ABSTRACT
To be competitive in today’s global market, it is of great importance that product development is done in an effective and efficient way. To enhance functionality, modern products are often so-called mechatronic systems. This puts even higher demands on the product development work due to the complexity of such products. Simulation and optimisation have been proven to be efficient tools to support the product development process. The aim of this thesis is to study how the properties of mechatronic products can be efficiently and systematically predicted, described, assessed and improved in product development.

An industrial case study of a water jet cutting machine investigates how simulation models and optimisation strategies can be efficiently developed and used to enhance functionality, flexibility and performance of mechatronic products. The knowledge gained from the case study is shown to be useful for companies developing machine tools. Most likely it is also useful for developers of other mechatronic products.

The thesis shows that with the presented optimisation strategies, comprising a mix of different computerised optimisation algorithms and more classical engineering work, design problems with a large amount of design variables can be solved efficiently.

A specific result is a validated simulation model for simulation and optimisation of a water jet cutting machine. As all mechatronic disciplines of the machine tool are considered simultaneously, synergetic effects can be utilised. Optimisation studies show a significant potential for improving manufacturing accuracy, for manufacturing speed and for a more light-weight design. Carrying out simulation and optimisation has also provided a great amount of information about the studied system, potentially useful in coming product development work.

By reducing the number of physical prototypes through simulation and optimisation, the resource consumption during product development is reduced. Also, with more optimised products, the resource consumption can be significantly reduced throughout the whole use phase. These benefits support the competitiveness of the product developing company as well as a sustainable development of society as a whole."
Modelling, Simulation and Optimisation of a Machine Tool

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Abstract

To be competitive in today’s global market, it is of great importance that product development is done in an effective and efficient way. To enhance functionality, modern products are often so-called mechatronic systems. This puts even higher demands on the product development work due to the complexity of such products. Simulation and optimisation have been proven to be efficient tools to support the product development process. The aim of this thesis is to study how the properties of mechatronic products can be efficiently and systematically predicted, described, assessed and improved in product development.

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A specific result is a validated simulation model for simulation and optimisation of a water jet cutting machine. As all mechatronic disciplines of the machine tool are considered simultaneously, synergetic effects can be utilised. Optimisation studies show a significant potential for improving manufacturing accuracy, for manufacturing speed and for a more light-weight design. Carrying out simulation and optimisation has also provided a great amount of information about the studied system, potentially useful in coming product development work.

By reducing the number of physical prototypes, through simulation and optimisation, the resource consumption during product development is reduced. Also, with more optimised products the resource consumption can be significantly reduced throughout the whole use phase. These benefits support the competitiveness of the product developing company as well as a sustainable development of society as a whole.
Appended Papers

This thesis comprises an introductory part and the appended papers A-D. The papers have been reformatted from their original publication into the format of this thesis but the content has been kept the same.

Paper A


Paper B


Paper C


Paper D

The Author’s Contribution to the Appended Papers

The papers appended to this thesis are results of joint efforts. The present author’s contributions are as follows:

Paper A

Responsible for planning and writing of the paper. Responsible for modelling, simulation and validation.

Paper B

Took part in the planning and writing of the paper.

Paper C

Took part in the planning and writing of the paper.

Paper D

Responsible for planning and writing the paper. Responsible for the simulation and optimisation.
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## Appended Papers

- Paper A  
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1. Introduction

1.1. Background

In the future society, unnecessary use of resources will be minimised. This affects both development of new products and use of existing ones. Integration of sustainability aspects in product development is therefore gaining more and more interest [1]. Fortunately, it has been shown that product development, including prototyping, can be made more resource efficient by so called virtual prototyping [2-5]. Virtual prototyping takes advantage of the fact that most of the behaviour of a product can be simplified and described by mathematics. The mathematical relationships can be implemented into computer models, so-called simulation models, and solved numerically. The solution reflects certain aspects of the product’s behaviour.

It has been shown that virtual prototyping can be more resource efficient than more conventional prototyping, that it can cut the time to market and that it can provide a higher knowledge about the product, all important factors on a highly dynamic market with fast changes and high demands on the products.

A substantial amount of research has been done showing the potential of using simulation in product development [2-6]. The potential is especially high when it comes to development of complex products which have behaviours that are hard to foresee intuitively. Products in short series or expensive products like aircrafts or customized machine tools can also benefit from simulation support during development. A major advantage of building simulation models of not yet existing products is that they can be used in optimisation studies. This ensures that the physical product will perform as good as possible under some given circumstances.

Due to the increasing demands on products, in terms of performance, quality and price, and also due to the possibilities to reduce expensive mechanical complexity, electrical engineering and software technology are more common in today’s products than ever before. Such products are complex for the simple reason that they are multidisciplinary and therefore their behaviour is difficult to foresee. The trend to use more electronics and software in products will change the way we develop products [7].
The integration of mechanical engineering, electrical engineering and information technology is known as mechatronics [8, 9]. The development of mechatronic products is less intuitive and puts new demands on the product development process [8].

1.2. Aim and Scope

The aim of this thesis is to clarify some strategies for optimisation of mechatronic systems and especially machine tools. This includes clarifying how simulation models can be efficiently built from given criteria, such as demands on resource consumption in terms of computational effort and time.

The overarching research question of this thesis is; “How can properties of mechatronic systems be more efficiently and systematically predicted, assessed and improved in product development?”

To find an answer to the research question an industrial case study has been carried out, with the aim of clarifying what the challenges are in using virtual prototypes for optimisation and how optimisation algorithms can be altered to suit the specific system.

The case study deals with a machine tool; more specifically a water jet cutting machine. Models of the mechanical system, the servo drives and the motors are simulated and connected to a real control system. All together this describes the behaviour of the complete machine tool.

As a general background to the appended papers, an overview discussion is given in the following chapters. The definition of the term mechatronics as well as a product development methodology for mechatronic products are described in Chapter 2. Simulation and optimisation is introduced in Chapter 3. The case study is described in Chapter 4. Summaries of the appended papers are provided in Chapter 5 and conclusions and suggestions for future work follow in Chapter 6.
2. Mechatronics

There is not yet one accepted definition of mechatronics [7]. There are instead several definitions that might be close to each other but that do not totally coincide. The definitions range from meaning an extended application of “motion control” technology into comprising everything treating modern products. The wide variety of definitions of mechatronics is troublesome since a definition that is too broad, encompassing almost everything, actually encompasses almost nothing and a definition that is too narrow does not do justice to the richness of the field [10].

Originally, the term mechatronics was coined in 1969 at YASKAWA Electronic Corporation [8, 11] to describe the electronic functional enhancement of mechanical products, in terms of brushless DC-motors in machine tools. The word came from merging the first part of mechanics with the last part of electronics. Soon, also information technology was introduced as a third discipline distinguishing the expression from electro-mechanics. A Venn-diagram as shown in figure 1 is often used to illustrate “mechatronics”. Over the years the term mechatronics has taken on a wide meaning, and is today a term describing an engineering discipline.

![Venn diagram of mechatronics](image)

*Figure 1. Venn diagram of mechatronics.*

Mechanics or mechanical engineering is the discipline which is the foundation of mechatronics, at least in the opinion of the author of this thesis. The electronics and the information technology might be as important as the mechanics but in terms of basic functionality the mechanical system is the dominant. Rolf Isermann is quoted as follows in [8]:

3
“Mechatronics is an interdisciplinary field in which the following disciplines interact: mechanical systems and systems coupled with them, electronic systems, information technology. The mechanical system is dominant here with regard to the functions. Synergetic effects are aimed for, comprising more than the mere addition of the disciplines.”

Two very important points can be extracted from this formulation. First, as mentioned; the mechanical system is dominant regarding the functions, meaning that although the electronics and information technology might add and improve functionality, it is the basic functionality of the mechanical system that is central, and by that the most important. Some even go as far as calling mechatronics a sub-discipline to mechanical engineering. Secondly, the integration of the three disciplines shall give rise to synergetic effects adding more value to a product than the mere addition of the disciplines. To use an old cliché; “The whole is greater than the sum of its parts”.

The main reasons to marry the three disciplines are to enhance the functionality, performance and flexibility, as well as simplify otherwise complicated mechanical products. Other great advantages of the integration are that it facilitates fundamentally new solutions with improved cost/benefit ratio as well as provides stimulus for new products.

Controlled systems have been around for a long time with good examples in the Watt governor, the Jacquard loom and other sometimes very complex mechanical systems. In common for all these controlled system is some kind of computation or information processing. Information technology, sometimes called software engineering, together with electronics is used for doing the computations in a mechatronic system.

The mechatronic technology has been driven by the explosive trend in automation within the automobile industry together with numerically controlled systems in the machine tool industry.

To understand the meaning of mechatronics it is a good idea to study the content of a mechatronic system. Once one is able to spot a mechatronic system it is easier to understand the core meaning of the discipline.

2.1. Parts of Mechatronic Systems

All mechatronic systems are built up according to figure 2, with a control system, actuators, sensors and a basic system which the actuators act upon and the sensors pick up information from. The basic system can be any type of physical system such as mechanical systems.
A sensor supplies state variables of the basic system to the control for information processing. Normally sensors are physical but occasionally they can be represented by software as so-called observers [8,12]. There are numerous sensor types, reading temperatures, light intensity, magnetic fields, force, displacement and many other system properties. Sensors usually convert the physical property or state to a proportional electrical signal carrying state information.

An actuator converts information from the control into energy acting on the basic system. Actuators can be electrical motors, piezo-electric drives, hydraulic, pneumatic drives, etc.

There are often other parts included or linked to a mechatronic system such as the interaction with humans and the environment, but figure 2 shows the parts that are always included.

2.2. Product Development within Mechatronics

Product development can be seen as an iterative decision-making process. To make well-informed decisions, it is necessary to have good knowledge about the studied system, and this as early in the product development process as possible. Changes late in the product development process cost more time and money. It is therefore of great importance to increase the knowledge about the studied system as early as possible. This can be done through experimentation either on physical systems or on virtual systems [3, 13].

The multidisciplinary nature of mechatronics puts new demands on product development. The basic disciplines that make up mechatronics have totally different product development methodologies, and no methodology can be directly applied as the product development methodology for mechatronic systems.
Since the mechanical engineering discipline is the most important field of mechatronics, this has influenced the development methodology of mechatronics the most.

A mechatronic system can be broken down into its components of basic system, electrical system and its software. The components can, however, not be developed separately. The very important synergetic effects would then be missed. The development of a mechatronic product therefore has to be seen as a system all the way through the whole development process, and only be separated as components when the functionality of the component has been established and the domain-specific design is carried out.

One should remark that a mechatronic system can be developed by designing electronics and software for an existing mechanical system and vice versa, however such a mechatronic system is not likely to perform as good as a mechatronic system that was designed as a system.

The life cycle of modern products is much shorter now than ever before, much due to the introduction of electronics and information technology. This leads to the need to shorten innovation cycles for companies to stay competitive. One way of doing this is to have a well-structured product development strategy together with state of the art product development tools. A short description of a structured way of doing product development is given below.

All successful product development strategies start with defining the product requirements in order to clarify the task, and planning for the product development work. These requirements define the product in terms of functionality and performance. The requirements are important for judging the outcome of product development. There is no way of declaring a design successful if it is not measured against requirements.

When the requirements are defined, the next step is to come up with a conceptual design for the complete system, aiming at breaking down the main function into sub-functions, and assigning them to the domains involved. This means that the domain-specific development methodologies are applied on specific sub-functions.

Once the domain-specific design has taken place everything is put together to form the complete mechatronic design. The challenges in this integration are the interfacing, making the parts work together in an efficient way, and how to make the parts compatible. To make the interfacing as easy as possible and make the parts as compatible as possible, this has to be considered already when the conceptual system design is carried out. It is in this integration the important synergetic effects might show up. When all the included parts have been put together to a complete mechatronic system, its properties have to be studied and measured against the requirements and the expected characteristics of the
conceptual design. This investigation can be done through real experiments, virtual experiments or through a combination of these. It has also been shown [14] that modelling and model analysis can help during both the conceptual system design and the domain-specific design to increase the understanding and knowledge. Once again the multidisciplinary nature of mechatronics is making the experimentation a somewhat more complicated task, but also more important. For this reason one chapter of this thesis describes virtual experiments as an important tool in product development of mechatronic systems.

This procedure of product development is very well explained in [8], where the so-called V-model for development of mechatronics is used to explain the methodology. Figure 3 shows the V-model, which makes it easier to follow the different steps of product development.

![Figure 3. Redraw of V-model [8].](image)

The V-model can be used in an iterative process throughout all the maturity stages of a product, as seen in figure 4 where every step through a product’s maturity is handled according to the same overall procedures.
Figure 4. Redraw of iterative V-model [8].
3. Simulation and Optimisation

As stated in the previous chapter, simulation or virtual experimentation is very important for successful development of mechatronic products. For this reason it seems appropriate to provide a brief introduction to simulation and its full potential as a tool in product development for mechatronic systems.

Product development can be seen as an iterative decision-making process [5] and it is important that well-informed decisions are made throughout the whole product development process. Experimentation can enable good decisions by raising the level of knowledge about the studied system.

In this thesis, simulation refers to experimentation on virtual models. Other definitions can be found in the literature. Experimentation is here defined as the act of conducting a controlled investigation for the testing of an idea or hypothesis aiming at an increased knowledge of the studied system. A model is a simplified representation of a system; it can be either a physical or a virtual model. Physical models can, for instance, be scale models or early prototypes built to give knowledge about one or many studied properties. Virtual models can be mathematical models solved either analytically or more often numerically. Building virtual models can either be done through so-called experimental modelling, where experiments constitutes the basis for the model via, for example, measurements and parameter estimations, through so-called theoretical modelling where theories form the basis, or a mix of the two.

To be able to trust a simulation model for use in the product development work its properties have to be investigated through verification and validation. Verification is commonly described as the investigation if the model works as intended and validation is often defined as the investigation of whether the model is useful for the intended purpose or not. The validation criteria might be grouped as follows [14]:

- **Empirical validity** – Correspondence between measurements and simulations.
- **Theoretical validity** – Consistency of a model with accepted theories.
- **Pragmatic validity** – Capability of the model to fulfil the desired purpose.
- **Heuristic validity** – Potential for testing hypotheses, for the explanation of the phenomena and for the discovery of relationships.

To fulfil all these criteria a large variation of validation strategies need to be applied, for instance through comparison with measured data or through sensitivity analysis.
Models can have different levels of fidelity, meaning to what extent a given representation reproduces the studied system. The highest level of fidelity is only possible with an exact replica of the studied physical system. Increasing the fidelity of a model normally increases the cost to build the model. It is therefore important to find a middle way, where the fidelity is high enough for the purpose but not too high, causing immense costs.

A simple model is always preferable if it fulfils requirements on fidelity and validity, due to the cost to build very detailed and complex models. A simple model is also easier to validate. The appended paper A shows an example of how a very complex system can be modelled in a very simple way without compromising on validity or fidelity. It is also of no use to build more complex and detailed models than what can be validated.

To justify the use of virtual experiments as a substitute for physical experiments a short summary of the main benefits follows. Virtual experiments are often more resource efficient than physical experiments, in terms of money, time and natural resources. Some states might not be measurable on a physical system, at least not with non-destructive methods. Virtual models are controllable and experiments on them are repeatable, something that cannot be guaranteed with physical models. Virtual experiments can be carried out in the time frame that suits the observation method best, something that cannot be done with physical experiments where all testing needs to take place in real time. Virtual experiments do not break any moral rules as might be the case with questionable experiments on humans or on vulnerable natural systems. Some disadvantages shall also be stated. All virtual experiments need validated and verified models of the system, where physical experiments can be done on already existing systems. The performance of a simulation model is limited by the computer capacity available, something that is very clear when simulations need to be done in real-time as in the case study of the appended papers.

An important factor of simulation is the knowledge found when building virtual models. This is often not fully recognised. The finished model is instead seen as the only outcome of modelling. When a virtual model is built, the builder learns about the physics of the studied system as well as how it can be simplified and described as straightforward as possible.
3.1. Optimisation

Figure 5 shows a flow chart of traditional product development where all experimentation is done on physical systems.

![Flow chart of traditional product development process.](image)

Figure 5. Traditional product development process.

The iterative process of modifying and improving physical prototypes and products is very costly as regards both money and natural resources. If instead the prototyping and testing is done virtually the resource consumption can be decreased. Figure 6 shows a flow chart of a product development process that uses virtual prototyping and by this moves the resource-consuming actions outside the iterative process.
The iterative process of such a process can be made with very low costs for each iteration. This means that a large number of different designs can be evaluated more or less automatically and therefore a more optimal design can be found.

The meaning of optimising is to find the “best design”. To do this one need to define what is meant by “best design”. An objective also needs to be defined, that is a quantitative measure of performance, and some design variables affecting the objective. The need for design variables restricts optimisation to a tool in product development for an already established concept. It is not possible to put up optimisation studies before an overall description of the developed product exists. The early stages in conceptual design can however still make use of simulation as a tool in the design work, and by this reduce the need for physical prototypes; so-called simulation-driven design [4, 5].

When setting up an optimisation problem it is also necessary to clarify what constraints the design variables and objectives are subjected to. A large number of optimisation algorithms can be applied to solve the optimisation problem, all with different advantages and disadvantages depending on the current problem.
As for most tools supporting product development, optimisation shall be seen as an aid and not as a replacement to engineering. The decision making still needs to be done by humans. The results of paper D indicate that computerised optimisation mixed with classical engineering is the most efficient way to design products.
4. Industrial Case Study

4.1. Machine Tools

A machine tool’s main function is to position a tool and/or work piece for machining. This positioning can either be done manually or by a control system which uses some kind of actuator for positioning.

According to the prior given definition of mechatronics, modern machine tools are mechatronic systems, containing the basic mechanical system, control system, sensors and actuators.

Modern machine tools have computer numerical control systems or CNC systems. CNCs can have different degrees of complexity. The control system of a modern machine tool often takes instructions in the form of text, numbers or some other type of code. The instructions are processed and the control system sends out the position commands to servo drives. Normally the machine position is fed back to the control system via sensors closing a control loop.

The actuators of a modern machine tool are usually electrical motors, often permanent magnet synchronous motors, which are driven by digital servos and drives. The close integration between the dynamic behaviour of the mechanical structure, servo drives, and numerical control requires skilled designers, capable of having a holistic view of the design process, and of the objectives. Machine tools are more thoroughly described in [15].

Figure 7 shows an example of a modern machine tool.

![Figure 7. Example of a water jet cutting machine, courtesy of Water Jet Sweden AB.](image-url)
The dynamics of a machine tool is dependent of its pose, that is, the mechanical structure cannot be described in one way only but needs to be described for every possible position of the tool and work piece.

In the case study of this thesis the studied machine tool is a water jet cutting machine. Water jet cutting is described further in [16].

4.2. Product Development of Machine Tools

Designing machine tools differs some from designing mechatronic systems in general. The main difference lies in that the domain-specific design of control systems and servo drives has come a long way and machine tool designers often use standard control systems and servo drives almost regardless of what kind of machine tool they are designing. This does, however, not mean that the design work becomes an easier task. The control systems are built in a general way with the aim to fit any type of machine tool and for this reason the control systems become very complex with a lot of variables that can be changed between different types of machine tools. Setting these variables so that they fit the specific machine tool becomes one of the greatest challenges.

Since synergetic effects between control system, servo drives and the mechanical system is sought for it is of great importance that the control system is set up in parallel with the design of the mechanical system. It is very common that the mechanics are built first and after that the control system is adjusted to fit the construction as well as possible. It is shown in appended paper C that the final machine tool can be designed in a better way considering the complete mechatronic system in parallel throughout the complete product development work, utilising synergetic effects.

4.3. Simulation and Optimisation of Machine Tools

Simulation and optimisation of machine tools have been shown to be interesting subjects for research [17]. Although optimisation of solely the mechanical system is shown to be a good tool in the design process [18, 19] it has been demonstrated that the complete mechatronic system needs to be studied to utilise the full potential of optimisation [20, 21].

To be able to perform virtual experimentation and optimisation on a machine tool it needs to be simulated as a complete system. This means that all included parts such as mechanical parts, electrical parts and control system need to be included in the simulation.

It would be extremely complex to reproduce correctly the dynamic behaviour of the control system. This complexity can be dealt with by two approaches; either by using a real control system and connecting that to the simulation models or by using so-called “soft control systems” provided by some of the NC control
suppliers. In the case study of this thesis, the first approach is used, with a unique simulation model of a complete machine tool, including a physical control system that is automatically configurable for use in optimisation studies.

Since the real control is connected to the simulation model, there are extreme demands on the speed/performance of the model. In this work the models are deployed on a real-time operating system, enabling solving times of less than 100 microseconds.

The simulated machine tool is described in further detail in [22]. The appended papers B, C and D present optimisation strategies for optimisation of a complete machine tool with different numbers of objectives and variables, showing the potential of using optimisation in product development and in utilising the full potential of existing products.
5. Summary of Papers

5.1. Paper A

In this paper a highly simplified model of a servo motor and servo drive is presented, as a part of the development of the virtual water jet cutting machine. The aim was to develop a robust model of the commonly used permanent magnet synchronous motor and their servo drives. Here, robust includes the model being: sufficiently accurate for different motor characteristics without extensive “tuning”, dependent only on commonly available data, computationally efficient and numerically stable. Simulation results for various configurations agree well with corresponding experimental results obtained from a physical test setup. The suggested model makes it possible to readily implement any permanent magnet synchronous motor and servo drive in a simulation model of machine tools.

5.2. Paper B

In this paper a virtual model of an existing water jet cutting machine is used in an introductory optimisation study, aiming at utilising the full potential of the machine tool by altering control system settings and NC-programs, for each specific work piece. Two test cases with different geometry and geometrical tolerances are manufactured “virtually”. It is shown that the ability to adjust the CNC machine tool parameter setting to a specific work piece may significantly increase manufacturing productivity. This improvement would most likely not have been possible without this advanced simulation support within the same time, cost and general resource frame.

5.3. Paper C

In this paper the virtual model of a water jet cutting machine is used in an introductory optimisation study, aiming at improving the existing design of a water jet cutting machine regarding weight and manufacturing accuracy at maintained manufacturing speed. The design problem can be categorised as constrained multidisciplinary multi-objective multivariable optimisation. An optimisation approach using a genetic algorithm is therefore deployed. The outcome of the study, a significantly improved machine tool design, is presented and compared to the original design. It is also shown that interaction effects exist between structural components and control. Hence, this design improvement would most likely not have been possible with a conventional sequential design approach within the same time, cost and general resource frame. This indicates the potential of the virtual machine concept for contributing to improved efficiency of both complex products and the development process for such products.
5.4. Paper D

In this paper the virtual model of a water jet cutting machine is used in an optimisation study of a complete machine tool, with design variables within all mechatronic disciplines. The main goal was to design a water jet cutting machine with qualities satisfying a typical machine tool buyer, namely cutting as many parts as possible, within given tolerances, over a short a time as possible. Instead of making a multi-objective optimisation, one objective is chosen to be the most important one. By doing this, the post-processing work becomes more important. An iterative optimisation strategy was deployed using genetic algorithms together with gradient-based algorithms. Throughout the iteration, more hands on engineering work was carried out, controlling the convergence tests and updating tolerances and constraints. Once the optimisation did converge and one optimum was found, a substantial amount of work was carried out in post processing. The aim was to extract as much information (knowledge) as possible about the studied system. Studying the results implies that doing parameter studies would not be enough but an actual optimisation is necessary to find the best possible machine within a reasonable amount of time. It is shown that to be able to solve optimisation problems with a large number of design variables within a reasonable amount of time, an optimisation strategy utilising many computerised optimisation algorithms together with classical engineering work is effective.
6. Conclusions

The potential of using simulation and optimisation in product development of mechatronic systems is shown to be efficient and effective through an industrial case study. In the case study a water jet cutting machine, a type of machine tool, is studied as an example of a mechatronic system.

The multidisciplinary nature of mechatronic products puts high demands on the product development process, on simulation models as well as on optimisation strategies. When dealing with mechatronic products it is of great importance to consider all sub-disciplines in parallel, in order to be able to consider the important synergetic effects.

Simulation models of all included parts need to be validated, verified and efficient for the specific purpose. In the studied case, simulation efficiency is very important due to the demands on real-time capability. This demand comes from the use of a physical control system.

Through efficient optimisation strategies suggesting a mix of computational work and classical engineering work, complete mechatronic systems can be simulated and optimised. In this work an efficient optimisation strategy is presented, enabling the solving of optimisation problems with a large number of design variables. The efficiency is especially important when the strategy is used on optimisation problems where evaluation of the objective function for each set of variables takes a considerable amount of time. In earlier work, the number of design variables was limited due to the lack of an efficient optimisation strategy, limiting the possibility to optimise the complete mechatronic system.

An increasingly important factor in every engineering discipline is the sustainability problem of today’s society. Using simulation and optimisation as a substitute for physical prototyping is a good way of reducing resource consumption during product development. Also, with more optimised products the resource consumption is reduced throughout the whole use phase. These benefits support the competitiveness of the product developing company as well as a sustainable development of society as a whole.

The final simulation model and its results are usually seen as the only outcome when building simulation models. It is, however, probable that the process of building the models is as important as the final results. A lot of information about the studied system can be obtained during the process of building simulation models. The same reasoning can be used for optimisation; the final result is only one part of the outcome, the information about the studied system obtained while optimising is also a very important outcome.
On a general level this thesis contributes to science and technology by pointing out the importance of knowledge and information handling when using simulation and optimisation in product development. This thesis also contributes by confirming conclusions made by others regarding the benefits of optimisation and simulation in product development of mechatronic products, while emphasising the importance of efficient optimisation methods using real-time simulations. Contribution is also done by elaborating on the V-model together with simulation and optimisation as tools for product development of mechatronic products.

On a more specific level this thesis presents a simplified, validated and interchangeable real-time simulation model of servo motors for use in optimisation studies of machine tools. It is also suggested how optimisation can be used to utilise the potential of a water jet cutting machine as well as how optimisation can be used in the product development work of machine tools.

Interesting for future work is to find a way to clearly incorporate optimisation in the V-model. It would also be interesting to validate the optimisation algorithms, by, for example, building physical interchangeable prototypes.

One question, raised while carrying out this work and one that has not yet been treated, is how the information and knowledge gained while simulating and optimising can be used for improving mechatronic products, apart from information obtained about the optimum design.
References


A Robust Motor and Servo Drive Model for Real-Time Machine Tool Simulation
Paper A is published as:

A Robust Motor and Servo Drive Model for Real-Time Machine Tool Simulation

Johan Fredin, Johan Wall, Anders Jönsson and Göran Broman

Abstract

Modern machine tools are complex mechatronic systems. Recently “virtual machines”, incorporating models of relevant parts such as structural components, sensors, actuators and controls, have been proposed as design tools - to aid resource efficient experimentation for better understanding of the complete system and utilization of possible interaction effects. This paper focuses on actuator modelling, as part of the development of a virtual water jet cutting machine. The aim is to develop a robust model of the commonly used permanent magnet synchronous motors and their servo drives. Here, robust includes that the model should be: sufficiently accurate for different motor characteristics without extensive “tuning”, dependent only on commonly available data, and computationally efficient and numerically stable. A novel simple motor and servo drive model is presented and implemented in Simulink. Simulation results for various configurations agree well with corresponding experimental results obtained from a physical test setup. Furthermore, it is shown that the model is capable of producing sufficiently accurate results within the cycle time of the control system of the virtual machine (real-time capability) and it is concluded that numerical instability does not appear for any of the tested configurations even for integration time steps up to this cycle time. The suggested model makes it possible to readily implement any permanent magnet synchronous motor and servo drive in the virtual machine. This enables efficient system simulation to aid well informed design decisions regarding motor selection without expensive and resource consuming trial and error approaches with physical prototypes.

Keywords: Product development, Simulation, Machine tools, Virtual machine, Permanent magnet synchronous motor, Servo drive, Mechatronic system.
1. Introduction

Designing modern machine tools is a great challenge since these are often complex mechatronic systems. Successful design requires good understanding of included parts as well as of their interaction. To meet this challenge in water jet cutting machine design a “virtual machine concept” has been developed in earlier work [1, 2]. This includes virtual models of structural components, sensors and actuating devices. This machine simulation is connected to a physical control system and a virtual reality visualisation for overview understanding of the complete system. The use of a physical control system, which needs continuous sensor feedback, introduces real-time demands in the virtual models. The concept is shown in Figure 1.

![Figure 1. Virtual machine concept.](image)

The virtual machine enables resource efficient experimentation in comparison to traditional experimentation strategies based on physical prototypes. The potential of this concept as a design tool has been shown in an introductory optimisation study [3].

The focus in earlier work has been on developing accurate models of the structural components and the sensors [3, 4]. Highly simplified models of the actuating devices have been used and very limited investigations of their accuracy have been done. The motor model used up until now requires, for example, a lot of parameter adjustments to agree well with the corresponding physical motors and the servo drive is not at all included.

The aim of this paper is to develop a robust model of the commonly used permanent magnet synchronous motors and their servo drives. Here, robust includes that the model should be sufficiently accurate for different motor characteristics without extensive “tuning”, that data needed for the model should be commonly available in data sheets and manuals, and that it should be computationally efficient and numerically stable. The purpose is to facilitate inclusion of actuators in whole system optimisation.
If, in the design process, a motor is changed to another motor with different
characteristics, the motor model should still be valid, that is, it should also for
the new motor data agree with the corresponding physical motor. Motor models
that are dependent on data that is not available (secret) to the end user (machine
designer) are obviously not useful for optimisation. Such lack of information is
often the case. In this paper, emphasis is therefore put on developing models
that can be defined solely from commonly available information.

Simulation models of permanent magnet synchronous motors are often
expressed in a rotor fixed reference frame [5-7]. It was, however, noticed that
instability can occur when the time step in such simulation models is increased.
This is confirmed in the literature [8] and must be considered to be a significant
drawback when real-time simulation is desired. Therefore, a highly simplified
but seemingly sufficient theory for torque production in such a motor is
developed and implemented in the simulation models.

2. Studied System

A typical machine tool includes of several axis. For each axis an electrical
motor is usually used to actuate the mechanical parts. The motion pattern for the
motor is described by a control system. The signals from the control system are
amplified in a servo drive to give the right amount of power to the motor. When
the virtual machine is used to support actual design work, the motor and servo
drive model is an integrated part of the whole machine tool model. However,
since the focus of this paper is the motor and servo drive model itself, a
simplified system is studied, with the mechanical parts represented as pure
inertia loads.

The structure of the studied servo drive can be seen in Figure 2. Where the
dash-dotted line encloses what is usually included in a fully digital servo drive,
where all servo loops are handled by the control system and the power inverter
is communicating with the control system digitally. Such a control system is
used in the real water jet cutting machine.
The servo drive consists of a number of control loops. A position loop generates a velocity command by processing the deviation between the motion command and the position feedback from the motor. The velocity command is compared to the velocity feedback and processed in the velocity loop creating a torque command. Since the torque-current relationship is assumed to be linear, the torque command can be seen as a current command. The current command is compared to the current in the motor windings and is processed in the current loop to a voltage command. The power inverter converts the voltage command into the voltage given to the motor windings.

Unfortunately the digital signals are not accessible in the present virtual water jet cutting machine setup (due to restrictions from the control system supplier), so as a compromise an analog interface is used to read the velocity command from the control system. The velocity command is a voltage proportional to the velocity, and a parameter in the control system is set to define the voltage-velocity relationship. In effect, the control system of the present setup can therefore be seen as the part inside the dashed line in Figure 2. This means that in-house models for the velocity loop, the current loop and the motor position feedback must also be developed.

Data for the studied motor and servo drive, available from the manufacturer, is shown in Table 1.
**Table 1. Motor and servo drive data.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Speed</td>
<td>( N_{\text{max}} )</td>
<td>5000</td>
<td>rpm</td>
</tr>
<tr>
<td>Maximum Torque</td>
<td>( T_{\text{max}} )</td>
<td>8.8</td>
<td>Nm</td>
</tr>
<tr>
<td>Rotor Inertia</td>
<td>( J_{\text{rot}} )</td>
<td>0.000515</td>
<td>kgm(^2)</td>
</tr>
<tr>
<td>Torque Constant</td>
<td>( K_t )</td>
<td>0.66</td>
<td>Nm/A (RMS)</td>
</tr>
<tr>
<td>Back EMF Constant</td>
<td>( K_v )</td>
<td>0.22</td>
<td>Vs/rad (RMS)</td>
</tr>
<tr>
<td>Armature Resistance</td>
<td>( R_a )</td>
<td>0.61</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>Maximum Current of Servo Amp</td>
<td>( I_{\text{max}} )</td>
<td>20</td>
<td>A (peak)</td>
</tr>
</tbody>
</table>

3. A Model of Permanent Magnet Synchronous Motors and Servo Drives

To accurately model all aspects of the motor and servo drive in the water jet cutting machine, much data that is usually hard to access has to be known. With the aim of creating a simulation model based on data normally given to the end user of the motors and servo drives, such as data sheets and manuals from the manufacturer, the part models have to be fairly simple. Of course, the resulting model still needs to produce accurate enough simulation results for some relevant aspects of the physical system. Models of the control loops and the motor, respectively, following these intentions, are presented below, where the mechanical system and model constraints are also briefly discussed.

3.1. Control Loops

The power inverter together with the current loop is providing the motor windings with the right amount of current according to the current/torque command given from the velocity loop. The current in the windings depends on the applied voltage and the way the circuits are constructed. However, details of
this are often unknown. Instead an ideal current control is therefore assumed, meaning that the current in the windings is at all time the same as the current command given from the velocity loop. In this way, there is no need for further models of the current loop and the power inverter.

The simulated velocity loop should perform as the velocity loop in the actual digital servo. It is known from the control system description that this velocity loop is a proportional integral control (PI control). A velocity loop scheme according to Figure 3 is therefore assumed. This is one of the most common PI schemes for velocity loops found in the literature.

![Figure 3. PI control loop scheme.](image)

The input named VCMD is the velocity command from the position loop in the actual control system. The velocity is represented as a voltage proportional to the velocity and converted to angular velocity in the block named “Voltage to Velocity”. The conversion is defined by a setting in the control system. The input named VEL is the angular velocity of the rotor of the motor. The difference between the reference value and the actual value is run through the two gains and the integrator to create the torque/current command. The parameters of the simulated velocity loop are given values that make it agree with the behaviour of the actual control system. Some control system settings have to be changed, in order to make the axis with the analog interface agree better with the digital servo axis.

### 3.2. Motor Model

The studied motor is of a permanent magnet synchronous type with sinusoidal stator currents. The stator consists of three windings, evenly distributed around the rotor, that is, the stator windings are located 120 degrees apart. By applying a three phase current over the windings with an electrical phase difference of 120 degrees, as shown in Figure 4, a rotating magnetic field is created. The rotor angle is denoted with $\theta$. 
Maximum torque is achieved when the magnetic field rotates synchronously with the rotor of the motor [5], that is, when the angle between the rotating magnetic field and the rotor of the motor is kept constant.

The relationship between applied stator current and the produced torque is called the torque constant and is a motor-specific constant given by the manufacturer. This is denoted $K_t$ in Table 1. The torque on the rotor produced by an individual stator winding is dependent on the angle between the rotor and that stator winding. The total torque of the three windings can therefore be written as

$$T = \frac{1}{\sqrt{2}} \cdot K_t \cdot I$$

(1)

where

$$K_t = K_t \begin{bmatrix} \sin \theta & \sin \left( \theta - \frac{2\pi}{3} \right) & \sin \left( \theta - \frac{4\pi}{3} \right) \end{bmatrix}$$

(2)
and

\[
I = I \cdot \begin{bmatrix}
\sin \theta \\
\sin \left( \theta - \frac{2\pi}{3} \right) \\
\sin \left( \theta - \frac{4\pi}{3} \right)
\end{bmatrix}
\] (3)

where \( I \) is the amplitude of the current applied to the windings. The factor square root of two is introduced since \( K_t \) in Table 1 is based on the root mean square (RMS) value of the current.

Expanding equation (1) gives

\[
T = \frac{1}{\sqrt{2}} \cdot K_t \cdot I \cdot \left( \sin^2 \theta + \sin^2 \left( \theta - \frac{2\pi}{3} \right) + \sin^2 \left( \theta - \frac{4\pi}{3} \right) \right)
\] (4)

which can be written as

\[
T = \frac{3}{2 \cdot \sqrt{2}} \cdot K_t \cdot I
\] (5)

The simulation model for converting current into torque thus consists of a simple gain. With the previous assumptions, the input is the current command from the velocity loop and the output is the produced torque.

**3.3. Mechanical System**

The mechanical part of the model is derived from Newton’s second law of motion. The expression is

\[
J \cdot \ddot{\theta} = T - c \cdot \dot{\theta}
\] (6)

Where \( J \) is the total mass moment of inertia, including applied load and rotor inertia, \( \ddot{\theta} \) is the angular acceleration, \( T \) is the torque, \( \dot{\theta} \) is the angular velocity and \( c \) is the damping coefficient. The damping coefficient unfortunately needs to be estimated. It is adjusted to make the agreement between the physical system behaviour and the simulated behaviour as good as possible. This is, of course, a drawback of the motor model. However, when the motor model is part of the whole machine tool model, the damping of the motor is probably small compared to the total damping. And this total damping needs to be estimated.
Damping estimation is therefore not considered to be a serious drawback of the motor model.

3.4. Constraints

In Table 1 the maximum current and the maximum torque for the servo system is given. These constraints are implemented by limiting the torque output from the motor and limiting the current output from the PI-loop.

The simulation model of the total motor and servo drive system is shown in Figure 5.

The input in the simulation model is the velocity command from the control system and the output is the rotor angular velocity.

![Figure 5. Complete simulation model of motor and servo drive system.](image)

4. Experimental Setup

To validate the simulation model a simple experimental setup is used. In this, a corresponding physical motor and digital drive (Table 1) is run with loads in the form of steel discs with well defined moments of inertia. By varying the number of discs the load can be varied in the range from no external load (only the inertia for the rotor of the motor) to loads equivalent to a complete machine tool axis. This makes it possible to investigate the robustness of the simulation model.

The physical and the simulated servo drives are controlled by the same control system. The motion pattern is programmed to be exactly the same for the two drives, which makes direct comparisons between their outputs possible.
5. Results

To judge how well the motor and servo drive model agrees with the physical one, simulated and measured velocities are compared during a forward-backward rotation. Figure 6 shows typical velocity curves.

![Figure 6. Simulated and measured velocity curves.](image)

The area enclosed by the dotted line in Figure 6 is zoomed in and shown in Figure 7. The agreement between the simulated and the measured velocities is good. The same good agreement is obtained with other loads, with other velocities and with other parameter settings for the control loops. This indicates the robustness of the simulation model.
It could be interesting to make the same comparison also with the motor and servo drive model that has been used in the virtual water jet cutting machine up until now. This includes a direct current motor model, which is straightforward and easy to understand. A severe drawback is, however, that, unknown data needs to be estimated and re-estimated for new configurations. It was implemented as a quick solution to get the system up and running for proving the concept of the virtual machine. Typical results are shown in Figure 8, where the same area as in Figure 7 is zoomed in. It is obvious that the new model performs much better when acceleration is going over in constant velocity.
Real-time performance of the simulation model is crucial since the physical control system cannot be run without continuous feedback from the sensors. Through numerous test runs it is shown that the new model is also capable of producing sufficiently accurate results within the cycle time of the control system of the virtual machine. Since the motor and servo drive model is only a small part of the whole machine tool model, it is important that it is computationally efficient. Keeping the model simple aids this. Being able to use longer integration time steps also helps as regards computational efficiency. Extensive tests with different time steps shows that numerical instability does not appear for any of the tested configurations even for time steps up to the cycle time of the control system. Thus the model seems to be robust also in this respect.

6. Conclusion

The presented work is part of a project aiming at developing a “virtual machine” intended to aid the design of machine tools (mechatronic system). In this project, actuator modelling has been identified as a weakness. A novel
simple permanent magnet synchronous motor and servo drive model is therefore presented and implemented in Simulink. Simulation results are generated for various configurations and compared to corresponding experimental results obtained from a physical test setup. The agreement is good. The model shows good computational efficiency (real-time capability) and numerical stability. The superiority of the model compared to a model used in the virtual machine up until now is also shown.

In summary, the suggested model makes it possible to readily implement any permanent magnet synchronous motor and servo drive in the virtual machine (using commonly available data). This enables efficient system simulation to aid well informed design decisions regarding motor selection without expensive and resource consuming trial and error approaches with physical prototypes. A small remaining drawback is that the mechanical damping still has to be estimated and adjusted. However, the damping is quite simple to make a decent estimation of, the damping in the motor is relatively small compared to the total damping in the machine tool (making it less important how well the motor damping is estimated), and this total damping needs to be estimated anyhow. This is therefore not considered to be a serious drawback of the presented model.

7. Acknowledgments

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Paper B

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Increasing Productivity in CNC Machine Tools through Enhanced Simulation Support – an Introductory Study

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Abstract

One way to increase the productivity of numerically controlled machine tools is to optimise settings such as parameters in the NC-program or in the control system for each specific work piece. Finding optimal parameter settings through trial and error testing is in the general case impractical. The increased productivity potential of optimal parameter settings can however be realised through incorporation of computer simulations and numerical optimisation.

The aim of this work is to show the potential of a “virtual machine” as a tool to increase productivity within manufacturing industries through optimisation of CNC machine tool parameter settings. Two test cases with different geometry and geometrical tolerances are manufactured “virtually”. It is show that the ability to adjust CNC machine tool parameter settings to a specific work piece may significantly increase manufacturing productivity. This improvement would most likely not have been possible without advanced simulation support within the same time, cost and general resource frame.

Keywords: CNC machine tools, Manufacturing, Optimisation, Productivity, Simulation, Virtual machine.
1. Introduction

To stay competitive on today’s global market manufacturing companies are forced to increase their productivity [1, 2]. As a consequence, every opportunity to save time is valuable. Methods and tools to aid this is therefore of interest.

There are numerous ways to increase productivity. A straightforward way is, for example, to invest in more efficient equipment. A more attractive approach is however to utilise existing resources better. One way to do so for numerically controlled machine tools is to optimise settings such as parameters in the motion control code or in the control system for each specific work piece (product) so that the manufacturing speed is as fast as possible while achieving required geometrical tolerances for that particular work piece. Machine tool users does not normally change control system parameters in their machines. By relying on the default settings made by the builder of the machine users may miss out on a potential for increased productivity. The default settings are commonly made to suite a wide variety of parts with different geometry, material et cetera. These settings may therefore be far from optimal for a specific part.

Finding optimal parameter settings through trial and error testing is in the general case impossible due to resource restrictions (time and money). The increased productivity potential of optimal parameter settings can however be realised through incorporation of computer simulations and numerical optimisation. Simulation tools are nowadays common in the manufacturing industry. Their traditional application is however manufacturing system design, for example predicting the need for and quantity of equipment and personnel, and simulation for scheduling [3, 4]. Several opportunities to widen the scope of simulation tools and methodologies within the manufacturing industry exist. Optimisation of parameter settings in CNC machine tools is such an example.

Modern machine tools are mechatronic systems, i.e. multi-disciplinary products including mechanical as well as electronic components and computerized control systems. Designing and optimising such systems demands an overall understanding of the behaviour of the complete system. Advanced simulation tools are therefore needed, incorporating all relevant aspects of the multi-disciplinary design problem. A virtual machine concept to support simulation-driven mechatronic design of CNC machine tools has therefore been developed in earlier work [5]. The virtual machine includes a real control system and simulation models of the machine having real-time capabilities. This parallel
multidisciplinary design approach, simultaneously analyzing the mechanics and the control, and thereby utilising interaction effects, is believed to be superior to the traditional sequential design approach [6, 7]. Other works related to the idea of a virtual machine are, for example, [8, 9]. However, none of these incorporates detailed time-varying structural dynamics simulation capabilities.

The aim of this paper is to present a simulation approach, based on the virtual machine, for numerically controlled machine tools, that optimise settings such as parameters in the motion control code, from here on referred to as NC-program, or in the control system for each specific work piece so that the manufacturing speed is as fast as possible while achieving required geometrical tolerances for that specific work piece.

2. Virtual Machine Overview

Due to the multi-disciplinary nature of modern CNC machine tools advanced simulation tools, incorporating all relevant aspects of the problem, are needed. The virtual machine used in this work includes a real control system, a hardware-in-the-loop (HIL) simulation of the machine and a virtual reality model for visualisation, see figure 1.

![Figure 1. Overview of the virtual machine.](image)

The HIL simulator contains a machine simulation model, I/O hardware for reading actuator control signals as well as hardware for emulation of sensors, see figure 2.
The machine simulation model is capable of describing the time-varying structural dynamic response of the studied machine in real-time. The need for real-time performance is due to that the inputs and outputs to and from the simulation have to be synchronised with a real control system. Therefore the cycle time of the simulation has to be the same as, or lower than, the cycle time of the control, in this work 250 μs.

The virtual machine implementation is fully automated; featuring: building of simulation models, setting of simulation and control parameters, start and stop of simulation and NC-program, and post processing of simulation results. This implies that the parameters in the models are changeable and that the simulations run without human interaction. This includes parameters for the CNC, NC-program and HIL simulator. For a detailed description of the virtual machine see [5]. The actual cutting process (removal of material) is not accounted for in the current study.

3. Case study

A case study is performed to investigate the usefulness of the virtual machine as a tool to increase productivity of CNC machine tools. This chapter describes the case study specifically while also giving general information about the chosen optimisation approach.

3.1. Waterjet Cutting Machine

In the case study the virtual machine is used to simulate the behaviour of a waterjet cutting machine, an example of a CNC machine tool. Waterjet cutting
is a manufacturing technique that uses the erosion power of water to shape the work piece. The working principle is to force highly pressurised water (400 MPa or more) through a fine nozzle in the cutting head, concentrating an extreme amount of energy in a small area and thereby creating massive cutting power. Pure water is an excellent medium to cut soft materials. Abrasives may be added to extend the cutting capability to include harder materials such as metal and stone. In that case the abrasives erode the material instead of the water. More information about waterjet cutting can be found in, for example, [10, 11]. A typical machine design can be seen in figure 3.

![Figure 3. Waterjet cutting machine.](image)

### 3.2. Test Cases

Two different test cases are manufactured “virtually” in the case study. In the first one the tool centre point is programmed to follow a circular path with a diameter of 10 millimetres. In the second one the tool centre point is programmed to follow a quadratic path with 40 millimetre sides. The two test cases are schematically shown in figure 4.

![Figure 4. Test cases.](image)
When cutting closed contours with a waterjet the material needs to be pierced by the jet, i.e. the jet needs to penetrate through the material. This piercing is preferably done outside the contour since it leaves a mark [11]. In the two test cases the piercing is done in the centre of the respective geometry. From this starting point the contour is approached by linear interpolation. When the contour is reached the procedure of cutting the actual part is initiated. In the case with the circular path the contour is represented by a single circular interpolation and in the case with the quadratic path the contour is represented by a number of linear interpolations, all interpolations during cutting is done with a given cutting feed rate, not said it have to be the same for all cutting interpolations. When the contour cutting is finished the waterjet is shut off and the program is finished off with yet another linear interpolation back to the centre of the respective geometry this time with rapid feed rate.

To be accepted as a successful run the simulated position of the tool centre point must not deviate more than a given tolerance from the programmed (nominal) path. The tolerances are given by the international standard for general tolerances ISO 2768-1:1989 [12] and is 0.2 millimetres for the circular geometry and 0.3 millimetres for the quadratic. Besides deviation in size is the orientation as well as the location of the part criteria for acceptance.

3.3. Optimisation Procedure

The machine tool behaviour is simulated using the virtual machine. Inputs to the virtual machine are control system configuration and NC-program. By selecting certain control system parameters and parts of the NC-program as optimisation variables the virtual machine may be varied and controlled by the optimisation routine. Output from the virtual machine is the simulated motion of the tool centre point running the current NC-program. This simulated behaviour is processed and analysed by the optimisation routine to get the final geometry of the part and the time it took to manufacture the part. It is also ensured that all prerequisites are met, for example regarding shape and size. If the optimisation problem has converged the iteration stops otherwise a new guess for optimal values for the optimisation variables is generated and the iteration continues. The optimisation procedure is schematically shown in figure 5.
Figure 5. Optimisation procedure.

The optimisation routine is based on a genetic algorithm (GA) due to its ability to handle a mix of discrete and continuous variables. An in-house developed GA code is implemented in MATLAB. Real coded chromosomes are used for the discrete variables and binary coding is used for the continuous ones. Reproductive operators are single-point crossover, mutation and elitism. Duplicate chromosomes are not allowed in the population. Parents are chosen by proportionate selection, i.e. based on their fitness relative to all other individuals in the population. The optimisation routine in this work is thoroughly described in [7]. GA’s in general are described in detail in for example [13].

3.4. Optimisation Problem

The problem can be categorised as constrained multidisciplinary multivariable optimisation with a mix of discrete and continuous variables. The problem is multidisciplinary since the simulation model is connected to a real control system.

3.4.1. Objectives

The objective of the optimisation study is to find a unique configuration for each specific work piece so that the manufacturing speed is as fast as possible.
3.4.2. Variables

The control system alone contains hundreds, if not thousands, of parameters that could be tweaked for optimal performance. Combined with the NC-program which of course also can be written in numerous ways, this makes it impractical to vary all of them in an optimisation study. In this introductory study a few key parameters in the control system and the NC-program are chosen as variables.

In the control system the time constant used for acceleration/deceleration of the feed rate in cutting mode is used as a variable. A low time constant gives a higher manufacturing speed while also inducing more vibrations in the system which deteriorates the positioning accuracy of the machine. This might be a problem when for example cutting sharp corners as exemplified in figure 6. The results from two test runs are overlaid in figure 6. The solid line has a high time constant and the dashed line has a low. The same feed rate is used in both cases. A to high time constant on the other hand makes it difficult to accurately manufacture parts of small dimensions unless the feed rate is significantly reduced. Depending on the part to be manufactured it might also be beneficial to set different time constants on different axes.

![Figure 6. Influence of time constant.](image)

In the NC-program the feed rates in cutting mode are used as variables. As the optimisation objective is to cut the part as fast as possible high feed rates are
preferable. A high feed rate however makes it more difficult to achieve required geometrical tolerances. Two different feed rates are used to cut the test pieces. One for “piercing” the material and one for cutting the contour of the part. Both these feed rates are used as variables in this study.

The chosen variables with allowed values for the discrete ones and bounds for the continuous ones are given in table 1. “Default” variable values used in corresponding standard machines are given in bold.

Table 1. Optimisation variables.

<table>
<thead>
<tr>
<th>Variable description</th>
<th>Type</th>
<th>Values (original values in bold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time constant used for acceleration/deceleration of</td>
<td>Discrete</td>
<td>50, 75, 100, 125, 150, 175, 200, 225, 250 (ms)</td>
</tr>
<tr>
<td>cutting feed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate, “piercing”</td>
<td>Continuous</td>
<td>Bounds: 1000 - 8000 (mm/min)</td>
</tr>
<tr>
<td>Feed rate, contour</td>
<td>Continuous</td>
<td>Bounds: 1000 - 8000 (mm/min)</td>
</tr>
</tbody>
</table>

3.4.3. Constraints

There are restrictions on how values for the optimisation variables may be assigned. In the current study the following constraints are applied: tool center point accuracy given by required tolerances regarding size and geometrical characteristics for the considered work piece as well as domain constraints (lower and upper bounds for chosen optimisation variables). The domain constraints are enforced automatically by the optimisation algorithm.

The upper bound for the cutting speed variable is approximated using the Zeng and Kim model [14] where the test pieces are assumed to be cut out of aluminium sheet metal using a standard waterjet cutting machine.

3.5. Results

The outcome of this introductory optimisation study shows that optimum settings of control system parameters and NC-program differs between the two test cases when the objective is as fast machining as possible. Optimal feed rate
in cutting mode are obviously case dependent. This is also shown in the present study where the optimal feed rate cutting the contour is found to be 5742 mm/min for the circular case and 7774 mm/min for the quadratic case. A similar difference between the two cases is found looking at the “piercing” feed rate. More interesting is the result for the control parameter (acceleration/deceleration time constant) which shows that also this setting is case dependent.

The optimised settings for the two test cases are shown in table 2.

Table 2. Optimised parameter settings.

<table>
<thead>
<tr>
<th>Variable description</th>
<th>Circle</th>
<th>Quadrangle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time constant used for acceleration/deceleration of cutting feed [ms]</td>
<td>75</td>
<td>125</td>
</tr>
<tr>
<td>Feed rate, “piercing” [mm/min]</td>
<td>4839</td>
<td>7548</td>
</tr>
<tr>
<td>Feed rate, contour [mm/min]</td>
<td>5742</td>
<td>7774</td>
</tr>
</tbody>
</table>

A typical simulation result from the quadratic test case is shown in figure 7. One corner of the quadrangle is zoomed in and placed on top of the original quadrangle. The dash-dot line is the nominal path that the tool centre point is programmed to follow. The solid line represents the actual path produced by the machine tool (simulated motion of the tool centre point) when trying to follow the nominal path. The dashed lines represent allowed variations in size and geometrical characteristics. As long as the solid line stays in between the two dashed lines all prerequisites regarding geometry is met.
The objective for the optimisation study was to minimize the time for completion of cutting one part, i.e. follow the programmed path from start to finish. Using the optimised settings it takes 1.27 seconds to complete the circular path and 2.49 seconds to complete the quadratic path. As a comparison an optimisation study keeping the default settings in the control system and only varying the NC-program is carried out. It should be noted that this is a best case scenario as feed rates in the general case are chosen from hand books or based on experience and not numerically optimised. In this comparative study it takes 1.75 seconds to complete the circular path and 2.68 seconds to complete the quadratic path. Hence, the performance is reduced by 37.8 and 7.6 per cent respectively in comparison with the optimisation also including the control system parameter. As the comparison is made with a best case scenario the benefit of including both NC-program and control system parameters in the optimisation is probably higher in the general case.

4. Discussion and Conclusion

A virtual machine is used in an introductory optimisation study to improve the productivity of a CNC machine tool. The manufacturing speed is used as
objective function and parameters in the NC-program and control system are used as variables in the study.

Already in this limited introductory study it is shown that the ability to adjust CNC machine tool parameter settings to a specific work piece may significantly increase manufacturing productivity. It is shown in the case study that optimal parameter settings depend on the geometry to be cut as well as the geometrical tolerances required. The ability to optimise the settings for a specific work piece is therefore important.

This potential for productivity improvement regarding CNC machine tools is most likely not possible to exploit without advanced simulation support within the same time, cost and general resource frame. Companies incorporating such advanced simulation tools could thus improve its own competitiveness as well as contribute to improved resource efficiency of society at large.

In this introductory study the virtual machine includes an ideal model of the cutting process (removal of material). A fair comparison can therefore not be made between the presented simulation results and results using the machines original configuration and cutting feeds recommended by the machine supplier. The presented results can however be compared to each other. Such a comparison clearly shows the potential for improved productivity enabled by optimal CNC machine tool parameter settings.

Incorporating the cutting process in the simulation is an interesting and important part of improving the presented virtual machine. Furthermore the procedure should be validated through measurement on a physical waterjet cutting machine.

5. Acknowledgments

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6. References


Paper C

Introductory Design Optimisation of a Machine Tool Using a Virtual Machine Concept
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Introductory Design Optimisation of a Machine Tool Using a Virtual Machine Concept

Johan Wall, Johan Fredin, Anders Jönsson, Göran Broman

Abstract

Designing modern machine tools is a complex task. A simulation tool to aid the design work, a virtual machine, has therefore been developed in earlier work. The virtual machine considers the interaction between the mechanics of the machine (including structural flexibility) and the control system. This paper exemplifies the usefulness of the virtual machine as a tool for product development. An optimisation study is conducted aiming at improving the existing design of a machine tool regarding weight and manufacturing accuracy at maintained manufacturing speed. The problem can be categorised as constrained multidisciplinary multi-objective multivariable optimisation. Parameters of the control and geometric quantities of the machine are used as design variables. This results in a mix of continuous and discrete variables and an optimisation approach using a genetic algorithm is therefore deployed. The accuracy objective is evaluated according to international standards. The complete systems model shows non-deterministic behaviour. A strategy to handle this based on statistical analysis is suggested. The weight of the main moving parts is reduced by more than 30 per cent and the manufacturing accuracy is improvement by more than 60 per cent compared to the original design, with no reduction in manufacturing speed. It is also shown that interaction effects exist between the mechanics and the control, i.e. this improvement would most likely not been possible with a conventional sequential design approach within the same time, cost and general resource frame. This indicates the potential of the virtual machine concept for contributing to improved efficiency of both complex products and the development process for such products. Companies incorporating such advanced simulation tools in their product development could thus improve its own competitiveness as well as contribute to improved resource efficiency of society at large.

Keywords: Machine tools, Mechatronics, Non-deterministic, Optimisation, Product development, Virtual machine.
1. Introduction

On the increasingly competitive global market, users of machine tools demand increased accuracy and efficiency. This forces machine tool developers to incorporate new methods and tools in their development processes. Virtual experimentation (advanced simulation tools) seems promising for addressing these new demands while at the same time attaining other benefits, such as shortened time-to-market. This has been shown in other areas of engineering; see, for example, [1].

A virtual machine concept to support simulation-driven mechatronic design of CNC machine tools has therefore been developed in earlier work [2]. The virtual machine includes a real control system, simulation models of the machine having real-time capabilities as well as visualisation of the machine. The control system is a standard control system commonly used in the studied type of machine tools. This limits the design work to choosing suitable control system parameters. This parallel multidisciplinary design approach, simultaneously analyzing the mechanics and the control, and thereby utilising interaction effects, is believed to be superior to the traditional sequential design approach [3]. Other works related to the idea of a virtual machine are, for example, [4-6]. However, none of these incorporates detailed time-varying structural dynamics simulation capabilities.

The aim of this paper is to show the usefulness of the virtual machine concept for machine tool design optimisation. Designing a machine tool includes a wide variety of tasks ranging from selecting off-the-shelf products to designing unique parts from scratch. The design problem therefore usually consists of a mixture of continuous and discrete variables. Hence, a non-gradient based optimisation algorithm is well suited for the problem. Furthermore, in this type of problem many, often conflicting, objectives are usually present, i.e. it is a multi-objective problem. Methods able to handle this type of optimisation problem are discussed by, for example, [7, 8].

The complete multidisciplinary model of the studied mechatronic system shows a non-deterministic behaviour. Methods and strategies for non-deterministic simulations have in recent years received increased attention within the research community; see, for example, [9, 10]. The focus has been on systems with uncertain or variable model properties. However, in the virtual machine
simulation, the source of non-determinism is inherent to the set-up. Statistical methods that consider this are suggested.

2. Virtual Machine Overview

The virtual machine includes a real control system, a hardware-in-the-loop (HIL) simulation of the machine and a virtual reality model for visualisation of the machine, see figure 1.

![Figure 1. Overview of the virtual machine.](image1)

The HIL simulator contains a machine simulation model, hardware for reading actuator control signals as well as hardware for emulation of sensors, see figure 2.

![Figure 2. HIL simulator.](image2)
The machine simulation model is capable of describing the time-varying structural dynamic response of the studied machine in real-time. The need for real-time performance is because the inputs and outputs to and from the simulation have to be synchronised with a real control system. Therefore the cycle time of the simulation has to be the same as, or lower than, the cycle time of the control, in this work 250 $\mu$s. For a detailed description of the virtual machine see [2].

3. Case Study; Design Optimisation of a Water Jet Cutting Machine

This chapter describes the case study specifically while also giving general information about the chosen optimisation approach.

3.1. Water Jet Cutting Machine

Water jet cutting is a manufacturing technique that uses the erosion power of water to shape the work piece. The basic principle is to channel highly pressurised water (400 MPa or more) through a narrow nozzle in the cutting head, concentrating an extreme amount of energy in a small area and thereby creating massive cutting power. To further increase the cutting power abrasives are usually added to the process. More information about water jet cutting can be found in [11].

A schematic of the studied water jet cutting machine can be seen in figure 3. The machine has two axes of motion in the horizontal xy-plane.
A typical machine contains several cutting heads. In the studied machine design, the cutting heads are attached to the cutting head holder beam (1) which is mounted on the X-unit (2). The X-unit is able to move along the boom (3) enabling motion in the x-direction. The boom is able to move along the stand (4) enabling motion in the y-direction. Both axes are driven by electric motors via ball screws. A more thorough description of the machine design is given in [12].

3.2. Machine Simulation Model
The machine simulation model contains several sub-models; a structural dynamics model simulating the flexibility of the moving mechanical parts, a motor model and a multi-body model of the transmission. The complete model is built in Simulink (MATLAB) and controlled from MATLAB.

An ABAQUS finite element (FE) model constitutes the basis for the structural dynamics model. To achieve real-time capability the FE-models needs to be
reduced in several steps by retaining only those modes that have a major influence on the dynamic response in the frequency range of interest and by only retaining the degrees of freedom of interest. The modal model is converted into state space model to enable implementation in Simulink. The development and validation of the FE-models are described in further detail in [12]. The reduction procedure as well as a further description of the simulation model of the transmission can be found in [2].

For the simulation model to be functional in an optimisation study it has to be parameterised and automated, i.e. the optimisation algorithm must be able to influence the model by varying certain aspects of it. While this is straightforward for the Simulink sub-models, tools enabling data exchange with ABAQUS is needed. This is realized through the software packages’ ability to read and write ASCII-files.

The parameterisation of the FE-model is based on a sub-structuring approach. The unique parts of the machine are isolated as subsystems. Models for these subsystems are developed and validated. Some subsystem models are dynamic in the sense that they for arbitrary model parameters, for example, geometric quantities or material properties, may be changed and re-built. Which subsystem models that are allowed to be dynamically changed and which are kept unchanged (static) depend on the choice of variables in the optimisation study. The subsystem models are then assembled into the complete FE-model of the machine in MATLAB. The model is sent to ABAQUS and solved. The results are imported back into MATLAB and used as a part of the machine simulation model.

The described simulation environment, combining ABAQUS with MATLAB, is very flexible, allowing automatic simulation and assessment of different machine configurations.

The complete machine simulation model is compiled into a real-time executable, and run on a real-time operating system, constituting the HIL-simulator described earlier.

3.2.1. Simulation Model Behaviour

Simulation results show a non-deterministic model behaviour, which is most likely due to the HIL-setup. Typical results of manufacturing accuracy from one typical machine configuration can be seen in figure 4 for 1000 simulation runs.
The solid line is an estimated probability density function, assuming a Gaussian
distribution, with the sample mean and sample standard deviation. Based on
this, Gaussian distributed simulation results are assumed. The performance
measure presented in figure 4 is re-scaled on request of the industrial partner. It
is unit-less and does not explicitly represent the performance of the actual
machine.

The variation must, of course, be considered when assessing machine tool
performance. To get stable results, sufficiently many simulation runs with a
given machine configuration must be carried out. To ensure this, the confidence
interval of the predicted mean value is calculated. If the calculated interval is
larger than a given threshold level (related to the expected magnitude of studied
manufacturing accuracy) for a certain confidence level (99%), additional
simulations are performed until the mean value is predicted with acceptable
certainty. The confidence interval is calculated according to equation 1 [13]:

\[
\bar{X} \pm t_{n-1} \left( \frac{\alpha}{2} \right) \frac{s}{\sqrt{n}}
\]

(1)
where $\bar{X}$ is the sample mean, $t_{n-1}$ is Student’s $t$ distribution with $n-1$ degrees of freedom, $1-\alpha$ is the probability that the true mean value, $\mu$, is contained within the calculated interval, $s$ is the sample standard deviation, and $n$ is the sample size.

From a robust design point of view, the variance of the performance measure used must also be considered in the optimisation study.

3.3. Optimisation Problem

The problem can be categorised as constrained multidisciplinary multi-objective multivariable optimisation with a mix of discrete and continuous variables. The problem is multidisciplinary since the simulation model is connected to a real control system.

3.3.1. Objectives

Obvious performance related objectives are accuracy, manufacturing speed and repeatability. Also of interest is the stroke of the $x$-axis, implying a trade-off between how large work pieces that can be machined in one set-up and the ability to cut several work pieces at the same time. A light weight design is also desirable, not the least from a general societal resource efficiency point of view. Three objectives are pursued in this introductory study: the weight of the main moving parts (which should also benefit energy and cost efficiency), the manufacturing accuracy and the manufacturing speed (i.e. the time it takes to cut the work piece). Since the feed rate is not a design variable in this study, the goal as regards the manufacturing speed is only to not have it significantly reduced.

The weight of the system is calculated by the finite element software. The manufacturing speed is easily obtained since the simulations are performed in real-time. The manufacturing accuracy is assessed according to the International Standard 230-4 [14]. A circular test is performed and the radial deviation is calculated. A fictitious test case is shown in figure 5.
Figure 5. Test case.

The dash-dot line is the nominal path of radius $r_{\text{nom}}$ that the machine tool is programmed to follow. The solid line represents the actual path produced by the machine tool (simulated motion of the tool centre point) when trying to follow the nominal path. The dashed lines are minimum and maximum concentric circles of radius $r_{\text{min}}$ and $r_{\text{max}}$, respectively, enveloping the actual path. $r_{\text{max}}$ and $r_{\text{min}}$ are compared to $r_{\text{nom}}$ and these deviations are used as a measure of the manufacturing accuracy ($F_{\text{tot}}$) according to equation 2.

$$F_{\text{tot}} = |r_{\text{max}} - r_{\text{nom}}| + |r_{\text{nom}} - r_{\text{min}}|$$

(2)

In this study the radius of the nominal path is 5 mm and the feed rate is 5000 mm per minute. This feed rate is higher than feed rates normally used in the industry today. The purpose of this is to provoke larger differences between machine configurations.

3.3.2. Variables

The virtual machine, including the machine model as well as the control, contains thousands of parameters. It is of course not practically possible to vary all of them in an optimisation study. Some key parameters in the machine and the control are chosen as variables. This selection was guided by experience among the industrial partners as well as from previous simulations.
The following parameters in the machine model are considered as variables in the current study: the cross section of the cutting head holder beam, the cross section (box type) and length of the boom and finally the width of the X-unit. These are parameters that are easily changed in practice. Some of them vary within the industrial partners’ current product range.

The controller used is a closed-loop servo system. It includes a position loop as well as a velocity loop. The position loop gain is chosen as a variable in the study. The loop gain determines how hard the servo tries to reduce possible errors. As the loop gain increases, the response is improved. A too large loop gain, however, might make the servo system unstable. The time constant used for acceleration/deceleration of the cutting feed is also used as a variable. A low time constant gives a higher manufacturing speed while also inducing more vibrations in the system.

The chosen variables with allowed values for the discrete ones and bounds for the continuous ones are given in table 1. Variable values for the original design is given in bold.
Table 1. Design variables.

<table>
<thead>
<tr>
<th>Variable description</th>
<th>Type</th>
<th>Values (original values in bold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section of cutting head holder beam</td>
<td>Discrete</td>
<td>40x80 light version, 40x80, 80x80 (mm)</td>
</tr>
<tr>
<td>Width boom cross section</td>
<td>Discrete</td>
<td>0.125, 0.150, 0.175 (m)</td>
</tr>
<tr>
<td>Height boom cross section</td>
<td>Discrete</td>
<td>0.225, 0.250, 0.275 (m)</td>
</tr>
<tr>
<td>Thickness of material in boom cross section</td>
<td>Discrete</td>
<td>0.005, 0.010, 0.015 (m)</td>
</tr>
<tr>
<td>X-unit width</td>
<td>Continuous</td>
<td>Bounds: 0.55 - 1.0 (m) (0.8)</td>
</tr>
<tr>
<td>Length of boom</td>
<td>Continuous</td>
<td>Bounds: 3.875 - 4.325 (m) (4.125)</td>
</tr>
<tr>
<td>Time constant used for acceleration/deceleration of cutting feed (#1622)</td>
<td>Discrete</td>
<td>50, 75, 100, 125, 150, 175, 200, 225, 250 (ms)</td>
</tr>
<tr>
<td>Loop gain for position control (#1825)</td>
<td>Discrete</td>
<td>1000, 1750, 2500, 3250, 4000, 4750, 5500, 6250, 7000 (0.01 s⁻¹)</td>
</tr>
</tbody>
</table>

The number of possible combinations of the variables presented in table 1 depends on how the continuous variables are encoded (see chapter 3.4). With the “resolution” used, over 6 700 000 combinations are possible. Thus, the problem is well suited for numerical optimisation.

3.3.3. Constraints

There are restrictions on how values for the design variables may be assigned. In the current study the following constraints are applied: A minimum axis stroke is given as well as domain constraints (lower and upper bounds for chosen design variables). The calculation of the axis stroke is approximated as
boom length minus X-unit length. A minimum value of 3.325 meters is given. The domain constraints are enforced automatically by the optimisation algorithm.

3.4. Optimisation Algorithm

A genetic algorithm (GA) is chosen since such have the ability to solve problems including both discrete and continuous variables. An in-house developed GA code is implemented in MATLAB. Real coded chromosomes are used for the discrete variables and binary coding is used for the continuous ones. Reproductive operators are single-point crossover, mutation and elitism. Duplicate chromosomes are not allowed in the population. Parents are chosen by proportionate selection, i.e. based on their fitness relative to all other individuals in the population. GA’s in general are described in detail in for example [15].

While the purpose of the current work is to show the potential of the virtual machine concept and not necessarily to develop a perfect machine tool, a simple strategy to handle the multiobjective aspect of the problem is adopted. The different objectives are aggregated to one single figure of merit by a weighted sum approach. Weights are assigned to each objective by the decision maker. The sum of all objectives adjusted by their respective weight factor is used as the figure of merit according to equation 3 [7].

\[
f_w(x) = \sum_{i=1}^{m} \left[ \frac{f_i(x)}{f_{i0}} \right]^{\gamma_i}
\]

(3)

where \(f_w\) is the aggregated figure of merit, \(m\) is the number of objectives, \(\gamma_i\) is the weight factor, \(f_i\) the \(i\):th objective function, \(f_{i0}\) the \(i\):th objective function value for the best known solution so far and \(x\) the variable set.

The constrained problem is converted into an unconstrained problem through penalization of infeasible solutions. If a constraint is violated, a penalization term is added to the objective function. Penalizing a solution, still keeping it in the population, adds diversity compared to just removing the chromosome in question. This helps the GA avoid premature termination. A thorough discussion about constraint handling in GA can be found in [16].
3.5. Simulation Scheme

A worst case function call may take up to seven minutes to complete. This includes that a new FE-model needs to be built and solved, variable values changed that forces a re-start of the control system and that many samples are needed to get a stable mean. An efficient simulation scheme is therefore necessary.

This is achieved by carefully planning the order in which the individuals in each generation are simulated. This might be seen as an optimisation problem in itself. Here, however, a simple rescheduling is applied where the individuals are sorted in groups related to the variable that is most time consuming to change. Within these groups the individuals are sorted once again in respect to the variable that is the next most time consuming to change. This procedure is continued until the generation is sorted for all variables.

When a variable combination is simulated the results are saved in a data base. If this variable combination appears again in a subsequent generation the results are loaded from the data base avoiding time consuming simulation of known data. The same is true for the FE-model, once a model is built it is saved in a data base and re-used if needed.

3.6. Results

The optimisation algorithm converged to a design containing the following variable setting. Cross section 3 is selected for the cutting head holder beam. This cross section is stiffer than the original one. The X-unit becomes 0.61 meters long. Hence it is close to its lower bound (0.55 meters). A cross section of 175x250x5 (mm) is selected for the boom and it is given a length of 3.99 meters. This significantly lighter boom combined with the chosen X-unit results in an axis stroke of more than 3.325 meters, i.e. satisfying the minimum stroke constraint. The time constant (control variable # 1622) is set to 100 (reduced by 33 %) and the loop gain (control variable # 1825) is unchanged and remains at 6250.

The normalised aggregated objective function shows a decrease from 1 to 0.60 which is a considerable improvement. The improvements of the individual objective functions are shown in table 2.
Table 2. Optimisation results.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Relative improvement compared to original design [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of the system</td>
<td>31</td>
</tr>
<tr>
<td>Manufacturing accuracy</td>
<td>64</td>
</tr>
<tr>
<td>Manufacturing speed</td>
<td>2.0</td>
</tr>
</tbody>
</table>

A typical simulation of the test case used comparing the improved machine design to the original one can be seen in figure 6. The dash-dot line is the nominal path (normalised) that the machine tool is programmed to follow. The solid and dotted lines represent the actual path produced using the improved and the original design, respectively.

![Figure 6. Typical simulation results.](image)

One could argue that the large difference may to some extent be explained by a misfit of the original control parameters and the chosen test case. However, a design combining the original mechanics with the optimised control parameters
is 52 per cent more accurate than the original design, i.e. it is still less accurate than optimised design (see table 2, 64 per cent improvement). It is also interesting to note that the opposite combination, i.e. a design combining the optimised mechanics with the original control parameters, is 4 per cent less accurate than the original design. These comparisons indicate that interaction effects between the mechanics and the control exist. This is also illustrated by carrying out a sequential optimisation. That is, first optimising the mechanics using the original control (not varying any control parameters) and then optimising the control using optimal mechanics obtained from the first step. This sequentially optimised design is 44 per cent more accurate than the original design, i.e. far less accurate than the design obtained from the simultaneous optimisation.

4. Discussion and Conclusion

A virtual machine is used in an introductory design optimisation study to improve an existing water jet cutting machine design. The weight of the main moving parts of the machine, the manufacturing accuracy and the manufacturing speed at a specified feed rate are used as objective functions. A genetic algorithm is used because of the discrete nature of some of the chosen design variables, and this method performs well in the presented test case.

In-house developed tools for data exchange between ABAQUS and MATLAB enable parameterisation of the simulation model, which yields a flexible simulation environment that works very well in the presented test case. Furthermore a strategy to handle non-deterministic simulation results based on statistical methods for Gaussian distributed data shows good performance in the presented test case.

Already in this limited introductory study a significant potential for design improvements is revealed. The weight of the main moving parts is reduced by more than 30 per cent, the manufacturing accuracy is improved by more than 60 per cent and the manufacturing speed is increased by 2 per cent (i.e. at least maintained as desired).

It is also shown that interaction effects exist between the mechanics and the control, i.e. this improvement would most likely not been possible with a conventional sequential design approach within the same time, cost and general resource frame. This indicates the potential of the virtual machine concept for
contributing to improved efficiency of both complex products and the
development process for such products. Companies incorporating such
advanced simulation tools in their product development could thus improve its
own competitiveness as well as contribute to improved resource efficiency of
society at large.

The positive results already from this introductory study encourage further work
with the virtual machine concept. The HIL simulator as well as the optimisation
algorithm will be refined in preparation of more comprehensive optimisation
studies, in parallel with physical testing and redesign of real machine tools.

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Ronneby, Sweden, and GE Fanuc Automation CNC Nordic AB, Stockholm,
Sweden for invaluable support.

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Paper D

Holistic Methodology Using Computer Simulation for Optimisation of Machine Tools
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Holistic Methodology Using Computer Simulation for Optimisation of Machine Tools

Johan Fredin, Anders Jönsson, Göran Broman

Abstract

Virtual machine concepts supporting optimization of machine tools have been developed in earlier work. The virtual machine concept is a tool that can describe the behaviour of a machine tool while considering the interaction between mechanics of the machines and the control system. Considerable amount of work has been done proving the concept and showing the potential of such a design tool in different contexts. Several studies have shown the potential of using the virtual machine concept, although, no work has been found that is exploring the potential of a full optimization study.

The aim of this work is to show the potential of the virtual machine concept in an optimisation study of the complete machine tool, including the mechanical system, parameters in the control system, the NC-code as well as choice of servo and drive systems. An efficient optimisation strategy is presented, making it possible to solve the complex optimisation problem within a reasonable amount of time.

A combination of optimisation algorithms is used to achieve a fast and accurate way of solving the complex task to optimise the complete machine tool. Genetic algorithms, gradient based algorithms and more traditional hands on engineering are used for solving the optimisation problem. Post processing and data mining is suggested as a way of extracting as much information as possible from the optimisation results with the aim to increase the knowledge about the studied system. An important conclusion is that the virtual machine should support the decision making in product development, not replace the product developers as regards decision making.

Keywords: Machine tools, Mechatronics, Optimisation, Product development, Virtual machine.
1. Introduction

Due to increasing demands and competition on the global machine tool market, machine tool builders need to push the limits and produce better machines to a lower price. This puts new demands on the product development process, and mistakes are very costly. In account of that, a great amount of work has been carried out aiming at providing tools for machine tool builders to aid the product development process. This work will show how an optimisation study can be carried out on a complete machine tool, considering a machine tool as a mechatronic system.

A mix of optimisation algorithms are used to solve the problem as efficient as possible while learning as much as possible from the outcome by analysing data from different perspectives and summarizing it into useful information [1].

So called virtual machine tools have been developed by several groups of researchers and companies around the world aiming at describing the behaviour of machine tools without building physical prototypes [2-4]. Some virtual machine tools are used for operator training solely [5] with low demands on fidelity and some are used for design optimisation and detailed studies of the machine tool behaviour [6-8].

The virtual machine used in this work was developed as a tool to aid product development, and enabling optimisation of the complete machine tool with special focus on the integration of flexible models in real-time [8].

Optimisation studies can be done on real systems but they often do turn out to be studies of parameters rather than optimisation, due to the immense cost of building physical systems. Optimisation studies are instead rather done with simulation models of the studied system. To be able to perform optimisation of a complete machine tool, first complete simulation models need to be built and validated. Such simulation models have been built and validated in earlier work [9, 10].

When dealing with mechatronic systems, as modern machine tools are, it is of great importance that a full systems perspective of the mechatronic system is kept throughout the complete design process. The main parts of the machine tool are the mechanics, the servo drives and motors and the control system. Simulation models of the mechanics and servo drives can be built and the resulting models can be trusted with confidence. However it is extremely
difficult to reproduce correctly the dynamic behaviour of the control system. This complexity can be dealt with by two approaches; either by using a real control system and connect that to the simulation models or by using so called “soft control systems” provided by some of the NC control suppliers. In this work the first approach is used.

The resulting simulation model of a complete machine tool is called the “virtual machine” in this work. The “virtual machine” can be altered and built up in many different ways depending on how parameters are chosen. There are, of course, a limit to how much the simulation models can be changed and still be considered as trustworthy and validated. The optimisation study can be carried out within these boundaries and the optimisation bounds are limited accordingly.

Using a real control system puts high demands on the simulation models. They have to be able to run in real-time since the control system requires feedback within its cycle time. To deal with this the mechanical simulation models have been reduced in several steps to be able to be run as efficiently as possible. Since the flexibility of the structural elements of a machine tool have been shown to be important for the machine performance [10] some mechanical parts need to be modelled as flexible. The flexible models are reduced into state space models, following the steps shown in figure 1. The final state space model describing the machine is capable of handling time varying matrices. This enables the simulation of pose-dependent dynamics.
Figure 1. Reduction from physical system to state space model.

All other simulation models in the virtual machine needs also to be as efficient, robust and solved as fast as possible, since the complete machine tool behaviour needs to be computed in each time step of the real control system.

Simulated encoders are supplying the real control system with positional feedback. The physical control system contains position loops. The velocity loops is however present in the simulated servo drives according to [9]. Figure 2 shows a schematic figure of the studied system.
2. Optimisation Problem

The optimisation problem can be described as multi variable single objective. The problem is solved by a mix of different types of optimisation algorithms in parallel together with more hands on classical engineering.

2.1. Objectives

In the manufacturing industry the main goal is to produce as many parts as possible within the shortest possible time, and still produce parts within given tolerances. A machine tool is, of course, not only producing one specific part but a large variety of parts. A common way of describing the performance of a machine tool is to perform a test where the machine tool is run in a circle, according to ISO-standard 230-4 [11] and investigates the resulting positioning accuracy. Figure 3 shows a schematic picture of the circular test.
The dash dotted line is the nominal path of radius \( r_{\text{nom}} \) which the machine tool is programmed to follow. The solid line is the actual path produced by the machine while trying to follow the nominal path. A measure for machine accuracy is found by comparing the minimal and maximal radius of the actual path (\( r_{\text{max}} \) and \( r_{\text{min}} \) shown in figure 3) with the radius of the nominal path. The tolerances given for the produced part is given as the maximal radial deviation.

In this optimisation study the test is limited to be a one directional test, i.e. the circular path is followed clockwise only, according to figure 3.

This test is seen as an adequate replacement of performing numerous tests with parts with large variety in geometry. One remark though; the circular path followed in such a test might not give a fair description of the machine’s structural dynamics. The rather smooth movement when machining something round will not introduce much vibration and therefore it can be that structural behaviour might be seen as less important than it actually is. This problem is reduced by having a small radius of the circular path. A smaller radius leads to higher accelerations, for a given feed rate, leading to introduction of more vibrations.

Finding the minimum value for the time it takes to perform one circular test, within given tolerances, is the main objective in this optimisation problem.
2.2. Design Variables

The virtual machine concept is developed with the aim to make it possible to study the effect of changing practically any included part or parameter in the machine tool. This enables the user to choose any parameter as a variable in an optimisation study. It is, of course, not possible to choose all parameters as variables if the optimisation problem shall be solved within reasonable time. Each variable added have a great influence on the solution time.

The choice of variables was made based on estimates of the importance of parameters and through discussions with the industrial partners. The variables are chosen to cover all domains, i.e. the domains of mechanics, electronics and software. Some variables are discrete, like for example variables concerning boom cross sections which can only be chosen in certain measures, and some are continuous, like for example the length of the boom which can be chosen more freely.

The mechanical variables are the cross section of the cutting head holder beam, the cross section and length of the boom and the width of the so called X-unit. The variables associated with the control system are the proportional gain of the position control individually for x- and y-direction and the time constant for acceleration/deceleration for the cutting feed. There are also variables concerning choice of servo motors for each axis individually as well as feed rates for the circular test. A complete list of the variables is presented in table 1.
Table 1. Design variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Type</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cross section of cutting head holder beam</td>
<td>Discrete</td>
<td>3 possible values</td>
</tr>
<tr>
<td>2</td>
<td>Width boom cross section</td>
<td>Discrete</td>
<td>3 possible values</td>
</tr>
<tr>
<td>3</td>
<td>Height boom cross section</td>
<td>Discrete</td>
<td>3 possible values</td>
</tr>
<tr>
<td>4</td>
<td>Thickness of material in boom cross section</td>
<td>Discrete</td>
<td>3 possible values</td>
</tr>
<tr>
<td>5</td>
<td>X-unit width</td>
<td>Continuous</td>
<td>Binary coded, constrained</td>
</tr>
<tr>
<td>6</td>
<td>Length of boom</td>
<td>Continuous</td>
<td>Binary coded, constrained</td>
</tr>
<tr>
<td>7</td>
<td>Time constant acceleration/deceleration for cutting feed</td>
<td>Discrete</td>
<td>9 initial number of steps</td>
</tr>
<tr>
<td>8 &amp; 9</td>
<td>Proportional gain for position control individually for each axis</td>
<td>Discrete</td>
<td>9 initial number of steps</td>
</tr>
<tr>
<td>10 &amp; 11</td>
<td>Servo motor individually for each axis</td>
<td>Discrete</td>
<td>3 possible values</td>
</tr>
<tr>
<td>12</td>
<td>Feed rate for circular test</td>
<td>Continuous</td>
<td>Binary coded</td>
</tr>
</tbody>
</table>

The continuous variables are binary coded and with a sufficient resolution, the number of possible parameter combinations is well above hundred millions. The immense number of combinations puts great demands on the optimisation strategy to be efficient enough for solving the problem within a reasonable amount of time.

2.3. Constraints
The optimisation problem is constrained both when it comes to variables and objectives. The most obvious constraint is that the parts shall be produced
within given tolerances. This leads to a limitation in how fast a part can be produced. Constraints in how the variables can be chosen are: A minimum axis stroke is given; this affects the X-unit length and the boom length, since the axis stroke can be calculated as boom length minus X-unit length.

2.4. Optimisation Strategy

Prior work has shown that genetic algorithms are suited as an overall optimisation algorithm [12].

Initial tests were made using a genetic algorithm to solve the optimisation problem; the problem was however not solved within a reasonable amount of time, which justifies the extra work of developing an efficient optimisation strategy.

The two most important features for an optimisation algorithm are that it is fast and accurate. These two features are in conflict since a fast solution usually is less accurate. A small optimisation problem can be solved using genetic algorithms but when the number of variables is getting higher the time it takes for solving the problem is rapidly getting too long to be acceptable. For this reason the optimisation problem is broken down into several different optimisation problems that are solved in parallel. When the nature of the variable allows it, a much faster gradient based optimisation algorithm is used. An example of such a variable is the feed rate, due to its continuous relationship to the objective function. The gradient based optimisations are included in the overall genetic algorithm. The gradient based optimisation is carried out for each individual in the genetic algorithm, building complete individuals containing all variables. By doing so the optimisation is done considering all variables in parallel which is a must to utilise the interaction effects between the variables.

The optimisation is done in several steps. The first step is to run the optimisation letting the variables take any value between the minimum and maximum bounds. The next step involves updating the variable bounds by only letting them take values that were present in the best machines found in the first step. If any design variable takes values on the boundary or close to the boundary, this may indicate that the boundaries are too narrow, and better designs may be found outside the boundaries.

The accuracy of the optimisation algorithms can be influenced by setting tolerances. In this way the algorithm can be tuned to be either faster or more
accurate. The accuracy is set higher and higher for each step, but since the variables can take fewer and fewer values the algorithm continues to be relatively fast. See figure 4 for a graphical representation of the algorithm.

Figure 4. Optimisation method.
The genetic optimisation algorithm tries to mimic nature’s evolutionary behaviour, by letting the fittest individuals in each generation survive and reproduce. In contrast to natural evolution, this procedure can be done relatively fast with simulated models and many individuals and generations can therefore be evaluated. One main advantage of genetic algorithms is that the objective function does not need to be continuous or at all well known. The size of the generations in terms of individuals, the chance for mutation, number of individuals that are allowed to reproduce in each generation and some other parameters need to be set and adjusted individually for each optimisation problem.

If the objective function is continuous a gradient based optimisation algorithm is a better choice, since it is faster and sometimes more accurate. The gradient based optimisation algorithms uses, as the name states, the gradients of the studied objective function to forecast in what direction the optimum can be found. While this kind of algorithms is very fast for continuous functions it might get stuck on local optima and therefore not solving the problem with desirable results. A correctly setup genetic algorithm on the other hand will solve for global optima which, is desirable. For the gradient based algorithm, an inbuilt function in Mathwork’s MATLAB was used and the genetic algorithm is produced in house.

An example where the bounds were upgraded is variable 7 (time constant for acceleration and deceleration). Already after evaluating 500 individuals it can be seen that the bounds are too wide, since no individual producing the part in an acceptable time is having a time constant larger than 0.5 of the normalized value; see figure 5.
Figure 5. Variable 7 for first 500 individuals.

Figure 6 shows variable 7 for the first 2000 individuals and a confirmation that the upper bound is set unnecessarily high. This further investigation only needs to be carried out for uncertainties, and is done here only for demonstration.
The upper bound for variable 7 is therefore updated. Keeping the same number of possible values between the lower and the upper bound increases the accuracy of the optimisation algorithm.

The accuracy and tolerance of the optimisation algorithm can be altered by many parameters, such as the tolerances for the convergence tests, resolution for continuous variables, the number of possible values for discrete variables and the number of averages taken for each variable set. Averaging is done due to a small non-deterministic behaviour of the simulation model, which most likely is due to noise in electrical signals and possible noise in analogue to digital converters.

The above described procedure, deciding the bounds and tolerances, is hands on engineering work, somewhat more intuitively than the other parts of the optimisation strategy and a great opportunity to study the system and the effect of the variables.
Some variables and tolerance parameters are kept unchanged throughout the complete optimisation study. As an example the effect of the mechanical variables is hard to see during the optimisation and they are therefore unchanged in terms of bounds during the optimisation study. The effect can instead be studied in more detail in the post processing.

The way of mixing pure computational work with more hands on engineering is shown to be effective and time efficient. Routines could perhaps be derived for the engineering and solved for with computer models but this would consume resources and would be very hard to implement in a general way. At the same time the opportunity to study the system and the effect of the variables would be missed, resulting in a less optimal design.

3. Post Processing

Solving the optimisation problem is done by iteratively changing the value of the variables and investigating how the changes alter the resulting time consumption and accuracy. The outcome of the optimisation process is one optimum, in this case how the machine tool shall be put together to produce parts as fast as possible within the given tolerance. The outcome is also, a large collection of saved results. From these results a great deal of information about the studied system can be extracted through so called data mining. Data mining is the process of analysing data from different perspectives and summarizing it into useful information [1]. It can for instance be investigated how probable a certain variable set is in a good machine, i.e. if one specific variable value is more common than other values in a well performing machine. This investigation can be done for each variable or for combinations of variables. Studies are carried out on variables, and groups of variables, that are hard to study during the optimisation, such as the effect of the mechanical variables.

Data mining is especially useful when dealing with decision making involving judgement [1]. The optimisation study could have been multi objective and by weighing the objectives making it possible to find an optimum fulfilling more than one goal. But when the main objective is far more important, it may be better to optimise for solely this objective, and instead study the outcome more thoroughly by judging it according to the less important objectives.

The last iteration of the optimisation study contained just over 4200 individuals, i.e. 4200 combinations of the variables evaluated against the objective. There is
a great amount of extractable data from an optimisation study like this. It is, of course, not possible to present all data in this article but here follows some examples.

As a first step the individuals are sorted in terms of the objective and by judging the results it is found out how many individuals that can be seen as good machines. In the studied case it is shown that five individuals have practically the same objective value. This means that any of these five individuals represent machines with practically the same performance. By tracking these five individuals when carrying out data mining, information can be extracted about how a well performing machine should be put together. The studies made in post processing are favourably done through studies of graphical representation of data.

Each variable is first studied separately. Figure 7 shows the objective as a function of variable 6.

![Figure 7. Objective as a function of variable 6.](image-url)
Each dot in figure 7 shows at least one individual’s value for variable 6, some dots are in the same position, i.e. representing many individuals with a common value of variable 6. The bounds for variable 12 (feed rate) is updated during early iterations of the optimisation work which leads to that the objective is not taking values higher than 0.4 for the studied example. The circles are marking the five best individuals, giving an indication on how the variable shall be chosen for an optimal design. If instead variable 5 is studied the five best individuals are much wider spread, as can be seen in figure 8. It can therefore not be drawn any conclusions from variable 5 itself, but variable 5 in combination with other variables needs to be studied.

Figure 8. Objective as a function of variable 5.

Figure 9 shows how distributed the values for each design variable are for the five best individuals, by showing the probability for each value. The continuous variables are divided into three groups individually.
Figure 9. Distribution of variables.

In this figure it can for instance be seen that variable 4, 7 and 12 are invariant, some of the variables takes values from two out of the three groups and some are taking values from all three groups indicating how wide spread the values of the variables are.

Due to the multidimensional nature of the data, it is hard to get an overview of how combinations of variables affect the objective. One graphical representation, parallell coordinates, is used to show the individuals in terms of every design variable. Cubic interpolation is used to more clearly distinguish the individuals. Figure 10 shows the five best individuals highlightd in such a graphical representation.
By filtering the data so called *what if scenarious* can be studied. For instance, in retrospect, the effect of narrower bounds can be studied by filtering out the individuals outside of this new bound. It can be investigated if costly mechanical parts or motors can be excluded without spoiling the performance.

The fact that combinations need to be studied and results cannot be seen by studying individual variables justifies optimisations studies instead of the so much less complex parameter studies.

4. Results

As an outcome of the optimisation study two types of results can be extracted, one is the optimum, and one is the information gathered and the knowledge gained from the optimisation and post processing through so called data mining. The optimum in itself will not be discussed in details here, specific results will be left out and more general discussions will be held. By using an optimisation strategy, that uses different optimisation algorithms dependent on the nature of
the design variables together with more hands on engineering work, optimisation of a complete machine tool is made possible. Every evaluation of the objective function is very time consuming and for this reason an efficient optimisation strategy is very important. Such an optimisation strategy is presented and used with good results. By performing post processing and data mining more knowledge about the studied system can be extracted. Conclusions can be drawn regarding the effect of individual design variables as well as combinations of design variables.

5. Conclusions

A virtual machine is a proven to be a good tool when it comes to predict and optimise a complete machine tool’s properties. An efficient optimisation strategy is key when facing problems with large number of design variables. By introducing more hands on engineering work to the optimisation process, it can be expanded from only giving an answer about one good design to giving a great amount of information and knowledge about the studied system early on in the design work, something that is very important.

The information gathered can be used as a basis for discussion during design work, for instance to clarify and justify why certain components needs to be used, if such discussions occur between engineers and finance departments.

This supports decision making and keeps the number of physical prototypes to a minimum. Simulation and optimisation is done in product development to support decision making but it is very important to keep in mind that the decision still needs to be made by product developers, through collaboration with the sales organisation and other decision making units of the company.

A specific conclusion drawn from studying the effect of the mechanical design variables is that the relatively smooth motion when machining a circle might not introduce enough vibrations to see differences between slender and flexible mechanical parts and the stiffer variants. Using a different geometry, with for instance sharper corners, might give a different result. Investigations of what geometry and how it can be judged in terms of accuracy for use in optimisation is suggested for future work.
Acknowledgements

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ABSTRACT

To be competitive in today’s global market, it is of great importance that product development is done in an effective and efficient way. To enhance functionality, modern products are often so-called mechatronic systems. This puts even higher demands on the product development work due to the complexity of such products. Simulation and optimisation have been proven to be efficient tools to support the product development process. The aim of this thesis is to study how the properties of mechatronic products can be efficiently and systematically predicted, described, assessed and improved in product development.

An industrial case study of a water jet cutting machine investigates how simulation models and optimisation strategies can be efficiently developed and used to enhance functionality, flexibility and performance of mechatronic products. The knowledge gained from the case study is shown to be useful for companies developing machine tools. Most likely it is also useful for developers of other mechatronic products.

The thesis shows that with the presented optimisation strategies, comprising a mix of different computerised optimisation algorithms and more classical engineering work, design problems with a large amount of design variables can be solved efficiently.

A specific result is a validated simulation model for simulation and optimisation of a water jet cutting machine. As all mechatronic disciplines of the machine tool are considered simultaneously, synergetic effects can be utilised. Optimisation studies show a significant potential for improving manufacturing accuracy, for manufacturing speed and for a more light-weight design. Carrying out simulation and optimisation has also provided a great amount of information about the studied system, potentially useful in coming product development work.

By reducing the number of physical prototypes through simulation and optimisation, the resource consumption during product development is reduced. Also, with more optimised products, the resource consumption can be significantly reduced throughout the whole use phase. These benefits support the competitiveness of the product developing company as well as a sustainable development of society as a whole.