *Design Principles for Noise Reduction in Hydraulic Piston Pumps – Simulation, Optimisation and Experimental Verification*, Dissertation no 965, Department of Mechanical Engineering, Linköping University, 2005.
- [5] Pettersson M., *On Drive Train Optimization in Industrial Robot Design*, Licentiate thesis no 1226, Department of Mechanical Engineering, Linköping University, 2005
- [6] Grante C., *On Design of Safety Critical Automotive Systems – A Semi-automated approach for Balancing Profit and Safety*, Dissertation, Department of Mechanical Engineering, Linköping University June 2004.

Journal papers

- [7] Ölvander J., Johansson B., Gavel H., A Computerized Optimization Framework for Morphological Matrix Applied to Aircraft Conceptual Design, accepted for publication in *Computer-Aided Design*, DOI: 10.1016/j.cad.2008.06.005, 2008.
- [8] Johansson A., Ölvander J., Palmberg J.O., Experimental Verification of Cross-Angle for Noise Reduction in Hydraulic Piston Pumps, *Proc. IMechE, Part I: Journal of Systems and Control Engineering*, 221(I3), pp. 321–330, 2007.
- [9] Gavel H., Ölvander J., Krus P., Optimal Aircraft Fuel System Design, *AIAA Journal of Aircraft*, vol 43., No5, pp. 1334-1340, 2006.
- [10] Ölvander J., Robustness Considerations in Multi-Objective Optimal Design, in *Journal of Engineering Design*, vol 16. no. 5, pp. 511-523, 2005.
- [11] Gavel H., Lantto B., Ellström H., Jareland M., Steinkellner S., Krus P., Andersson J., Strategy for Modelling of Large A/C Fluid Systems, *SAE 2004 Transactions Journal of Aerospace*, pp 1495-1506, 2005.
- [12] Andersson J. and Krus P., A multi-objective optimization approach to aircraft preliminary design, *SAE 2003 Transactions Journal of Aerospace*, pp 454-460, 2004.
- [13] Krus P. and Andersson J., Simulation based optimisation for aircraft systems, *SAE 2003 Transactions Journal of Aerospace*, pp 461-470, 2004.
- [14] Zachrisson A., Rösth M., Andersson J., Werndin R., Evolve – A Vehicle Based Test Platform for Active Rear Axle Camber and Steering Control, *SAE 2003 Transactions Journal of Passenger Cars - Mechanical Systems*, pp. 690-696, 2004.
- [15] Grante C, Andersson J., A method for evaluating functional content in mechatronic systems using optimisation, *Research in Engineering Design*, vol. 14, No. 4, pp 224-235, 2003.

Book chapters

- [16] Andersson J., Design of Fluid Power Systems Using a Multi-Objective Genetic Algorithm, in *Applications of Multi-Objective Evolutionary Algorithms*, C. Coello Coello and G. Lamont (Editors), World Scientific series on Advances in Natural Computation, 2004.

- [17] Andersson J., Sensitivity Analysis in Multi-objective Evolutionary Design, in *Recent Advances in Simulated Evolution and Learning*, Kay Chen Tan, Meng Hiot Lim, Xin Yao and Lipo Wang (Editors), World Scientific series on Advances in Natural Computation, 2004.

Reviewed conference proceedings

- [18] Ölvander J., Feng X., Holmgren B., Optimal Kinematics Design of an Industrial Robot Family, ASME Design Automation Conference, New York, August 3-6, 2008.
- [19] Tarkian M., Ölvander J., Lundén B., Integration of Parametric CAD and Dynamic Models for Industrial Robot Design and Optimization, ASME Design Automation Conference, New York, August 3-6, 2008.
- [20] Ericsson L., Ölvander J., On optimal Design of Hydrostatic Machines, The 6th International Conference on Fluid Power (6th IFK), Dresden, Germany, March 31 - April 2 2008.
- [21] Gavel H., Ölvander J., Krus P., Aircraft fuel system synthesis aided by interactive morphology, optimization and probabilistic design, *46th AIAA Aerospace Sciences Meeting and Exhibit*, paper No AIAA-2008-0159, Reno USA, 2008.
- [22] Ericson, L., Ölvander J., Palmberg, J. O., Flow pulsation reduction for variable displacement motors using cross-angle, in *Proceedings of Bath Workshop of Power Transmission and Motion Control 2007*, Hadleys Ltd, Essex, UK, pp 103-116, 2007.
- [23] Feng X., Sander- Tavallaey S., Ölvander J., Cycle-based Robot Drive Train Optimization Utilizing SVD Analysis, ASME Design Automation Conference, Las Vegas, September 4-7, 2007.
- [24] Johanson B., Ölvander J., Pettersson M., Component Based Modelling and Optimization for Modular Robot Design, ASME Design Automation Conference, Las Vegas, September 4-7, 2007.
- [25] Pettersson M., Ölvander J., Adaptive Complex Method for Efficient Design Optimization, ASME Design Automation Conference, Las Vegas, September 4-7, 2007
- [26] Petterson M., Ölvander J., Andersson H., Adaptive Performance for Industrial Robotics, in proceedings of IEEE International Symposium on Industrial Electronics, Vigo, Spain, June 4-7, 2007.
- [27] Gavel H., Ölvander J., Johansson B., Krus P., Aircraft Fuel System Synthesis Aided by Interactive Morphology and Optimization, *45th AIAA Aerospace Sciences Meeting and Exhibit*, paper No AIAA-2007-0653, Reno, USA, 2007.
- [28] Gavel H., Ölvander J., Johansson B., An Algorithmic Morphology Matrix for Aircraft Fuel System Design, 25th Congress of the International Council of the Aeronautical Sciences, paper No ICAS-2006-9.2.2, Hamburg, Germany, 2006.
- [29] Ölvander J., Krus P., Optimizing the Optimization – A Method for Comparison of Optimization Algorithms, in proceedings of the 2nd AIAA Multidisciplinary Design Optimization Specialist Conference, Newport, Rhode Island, 1-4 May, 2006.
- [30] Petterson M., Andersson J., Krus P., On Optimal Drive Train Design in Industrial Robots, in proceedings of IEEE International Conference on Industrial Technology, Hong Kong, December 14-17, 2005.
- [31] Petterson M., Andersson J., Krus P., Methods for Discrete Design Optimization, in proceedings of ASME DETC'05, Design Automation Conference, Long Beach, California, September 24-28, 2005.
- [32] Gavel H., Krus P., Andersson J., Johansson B., Probabilistic Analysis in the Conceptual Phase of an Aircraft Fuel System, proceedings of the 7th AIAA Non-Deterministic Approaches Forum, Austin, Texas, 18-21 April, 2005.
- [33] Petterson M., Andersson J., Krus P., Feng X., Wäppling D., Industrial Robot Design Optimization in the Conceptual Design Phase, submitted to Mechatronics & Robotics 2004, IEEE Industrial Electronics Society, Aachen, Germany, September 13-15, 2004.
- [34] Krus P., Andersson J., An Information Theoretical Perspective on Design Optimization, in *Proceedings of ASME Design Automation Conference*, Salt Lake City, USA, September 28 - October 2, 2004.

- [35] Gavel H., Krus P., Andersson J., Quantification of the Elements in the Relationship Matrix. A conceptual study of Aircraft Fuel System, in *Proceedings of 42nd AIAA Aerospace Sciences Meeting and Exhibit*, Paper No AIAA-2004-0538, Reno, USA, 2004
- [36] Angantyr A., Andersson J., Aidanpaa J.O., Constrained Optimization based on a Multi-objective Evolutionary Algorithm, in *Proceedings of The Congress on Evolutionary Computation, Canberra, Australia, December 8-12, 2003*
- [37] Gavel H, Andersson J., Using optimization as a tool in fuel system conceptual design, in *proceedings of SAE World Aviation congress*, Montreal, Canada, September 8-12, 2003.
- [38] Andersson J., Krus P., A multi-objective optimization approach to aircraft preliminary design, in *Proceedings of SAE World Aviation Congress*, Montreal, Canada, September 8-12, 2003.
- [39] Krus P., Andersson J., Simulation based optimisation for aircraft systems, in *Proceedings of SAE World Aviation Congress*, Montreal, Canada, September 8-12, 2003.
- [40] Krus P., Andersson J., Optimizing Optimization for Design Optimization, in *Proceedings of ASME Design Automation Conference*, Chicago, USA, September 2-6, 2003.
- [41] Andersson J., Redhe M., Response Surface Methods and Pareto Optimization in Crashworthiness Design, in *Proceedings of ASME Design Automation Conference*, Chicago, USA, September 2-6, 2003.
- [42] Andersson J., Palmberg J.-O., The Evolve Project – a Mechatronic project for final year students, in *Proceedings of the International Conference in Engineering Design ICED'03*, Stockholm, Sweden, August 19-21, 2003.
- [43] Grante C. Andersson J., Safety considerations in optimisation of design specification content, in *Proceedings of the International Conference in Engineering Design ICED'03*, Stockholm, Sweden, August 19-21, 2003.
- [44] Johansson A., Andersson J., Effect of Cross-Angle on Piston Forces and Bending Moments in Axial Piston Pumps, in *Proceedings of FLUCOME'03*, Sorrento, Italy, August 25-28, 2003.
- [45] Andersson J., Application of a Multi-objective Genetic Algorithm to Engineering Design Problems, in *Proceedings of the 2nd International conference in Evolutionary Multi-Criteria Optimization*, Faro, Portugal, April 8-11, 2003.
- [46] Zachrisson A., Rösth M., Andersson J., Werndin R., Evolve – A Vehicle Based Test Platform for Active Rear Axle Camber and Steering Control, in *Proceedings of SAE World Congress*, Detroit, USA, March 3-6 2003.