KTH Industrial Engineering and Management

Design and optimization of parallel haptic devices
Design methodology and experimental evaluation

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This is an academic thesis which, with the approval of the Department of Machine Design, Royal Institute of Technology, will be presented for public review in fulfillment of the requirements for a Doctorate of Engineering in Machine Design. The public review will be held at Royal Institute of Technology, room B242, Brinellvägen 85, Stockholm, on 23 March 2012 at 10:00.

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Abstract

The simulation of surgical procedures, in the case of hard tissues such as bone or teeth milling, using a haptic milling surgery simulator requires a haptic device which can provide high stiffness and transparency. To mimic a real milling process of hard tissue, such as for example creating a narrow channel or cavity, the simulator needs to provide force/torque feedback in 5–6 degrees of freedom (DOF). As described in this thesis, research has been performed to develop and optimize a haptic device that can provide high stiffness and force/torque capabilities to facilitate haptic interaction with stiff tissues.

The main contributions of this thesis are:

(i) The use of a model-based design methodology for the design of haptic devices. The proposed methodology is applied to a case study, i.e. the design and optimization of a haptic device based on parallel kinematics. Device requirements were elicited through dialogues with a prospective user from a neurosurgery clinic. In the conceptual design phase, different parallel concepts have been investigated and analyzed based on functional qualities such number of degrees of freedom, workspace size and force/torque capabilities. This analysis led to the selection of a specific 6 DOF kinematic structure for which dimension synthesis was performed including multi-objective optimization followed by control synthesis. Finally, a device prototype was realized and its performance verified.

(ii) Optimization of the device for best kinematic and dynamic performance. For optimization, performance indices such as workspace-to-footprint ratio, kinematic isotropy and inertial indices were used. To cope with the problem of non-uniform units in the components of the Jacobian matrix, various normalization techniques were investigated. A new multi-objective optimization function is introduced to define the optimization problem, which is then resolved using multi-objective genetic algorithms. A sensitivity analysis of the performance indices against each design parameter is performed, as a basis for selecting a final set of design parameter values.

(iii) A control strategy is investigated to achieve high transparency and stability of the device. The control strategy is based on careful analysis of the dynamics of the haptic device, computed torque feed-forward control and force control based on current feedback.

(iv) Finally, experiments both separately in the lab and by using the device in a haptic milling surgery simulator were performed. Results from a face validity study performed in collaboration with orthopedists verify that the new haptic device enables high-performance force and torque feedback for stiff interactions.

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List of appended papers

Paper A:

Khan S., Andersson K. and Wikander J., "A Design Approach for a New 6-DOF Haptic Device Based on Parallel Kinematics", presented at the *IEEE International Conference on Mechatronics, ICM,* Malaga, Spain, April 2009.

Suleman performed the research and wrote the paper. Kjell and Jan provided feedback and assisted in editing the paper.

Paper B:

Khan S., Andersson K. and Wikander J., "Design Optimization and Performance Evaluation of a 6-DOF Haptic Device", submitted to the *Journal of Mechanical Design*, February 2012.

Suleman performed the research, experimental work and wrote the paper. Undergraduate students carried out the CAD modeling and prototyping. Kjell and Jan provided feedback and carried out technical and language corrections.

Paper C:

Khan S., Andersson K. and Wikander J., ": Multi-objective Optimal Design of a 6-DOF Haptic Device Based on Jacobian Normalization", submitted to the IEEE Transaction on Robotics and Automation, February 2012.

Suleman performed the research and wrote the paper. Kjell and Jan provided feedback and assisted in editing the paper.

Paper D:

Khan S., Andersson K. and Wikander J., "Dynamic Based Control Strategy for Haptic Devices", presented at the *IEEE International World Haptics Conference*, Istanbul, Turkey, June 2011.

Suleman performed the research, experimental work and wrote the paper. Jan provided ideas for improving the technical contents. Kjell and Jan carried out the corrections.

Paper E:

Khan S. and Andersson K., "A Design Methodology for Haptic Devices", presented at the *International Conference on Engineering Design (ICED 2011)*, Copenhagen, Denmark, August 2011.

Kjell provided an idea of design methodology and Suleman performed a case study. Kjell wrote the part of the paper related to design methodology and Suleman wrote the rest of the paper.

Paper F:

Erkisson M., Khan S., and Wikander J., "Face Validity Tests of a Haptic Bone Milling Surgery Simulator Prototype", submitted to the *Journal of Medical Devices*, February 2012.

Suleman performed and documented part of the research: integration of the haptic device with the H3DAPI, assistance in face validity tests. Magnus developed the test procedure and carried out the face validity tests. He analyzed the results and wrote the major part of the paper. Jan carried out the corrections.

Additional publications

[1] Andersson K. and Khan S., "Investigation of Parallel Kinematic Mechanism Structures for Haptic Devices", presented at the *2nd Nordic Conference NordPLM'09*, Gothenburg, Sweden, January 2009.

[2] Khan S., Andersson K. and Wikander J., "Literature Review of Haptic Devices", *Technical Report-TRITA-2008:22* of the Machine Design Department at the Royal Institute of Technology (KTH), Sweden, June 2008.

[3] Khan S., Andersson K. and Wikander J., "Optimal Design of a 6-DOF Haptic Device", presented at the *IEEE International Conference on Mechatronics, ICM 2011*, Istanbul, Turkey, March 2011.

[4] Khan S., Wikander J. and Eriksson B., "Control Architecture and Stability Issues of Haptic Devices", *Technical Report* of the Design Department at the Royal Institute of Technology (KTH), Sweden, January 2010.

[5] Aftab A., Khan S. and Andersson K., "Kinematic and Dynamic Analysis of a New 6-DOF Tau Haptic Device", presented at the *IEEE International Conference on Mechatronics, ICM 2011*, Istanbul, Turkey, March 2011.

[6] Khan S., Aftab A. and Andersson K., "Multi-criteria Kinematic Optimization of a New 6-DOF Tau Haptic Device", presented at the *3rd International Congress on Ultra-Modern Telecommunications and Control Systems, ICUMT 2011*, Budapest, Hungary, October 2011.

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Notations

The commonly used notations and terminology in the thesis are listed here to help make the reading of the thesis easier.

6- Degrees of freedom (DOF) – three translational and three rotational DOF.

Admittance control devices – in an admittance control system, the device sense forces and renders motion (velocity and position). The basic interaction loop between the user and the control system is "force in – displacement out". Admittance displays are well adapted to display rigid constraints. For a high level of fidelity, the admittance display must actively mask inertia and damping.

Backdrivability – the level of easiness of the transmission, from the output axis to the input axis, of the movement which occurs at the output axis by force, e.g. applied by a human. This is a characteristic of the device which shows how easy it is for the user to move the device in the workspace.

Bandwidth – represents the frequency range over which the haptic device provides feedback to the user.. Generally, small precise movements will require a higher frequency feedback than large and more powerful movements.

Design – refers to a plan or an activity of designing.

Design variables – a set of variables representing the design alternatives or design space. In this thesis, design variables are also called design parameters.

Design methodology – refers to a set of activities and techniques to perform a design task or to develop a system for a unique situation.

Face validity study – a face validity study is used to determine the realism of a simulator, e.g. does the simulator represent what it is supposed to represent?

GHPD – a general purpose haptic device.

Haptic adj. – relating to the sense of touch, tactile [*Haptic*, Greek *haptikos*, from *haptesthai*, meaning *to grasp, touch*].

Genetic Algorithms (GAs) – GAs are adaptive heuristic search algorithms based on the evolutionary ideas of natural selection and genetics.

Haptic – a mechanical actuated device that provides an interface between the human user and the virtual environment. It senses the position of the device's tool center point (TCP) and sends it to the virtual environment. It provides haptic feedback to the user based on the interaction of an object in the virtual environment.

Impedance control devices – in an impedance control system, the device senses motion (position and orientation) and renders forces to the user. The basic interaction loop between the user and the control system is "displacement in – force out". Impedance displays are adopted to simulate low inertia and a low damping environment, since they have low inertia and high backdrivability.

Interdisciplinary – combining or involving two or more academic disciplines or fields of study.

Model – A model is a simplified representation of a system intended to enhance our ability to understand, predict and possibly control the behavior of the system

Multi-objective optimization (MOO) – an optimization variant that involves more than one objective function called MOO. In this thesis, MOO and multi-criteria optimization are used interchangeably.

Optimization – is a process that finds the best or optimal solution to a problem. The optimization problems are centered around three factors: objective function, design variables and constraints.

Pareto front – represents a set of all non-dominant solutions with respect to all objectives in the case of MOO. All of the Pareto front solutions are optimal solutions.

Pareto-optimal solution – a solution is called Pareto-optimal if there is no other solution for which at least one objective function has a better value while the remaining objective functions are the same or better. In other words, one cannot improve any objective without deteriorating another.

Parallel mechanism – links and joints are connected in a parallel fashion or via a closed chain, with multiple paths leading out to the end effector.

Position resolution – the resolution of the system represents the smallest deviation which can be detected by the sensors under study.

Probe – the probe is a representation of the haptic device in the virtual environment. The location of the probe is calibrated to the real position of the haptic device and, therefore, follows the movements of the device in 6-D space.

Proxy – the proxy is a virtual representation of the probe in the virtual environment. A proxy is used for visualization (the probe itself is not visualized) and haptic rendering. The idea is always to keep the proxy on the surface of the object to be felt, while the probe follows the actual position of the haptic device which can be located inside the object. When no collision is detected, the proxy and probe positions are the same, but after the collision the proxy remains on the surface. Visualizing the proxy gives the user an augmented impression of touching the surface. The probe–proxy distance and orientation (direction) are used for haptic rendering and force/torque feedback using a spring model.

Psychophysics – the field of study of the relation between stimulus and sensation.

Tool center point (TCP) – TCP is the position of the tool center point. Its pose is used for the probe position and orientation in a virtual environment.

Transparency – shows the ability of the system to provide feedback forces and torques to the operator at the same level as they are generated through the contact models of the virtual objects.

Fidelity – the ability of the simulator to simulate the real-world interaction. A high-fidelity device has a high resolution, high update rate, low latency, high stability and high transparency in the transmission of the forces and torques.

Serial mechanism – links and joints are connected in a serial fashion from the base and then in a single path leading out to the end effecter.

Singularity – represents the configuration of the device at which the determinant of the Jacobian matrix becomes zero and the actuators can no longer provide motion to the TCP in all DOF.

Singular points – the points in the workspace at which the configuration becomes singular.

Stiffness – the ability of the haptic device to mimic stiff virtual surfaces such as hard tissues, e.g. bone. It has been reported that stiffness needs to be 25 N/mm in order to feel stiff to a user when vision is obscured.

Update rate – corresponds to the sample rate of a feedback loop. The complete simulator loop includes sensing encoder position, communication between device controller and VR simulator, computation of feedback force/torque in simulation, device force control, and actuation through actuators. For realistic haptic feedback, an update rate of 1 ms is a targeted condition.

Virtual reality (VR) – is an environment simulated by a computer. Most VR environments provide primarily visual experiences, displayed either on a computer screen or using special stereoscopic displays. However, some simulations include additional sensory information, such as sound and tactile/haptic feedback.

Section – 1

1. Introduction

This chapter presents the research framework, the objectives and research questions, the scope of the thesis and a brief literature review of haptic devices. The final part of this chapter focuses on the thesis outline.

1.1 What is haptics?

Haptics is related to the sense of touch. The word haptic derives from the Greek word haptikos, meaning "being able to come into contact with". One application of haptics relates to a recent enhancement to virtual environments, allowing users to "touch" and "feel" the simulated objects with which they interact. To be able to interact with an environment there must be feedback. For example, the user should be able to touch a virtual object and feel a response from it. This type of feedback is called haptic feedback. A haptic feedback system is the engineering answer to the need for interaction with remote and virtual worlds [1]. Currently, this modality of interaction with the virtual world is less developed compared with visual feedback.

In human-computer interaction, haptic feedback means both tactile and force feedback. Tactile feedback is the term applied to sensations felt by the skin. Tactile feedback allows a user to feel things, such as the texture of surfaces, temperature, vibration and even an object slipping from one's grasp, due to, for example, gravity. Force and torque feedback reproduce directional forces and torques that can result from, for example, solid boundaries, inertia of grasped virtual objects and the mechanical compliance of an object. A haptic device or interface is used to reflect or send these feedback forces and torques to the user, as illustrated in Figure 1.1.
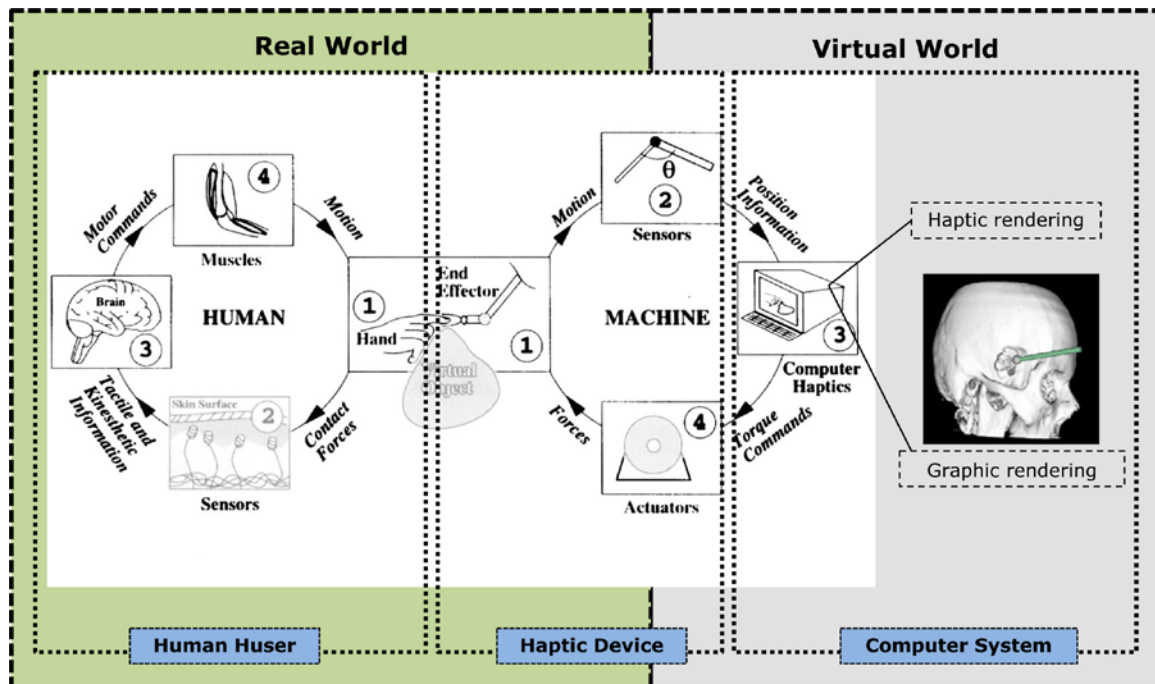

Figure 1.1 Haptic interaction loop includes a haptic device, human user and virtual world [2].

A haptic device senses user input, such as position or force, and the system sends this input to a virtual world. A response from the interaction with virtual objects is computed through models and haptic rendering. Finally, actuators on the haptic device display the corresponding touch sensations to the user.

The area of haptics research is an interdisciplinary field and it is generally subdivided into three main parts [3], see figures 1.1 and 1.2.

- **Computer haptics** – algorithms and software associated with generating and rendering the touch and feel of virtual objects (analogous to computer graphics). Generally, this topic spans object modeling and collision detection, graphical and haptic rendering, calculation of feedback response and the synchronization of haptic and graphic loops.

- **Machine haptics** – includes the mechanism and control design, development and implementation of the haptic device that provides the bridge between the user and the virtual environment for bidirectional communication (interaction). This device is a mechatronic system that is also called input/output haptic interface.

- **Human haptics** – the study of human sensing and manipulation through touch. It studies the mechanical, sensory, motor and cognitive components of the hand-to-brain system.

Consequently, multiple disciplines such as VR, neuroscience, psychophysics, biomechanics, mathematical modeling, simulations, design, control and software engineering converge to support haptics. Wide varieties of applications have emerged in this field and it spans many areas of human needs, such as medical simulation (simulation of surgical procedures), rehabilitation, design, virtual prototyping, games and entertainment.

In this thesis, the main focus is on machine haptics and how this can be applied in a medical situation.
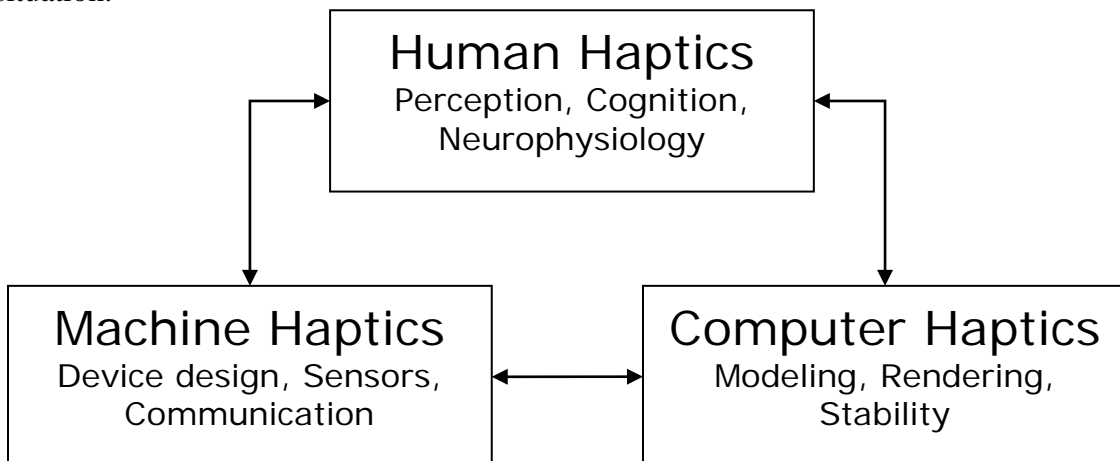
Figure 1.2 Haptic interaction as an interdisciplinary field of research

1.2 Introducing the problem

The research presented in this thesis is a part of the "haptic milling surgery simulator" project at the Mechatronics Lab, at the Royal Institute of Technology (KTH) [4][5], see Figure 1.3. The simulator is being developed for the manipulation of, and interaction with, stiff tissues such as bone or teeth. In such a scenario, a haptic cue is used to provide extra feedback to the user in addition to visual and audio feedback cues, to enhance the interaction. This additional

feedback can be provided using an actuated robotic mechanism which is called a haptic device. The intended application of the haptic device in this scenario is to provide an interface between the end user and the virtual environment, as shown in Figure 1.3. The haptic device makes it possible for the end user to manipulate and interact with objects in a virtual environment and also to provide feedback forces and torques to the user based on the interaction between a virtual tool and a virtual object.

Figure 1.3 Haptic milling surgery simulator at the KTH Mechatronics Lab.

The application context, surgery in bone structures, leads to three main haptic device requirements that are not simultaneously met by any commercially available device that we have found (for details, see section 1.5) [6]. These main requirements are [7]:
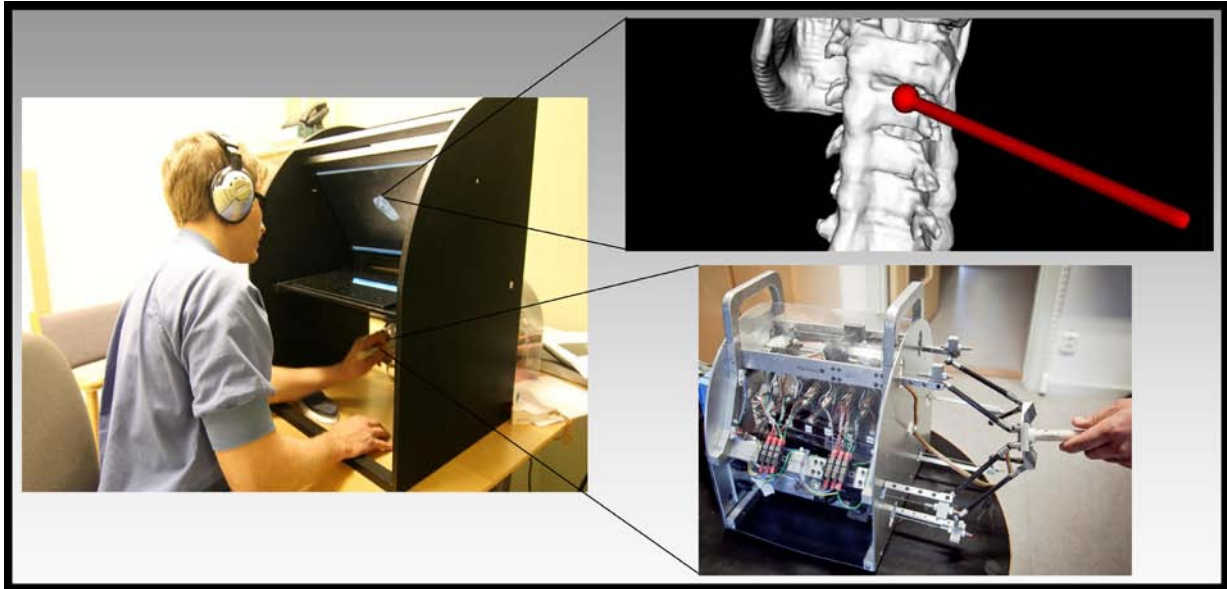
- Haptic feedback in 6-DOF, to allow both force and torque feedback from a virtual tool operating in a (narrow) channel or cavity.

- Device stiffness and force/torque performance that allows realistic simulation of stiff tool-to-bone contacts.

- Transparency and stability of the whole system.

Bone tissue surgery, in our scenario, is based on material removal by milling, including interaction in narrow channels and cavities. This may lead to multiple points of contact between the tool and the object, causing both reaction forces and reaction torques on the tool. This is the reason behind the requirement on feedback forces and torques in 5–6 DOF (translation and rotation).

Most of the existing haptic simulators for medical applications aim to interact with soft tissues. The hard tissue case targeted in this thesis is much more demanding regarding device stiffness, stability and force and torque performance.

The requirement on transparency means that motion in free space should feel free while motion in contact with a virtual or remote object should result in feedback forces and torques as close as possible to those that would appear due to real physical contact. In free space motion, transparency is affected by the dynamics (moving inertia, friction) of the device. The dynamic effects of the device itself must, therefore, be kept low or actively be compensated for to dynamically lower the resistance of the device. However, dynamics based control imposes hard requirements on the real-time implementation of the controller due to the complex computations of the complete dynamics equations.

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The stability of the whole system is a challenging issue, especially when the user is interacting with a virtual object or when moving in-between contact and free space. The stability of the haptic device depends on device dynamics and control design (friction, actuators' saturation, sensor noise and control sampling rate), dynamics of the virtual environment and of user dynamics.

1.3   Research objective and questions

The main objective of this research has been to develop an optimized haptic device to be used in the haptic simulation of surgical procedures in hard tissue. To achieve this goal, we formulated the problem in sublevel research questions and tried to address each question step by step, as follows.

- What state-of-the-art knowledge of 6-DOF haptic devices is used in similar applications?

- How to develop a systematic design approach/methodology to design an optimal haptic device for stiff tool-to-bone contacts given certain system requirements?

- How to optimize a selected design concept for maximum workspace-to-footprint ratio, isotropy and stiffness as well as for minimal inertial effects?

- How to design and develop a control strategy for haptic devices to achieve the required transparency and backdrivability?

1.4   Research approach

Development of a haptic device, particularly for the described application, is a challenging task, due to the multi-disciplinary nature of the overall aim, namely to demonstrate a functional simulator system for surgical procedures. The following research approach has been taken while conducting this thesis work.

- Literature review to explore the area of haptics and haptic interfaces, and to identify the main design parameters which influence the performance of haptic devices.

- Elicitation of requirements from the end user and transformation of these requirements into design specifications.

- Conceptual design and evaluation of different design concepts.

- Design, design optimization and development of the selected concept.
    - Inverse kinematic modeling
    - Forward kinematic modeling
    - Optimization of the mechanical system
    - Inverse dynamic modeling
    - Control design

- Realization, testing and verification of the optimized prototype design.

- Integration of the device within the complete haptic simulation system.

- Finally, testing, verification and validation of the whole system. This has included both tests of the device itself and tests of the complete haptic milling surgery simulator.

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1.5 Scope of the thesis

The research presented in this thesis mainly focuses on the development of a parallel kinematic haptic device and on using state-of-the-art optimization tools, i.e. in this case, GAs. For the systematic development of the device, a design methodology is proposed and applied to a case study. For control of the haptic device, we investigate an impedance control strategy, in order to avoid using a force sensor on the TCP. A force sensor would add inertia as well as cost to the device. In the dynamic modeling, we assume that passive joints are ideal (frictionless) for simplification. The stability of the system was determined by measuring the response from the system, we do not determine the closed loop stability mathematically in this thesis. Testing and verification of the prototype was done in the laboratory, both stand-alone and as integrated in the complete simulator system. Finally, the complete simulator system went through a successful face validity study performed in collaboration with the Division of Orthopedics at the Karolinska University Hospital. Forthcoming detailed product design and industrialization of the device is left out of and is regarded as future work.

1.6 State of the art

Research on the development of haptic devices has been conducted since the late 20th century [1]. Many haptic devices have been developed and some of these have been commercialized, see figures 1.4 and 1.5 [8][9][10][11][12][13]. An overview of 6-DOF haptic devices and their characteristics is given in Table 1.1, where we consider only maximum force and stiffness that these devices can provide. Apparently, various force-reflecting haptic devices are available either on the market or in research labs. In relation to the application studied in this thesis, the below-mentioned devices have some good and some less good characteristics.
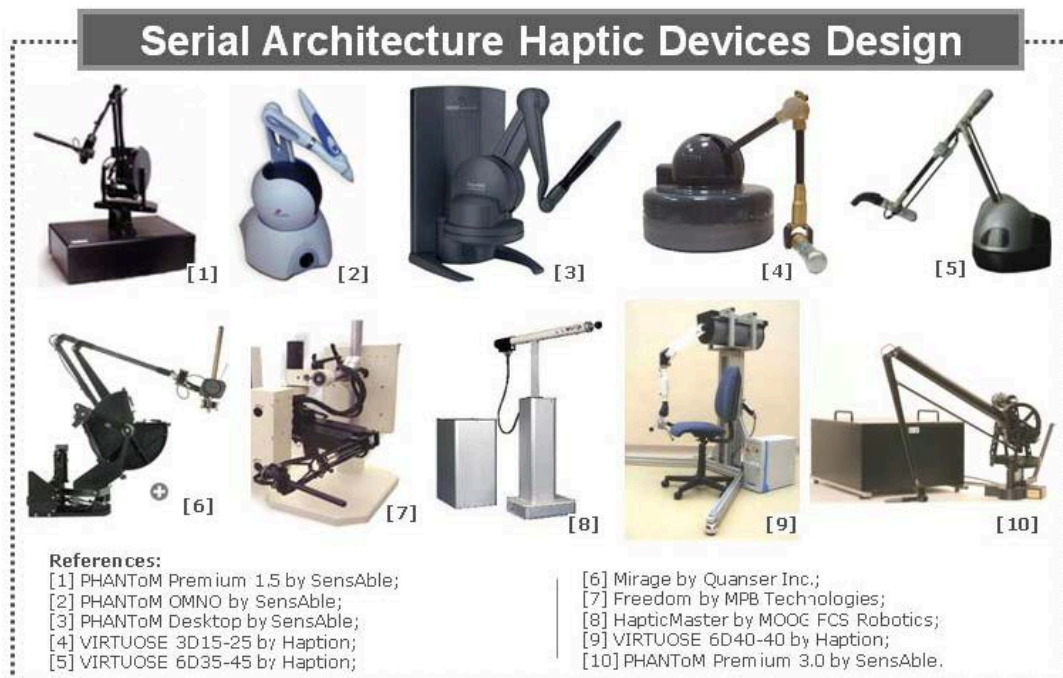

Figure 1.4 Examples of commercial haptic devices based on serial architecture [13].

Figure 1.5 Examples of commercial haptic devices based on parallel architecture [13].

Table 1.1 6-DOF Haptic devices available either commercially or in a research lab.

Device	Mechanism	Workspace [mm, deg]	Forces [N] Torque [Nm]	Stiffness [N/mm]	Price [$]	Ref
Phantom Premium 1.5	Serial	381 x 267 x 191 297 x 260 x 335	8.5–1.4 0.515–0.188	3.5	4,500	[14]
Premium 3	Serial	838 x 584 x 406 297 x 260 x 335	22–3 0.515–0.188	1	79,500	[15]
Haption Virtuos 6D35-45	Serial	1080 x 900 x 600 Sphere of 100 d	35–10, 3–1 15–3,	6.5 2.5	85,000	[16]
6-DOF Desktop	Parallel	35 x 35 x 35	0.5–0.14	2	--	
6-URS device	Parallel	Sphere of 150 d	99	--	--	[17]
SPIDAR-G	Parallel	Scalable	--	--	24,500	[18]
Omega (Desktop)	Parallel	360 x 360 x 300 20 x 20 x 20	20 0.150	14.5	54,330	[19]
Delta (force Dimension)	Parallel	30 x 30 x 36, 240 x 140 x 320	12	14.5	40,500	[20]
Modified Delta	Parallel	15 x 15 x 15 140 x 140 x 140	10	12	55,500	[21]
Cobotic	Parallel	170 x 170 x 170	20– 400	50–50	--	[22]
6-DOF haptic master	Parallel	Sphere 400 mm dia	30–3	12	--	[23]
Freedom 6S	Hybrid	170 x 220 x 330	2.5–0.6	2	--	[24]
New 6-DOF Haptic device	Hybrid	160 x 120 x 120 45 x 45 x 15	7	4.5	--	[25]
GPHD 6-DOF	Hybrid	160 x 160 x 160	10–2	20	--	[26]
Desktop Parallel Haptic device	Hybrid	150 mm dia 45 x 45 x 45	10– 4	1.2	--	[26]
New maglev haptic device	Magnitic	25 mm dia 20 x 20 x 20	55– 40	25	--	[27]
Ares haptic device	Parallel	75 x 75 x 100 45 x 45 x 45	54–20 1.2–0.85	50 1	--	Paper B

Some of the devices provide large workspace, but their ability to render high forces and stiffness is low. Another problem with some of the existing designs is that the actuators are not fixed to the ground, thus increasing the inertia of the system, which, in turn, affects the transparency of the device.

For example, the Phantom [14] haptic devices by Sensible Technology provides a large workspace compared with the Cobotic 6-DOF haptic device [22], but this device cannot display forces and torques high enough for interacting with stiff virtual objects. Also, the 6-DOF Phantom [14] devices are expensive. On the other hand, the Cobotic 6-DOF [19] haptic device provides high forces and stiffness, but the size (footprint) and weight of this device is not suitable for the described medical application and this device is not optimized to achieve the best performance. Cable-driven haptic devices, such as SPIDER-G [18], are characterized by low inertia and friction, which improve the backdriveability and transparency of the device. On the other hand, this device cannot provide high stiffness to the user due to the cable-based actuation mechanism.

Literature on haptic devices suggests that structures based on parallel kinematics are most suitable for high payload and stiffness due to the parallel actuators and low effective inertia by allocating the actuators on the ground [23]. The performance of such structures is highly dependent on their geometry and dimensions [28]. Thus, it is important to perform structural optimization in order to achieve the desired performance.

Formulating an optimization problem for a parallel kinematic structure often ends up as a multi-criteria design optimization problem due to many conflicting design objectives. In the optimization, multiple criteria such as for example, workspace; kinematic performance such as kinematic isotropy; static force transmission capability; stiffness; and dynamic performance need to be considered together. The optimization problem is typically non-linear and non-convex, with no explicit analytical expression. The Gradient and Hessian based optimization algorithms that generally converge to a local minimum are thus not suitable for solving this problem. An interval analysis-based approach was recently applied by Hao [29] to solve a multi-criteria design problem for parallel manipulators. This method establishes design parameter spaces that satisfy all design constraints, but it requires explicit analytical expressions of all constraints. The performance-chart based design methodology (PCbDM) proposed in [30], is an optimal kinematic design methodology for parallel mechanisms with a maximum of four design parameters, and is thus not suitable for optimization problems that have more than four design parameters.

On the other hand, multi-objective genetic algorithms (MOGAs) [31][32][33], multi-objective estimation of distribution algorithms (MOEDAs) [34] and modified complex RF algorithms [35][36] seem to be good candidates for these multi-criteria problems due to their ability to explore a Pareto front (solution) and due to their robustness. Lee et al. [25], Khorshidi et al. [37], Raza et al. [38], Valasek et al. [39], Guigue et al. [40], Tarkian et al. [41] and Gao [42] all used a GA approach for multi-criteria optimization of robotic structures, parallel kinematic machines and parallel haptic devices.

The physical design of haptic devices, in terms of the selection of the type of mechanism, type of actuation system, number and location of actuators and dimensioning of the components plays an important role in determining the capabilities and overall performance of the system. Thus, from a design point of view, further research is needed to improve the performance and functionalities such as workspace size in relation to device size (footprint), actuated DOF, stiffness, transparency, resolution and bandwidth of these devices. Applying optimization techniques in the design process is a necessity for efficient development and for improving device performance.

Improvements in the performance of these devices will create new opportunities for surgical procedures. One example is the VR medical training system for surgery in stiff tissue, in which the haptic device described in this thesis, has been used with promising results.

1.7 Thesis outline

The thesis is divided into two sections. Section 1 concentrates on the summary of research that was conducted during the PhD studies.

Chapter 1 introduces the research background, research questions and research approach that has been taken to perform the work. The application of the haptic device, i.e. the haptic milling surgery simulator and its related literature, are also outlined in this chapter.

The proposed design methodology for the development of haptic devices is outlined in Chapter 2. The proposed methodology is based on an iterative and parametric design approach. It includes the complete development process, i.e. requirements and specification, conceptual design, optimization process, detailed design, testing and verification. In the conceptual design, a preliminarily analysis, such as number of DOF, workspace and actuator capability, is performed using the multi-body simulation (MBS) software Adams View® [43]. Next is the optimization of the selected concept. For optimization, performance indices such as workspace volume, isotropy, stiffness and inertia were considered. The final part of this chapter briefly discusses detailed design, prototype development, testing and verification of the prototype. The aim of this chapter is to introduce a design methodology which proved to be efficient for the analysis and design of complex parallel kinematic structures.

Chapter 3 focuses on a case study where the proposed design methodology is applied to the design of a haptic device based on parallel kinematics. Conceptual modeling, design optimization and control design are also presented. For the analysis, advanced computational tools, such as the MBS tool Adams View® [43], Matlab® [44]and Simulink, are applied. Aspects of the detailed design and prototype development are also outlined. The last part of this chapter includes initial experimental work to evaluate the performance of the prototype. Workspace, force and torque capability and structural stiffness of the prototype are measured at different points in the workspace and are presented in the results section.

Chapter 4 reports on the integration of the haptic device with the 6-DOF haptic collision detection and force/torque rendering algorithms together with the performed face validity tests. Chapter 5 lists and summarizes the appended papers and focuses on the discussion, conclusion and future recommendations.

Section 2 contains the appended papers that have been published and those that have been submitted for publication by the author.

1.8 Summary

This chapter summarizes the field of haptics and haptic devices. The research framework of the haptic milling surgery simulator, where the haptic device is applied, is introduced. The simulator is developed for interaction with stiff tissues such as bone. The application of a haptic device in this particular case requires high stiffness, high force/torques capabilities and high transparency (low inertia and stiffness). A related literature survey of 6-DOF haptic devices is briefly summarized and it is concluded and there still is a need further research and development to improve device performance to meet the needs of advanced applications. Application of optimization techniques in the design process can help to improve the performance.

2. Design methodology

This chapter gives an overview of the proposed design methodology for the development of haptic devices. The aim is to apply and demonstrate feasibility of a general design methodology for the development of this type of devices. The methodology is applied to different case studies to verify the effectiveness of the proposed methodology. The design methodology is presented in detail in appended Paper A, Paper E and in [45].

A design methodology for haptic devices would, in general, be quite similar to any mechatronic product development methodology. However, the design of haptic devices involves specific difficulties, as they involve both human interaction and virtual environment manipulation, and both these aspects need to be considered in the design. Haptic devices present a difficult mechatronic design problem, as they are required to be backdrivable and light (low inertia and friction), as well as being able to provide enough stiffness, and feedback forces and torques as reflected from stiff contacts, arising from e.g. tool-to-bone interaction. Furthermore, transparency and stability is required so that the user can experience both free space and constrained motions in a realistic way. The user should feel the dynamics of the tool and of the manipulated objects, and not the dynamics of the haptic device itself.

A design methodology is proposed for the development of haptic devices. This design methodology is derived from the V-model, which is a basis for the design guideline *VDI 2206 Design methodology for mechatronic systems* [46], and also from the information framework suggested in [47]. The proposed methodology consists of five main process steps: requirements specification, conceptual design, detail design, industrialization and production, as shown in Figure 2.1.
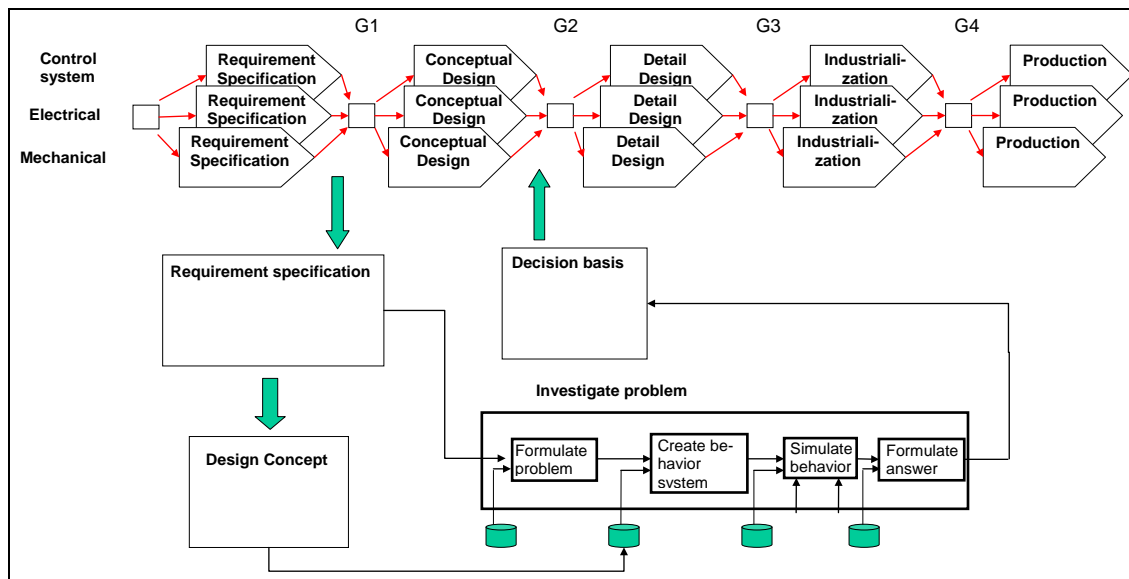

Figure 2.1 Proposed design methodology for haptic devices.

The proposed methodology is a parametric, iterative and integrated modeling and design approach that leads to easier design space exploration and the early verification of design concepts. In this thesis, conceptual design and parts of detailed (prototype) design are in focus. The first stage of the methodology is to define the market needs and the more direct device requirements. These requirements include, on an abstract level, the number of DOF, workspace, force/torque capability and stiffness. The second stage of the methodology is conceptual design. Here, the methodology includes preliminary analysis of the number of DOF, workspace size, actuator requirements and singularity points (which should not be within the workspace) for the different design concepts. In parallel, a rough layout of the mechanical structure, with preliminary material properties, should be made as well as an investigation of possible control strategies and which components to use. This is followed by a detailed design of the mechanical structure, actuation and transmission, and also an analysis of the achieved workspace, stiffness, inertia, force/torque capabilities and backdrivability. In parallel with designing the mechanics and actuation, the models necessary for control design are derived. In the control design, sensors and control strategies are selected and designed. Before the device is finally built and the control is implemented, thorough work should be undertaken for optimal design using both simulation and rapid prototyping to verify performance and, if necessary, iterate within the design process. After these stages, the industrialization and production phases are implemented; however, these are not within the scope of this thesis.

Apparently, there is a large number of design parameters that need to be fixed before a final design can be achieved. In addition to the direct specifications, it is important to consider additional design criteria towards an overall optimal design. Such criteria can, for example, include: (1) maximum workspace-to-footprint ratio; (2) uniform motions, forces and stiffness capabilities over the workspace (kinematic isotropy); and (3) minimum inertia of the structure, transmission and actuation system (dynamic and control characteristics). Some of these design criteria are mutually dependent, thus leading to a large and complex design problem with high computational complexity. To cope with this problem, an optimal solution is determined using MOGA (Multi Objective Genetic Algorithms) optimization and efficient computational tools. The goal of the methodology is to provide efficient support towards an optimal design.

Since the design methodology is presented in detail in two of the appended papers (Paper A and Paper E) we have chosen to focus mainly on concept evaluation and briefly on prototype design and verification in the rest of this chapter.

2.1   Concept evaluation

The evaluation of a product concept is something that is performed throughout the whole design process. This process is of an iterative nature and can be described as a generic process that can be mapped on the different evaluation activities that take place during the design of a haptic device. This means that this is a generic activity that is an integrated part of the design process, shown in Figure 2.1.

The evaluation activities occur between the process gates and are focused on detailing and resolving uncertainties about the actual concept, that is, on gaining knowledge about the concept. These activities are triggered by the specifications that define the target values for the properties of the proposed product. These activities can all be seen as part of an evaluation process that iteratively evaluates a concept against all critical requirements, either by simulating behavior or by using other sources of information, including collaborating with colleagues and looking at old designs. Representing these activities and their results will

enable the traceability and reuse of simulation models and thus make this evaluation process more efficient.

Figure 2.2 depicts a generic description of a concept evaluation process. The main activity in this process is to "investigate the problem", where the problem is whatever is unknown about a requirement and needs to be investigated further. The types of models that are needed to handle and document the data created during the evaluation process [48] are illustrated in Figure 2.2. The database symbols (see Figure 2.1) indicate that for each step in this process there are a number of predefined models that may be candidates that can be used to solve an actual problem.
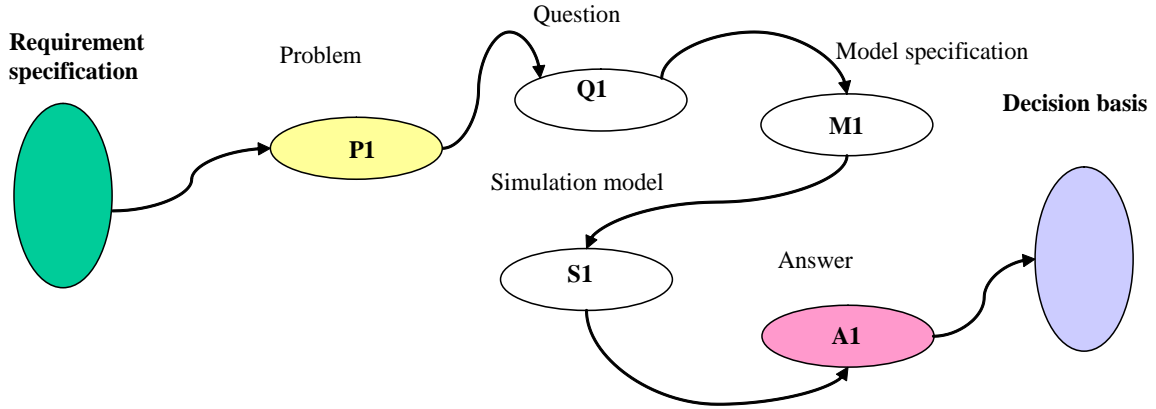

Figure 2.2 Models involved in the selection/evaluation process.

The concept evaluations described in the coming sections, 2.1.1–2.1.3, all deal with the conceptual design phase, where the generic process, as seen in Figure 2.2, has been used as a mind map.

2.1.1 Preliminary analysis

In the preliminary analysis in conceptual design, we need to investigate the device workspace (translation and orientation) and force performance at the TCP. The first investigation deals with the requirement to position and orient the TCP, while the second investigation aims to determine the required performance in terms of the desired force/torque from the actuators. In parallel, we also investigate the preliminary material properties of the mechanical structure as well as possible control strategies and components to use. These analyses and corresponding results are presented in detail in Paper A.

2.1.2 Design optimization

The outcome of the preliminary analysis in the conceptual design phase is used to decide which mechanism to select for further design optimization. In the following step, it is important to consider other criteria towards device design optimization. Such criteria can include: (1) maximum workspace-to-footprint ratio (workspace); (2) uniform motions, forces and stiffness capabilities over the workspace (kinematic optimization); and (3) minimum combined inertia of structure, transmission and actuators (optimal control strategy). The performance indices considered for the optimization of the device are workspace, isotropy, force requirements on actuator, stiffness and inertial indices. The defined performance indices were transformed to a general optimization problem formulation of the form

$$\text{minimize} \quad F(P) = \left[f_1(P), \quad f_2(P), \ldots\ldots \quad f_n(P) \right]^T$$

$$\text{subject to} \quad g_1(P) \le 0 \quad (1 \text{ is inequility constraints})$$

$$h_m(P) = 0 \quad (m \text{ is equlity constraints})$$

$$, \tag{2.1}$$

where *F(P)* is a vector of *n* objective functions and *P* is a vector of *k* design variables. In MOO problems, one needs to find a design variable vector, *P**, which minimizes the objective function, or, in other words, which finds a Pareto-optimal solution, in the case of conflicting objectives. The concept of Pareto optimality is characterized by all non-dominated solutions, which together constitute a so-called Pareto front. No objective function of a Pareto-optimal solution can be improved without making another objective function worse, as illustrated in Figure 2.3. In this figure, the axes represent different objectives and the circles represent different solutions, while the line represents the Pareto front.
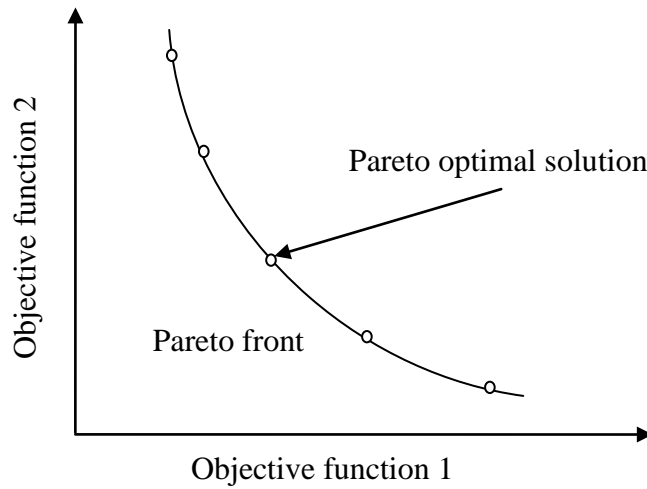

Figure 2.3 Illustration of the Pareto front and an optimal solution.

The terms objective function and performance index mean the same and may be used interchangeably. According to the definition of the Pareto-optimal solution, a solution that minimizes/maximizes the objective function without deteriorating the other objective functions, is a Pareto optimal solution. Different approaches/algorithms, e.g. weighted-sum, MOGA [31][32][49], NSGA-II [50], can be used to find a Pareto-optimal solution for the described MOO problem. There are also some other algorithms presented in the articles [51][52] that can be used for this purpose; however, in this thesis, we used only the following three approaches. A short description of each of these approaches is given below.

- **Weighted Sum Approach**

    This is a classical approach to solve a MOO problem. A weight w_i is assigned to each objective function f_i so that the problem can be converted to a single objective problem, as

$$\text{maximize} \quad GDI = \sum_{i=1}^{3} w_i f_i \quad \text{and} \sum_{i=1}^{3} w_i = 1 \tag{2.2}$$

    Solving a problem with the above-defined global design index (GDI) for a given weight vector $w = \{w_1, w_2, \ldots w_i\}$ yields a single solution. If multiple solutions are desired, the problem must be solved multiple times with different weight combinations. The main

difficulty with this approach is selecting a weight vector for each run. To automate this process, Hajela and Lin [53] proposed the Weight-based Genetic Algorithm for Multi-objective Optimization (WBGA-MO). In this approach, each solution in the population uses a different weight vector $w_j = \{w_1, w_2, \ldots w_i\}$ when calculating the objective function. The weight vector w_j is embedded within the chromosome of the solution. Therefore, multiple solutions can be simultaneously searched in a single run. In addition, weight vectors can be adjusted to promote diversity of the population. However, in many real-life problems, the objectives under consideration conflict with each other. Hence, optimizing with respect to a single objective (weighted sum approach) often results in unacceptable results with respect to the other objectives. Thus, a multi-objective solution that simultaneously optimizes each objective function is hardly found.

- **Multi-objective Genetic Algorithm (MOGA)**

A reasonable approach to a multi-objective problem is to investigate a set of solutions, each of which satisfies the objectives at an acceptable level without being dominated by any other solution. As discussed above, this is called a Pareto-optimal solution. MOGA is a MOO approach that explicitly combines Pareto-based ranking and niching techniques to encourage the search towards the true Pareto front while maintaining diversity in the population. In this approach, a random population of chromosomes (corresponding to vectors of selected design variables) is initially generated. Then, in each generation, the fitness value of each chromosome (individual in population) and the total fitness is evaluated on the basis of the MOO function. The way MOGAs operate to calculate the Pareto-optimal solution is described in Figure 2.4 [54].
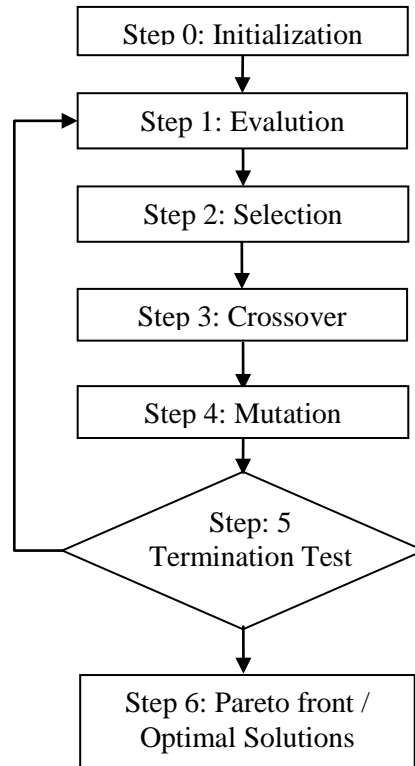

Figure 2.4 Flow chart for MOGA [31].

In each generation a certain number of best solutions (elite individuals) are randomly selected from the population. Elitism is very important in multi-objective optimization because it helps preserving the individuals that are closest to the Pareto front and the ones that have the best dispersion.

In order to generate the new population for the next generation, the chromosomes with the best fit are selected on the basis of the probability distribution of the fitness values. For each selected pair, a crossover operation is applied to generate two new chromosomes. Then a mutation operator is applied to the chromosomes to change the structure of the new population. There exits multiple procedures for the selection of chromosomes, crossover and mutation operations to generate new populations. In the GAs, the crossover represents the rate of genetic exchange of chromosomes from one generation to the next, while mutation is used to flip the gene inside the chromosome in a selected population. To find the Pareto-optimal solution in a robust way, crossover and mutation between the chromosomes are used to achieve convergence and coverage of the whole design space.

- **Non-dominant Sorted Genetic Algorithm (NSGA-II)**

The NSGA-II algorithm proposed by Deb et al. [50] is a new version of the NSGA [55] algorithm. NSGA-II incorporates elitism and crowding distance to enhance the performance and robustness of NSGA. In NSGA-II, the initial population is as usual randomly initialized as illustrated in Figure 2.5.
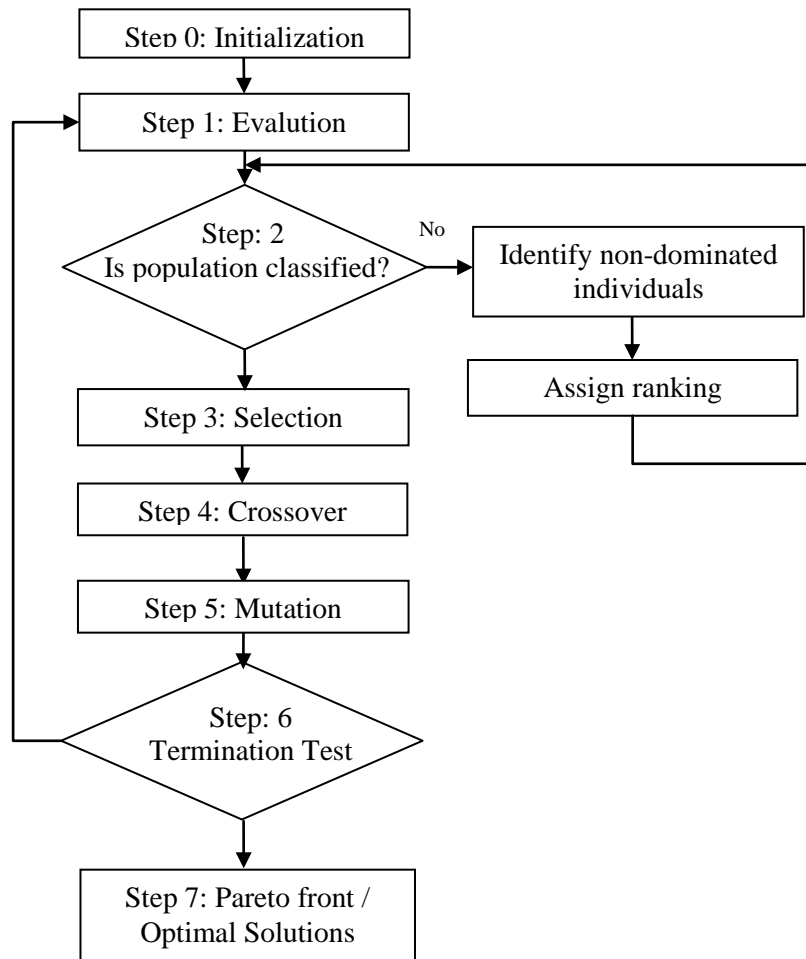

Figure 2.5 Flow chart of the NSGA-II algorithm.

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Once the population has been initialized, its individuals are sorted into fronts on the basis of non-domination by evaluating the objective function. The first front is the completely non-dominant set in the current population. The second front is dominated by the individuals in the first front only. Subsequent fronts are defined in the same fashion. Each individual in each front is assigned a rank (fitness) based on the front to which they belong. Individuals in the first front are given a fitness value of 1, individuals in the second front are assigned a fitness value of 2, and so on. In addition to fitness values, a new parameter, called crowding distance, is calculated for each individual. The crowding distance is a measure of how close an individual is to its neighbors. Large average crowding distances will result in better diversity in the population and thus improve the performance of the algorithm when calculating the Pareto optimum. Parents are selected from the population by using binary tournament selection based on the rank and crowding distance. An individual is selected if the rank is lesser than that of other or if crowding distance is greater than that of the other. Then, crossover and mutation operators are used to create offsprings from the selected population. The population, with the current offsprings, is sorted again based on non-domination and only the best N individuals are selected, where N is the population size.

2.1.3 Control design

During the conceptual design phase, control design is performed in parallel with the other design activities to obtain an overall design that is feasible from kinematic, dynamic, control and actuation points of view. The control design for haptic devices, particularly for the application described in section 1.1, is challenging, as the device needs to provide both high stiffness and transparency. The requirement on transparency means that the motion in free space should feel free while the motion in contact with a virtual object should result in feedback forces and torques as close as possible to those appearing in the remote or virtual world. In free space motion, transparency is affected by the dynamics (moving inertia and friction) of the device. Keeping the device inertia as low as possible, as well as compensating for it in control design, will increase the transparency. However, dynamics-based control imposes hard requirements on the real-time implementation of the controller, thus requiring a complete dynamics and control analysis for the device. To achieve high transparency, stability and execution time become challenging issues in the design process (a sample time less than approximately 1 ms is required for haptic feedback), [56][57].

At this stage in the design methodology, we need to investigate control strategies to increase the transparency and stability of the haptic device, as presented in detail in appended Paper E and in a master thesis carried out in conjunction with this PhD research [58]. The characteristics needing analysis are:

- Dynamic effects of the structure.
- Dynamic model of the human user hand
- Optimal selection of actuation and gear ratio.
- Simplification of the dynamic model for control design.
- Design and investigation of control strategies.
- Stability of the system.

2.2 Detail design and prototype development

This phase of the design process includes a selection of standard components (e.g. joints, electric motors, sensors, and motors drivers), detail design, material selection and creation of manufacturing documents of components to be manufactured. The description here shortly describes the work performed for design, manufacturing and verification of the haptic device prototype. The mechanics of the physical prototype is built based on a 3-D CAD model which is developed based on the results from the multi-objective optimization process. A complete device is assembled including the selected motors, sensors, drivers, auxiliary electronics and control system hardware. The developed control strategy is implemented, in this case using dSpace control desk® [59] and dSpace hardware. The last step in the process is testing and verification of the assembled prototype. For the prototype, this verification is covered in some detail in chapter 3

2.3 Summary

The design process of haptic devices is challenging, as it involves aspects of multiple disciplines, such as mechatronics, models of the human user and integration with a virtual environment; which all need to be considered in the design process. In this chapter, a design methodology for the development of a haptic device is briefly introduced. The discussion about the methodology focuses on concept evaluation and the generic nature of this process. Different aspects of concept evaluation are discussed as part of a generic concept evaluation process. Emphasis is given to the preliminary analysis and optimization of the concepts at a conceptual design stage. Detail design, prototype development, testing and verification steps are briefly outlined in the last section of the chapter.

3.   Case study: application to the design of parallel haptic devices

This chapter introduces the case study and application of the design methodology proposed in Chapter 2. In the first sections, conceptual modeling, analysis and the MOO problem are presented. The last section focuses on a CAD model, a prototype and testing and verification of the developed prototype.

As presented in the related literature (see section 1.5), both serial and parallel configurations have been used in haptic devices [60]. For the application context, surgery in bone structures (haptic milling surgery simulator), we selected parallel-based structures for the design. Parallel kinematic structures have several significant advantages compared with serial structures, including high stiffness, payload, accuracy and low inertia with the actuators located on the fixed base [61]. On the other hand, performance of parallel kinematic structures is highly dependent on their geometry and dimensions [29]. Thus, it is vital to consider dimension synthesis and structural design parameter optimization in order to achieve desired/optimal performance. Also, the design optimization of parallel mechanisms is challenging due to the complexity of their kinematics, dynamics and singularities [61]. Thus, the proposed methodology was used to achieve optimal performance.

3.1   Conceptual design

In the first step of the design methodology, a literature review and market analysis is performed in order to identify the potential users and their requirements. The list of preliminary requirement/specifications for the design of the device is given below:

- The device should have 6 actuated degrees of freedom [6-DOF input/output] motion.

- The whole device [footprint] should fit within the space of 250 x 250 x 300 mm.

- The translational workspace should be a minimum of 50 x 50 x 50 mm with no singularities within that space.

- The rotational workspace should be ±40 degrees in all directions (at the center of the translational workspace).

- The tool center point (TCP) force and torque performance should be at least 50 N and 1 Nm respectively.

- The stiffness of the device should be a minimum of 50 N/mm.

Next, in the conceptual phase of the design methodology, two design concepts based on parallel kinematics are selected for initial analysis. The first concept (concept 1) is a modified Stewart Gough (Merlet kinematic) mechanism [28][62], which consists of a fixed base, a moving platform and six identical legs connecting the platform to the base, as shown in Figure 3.1.
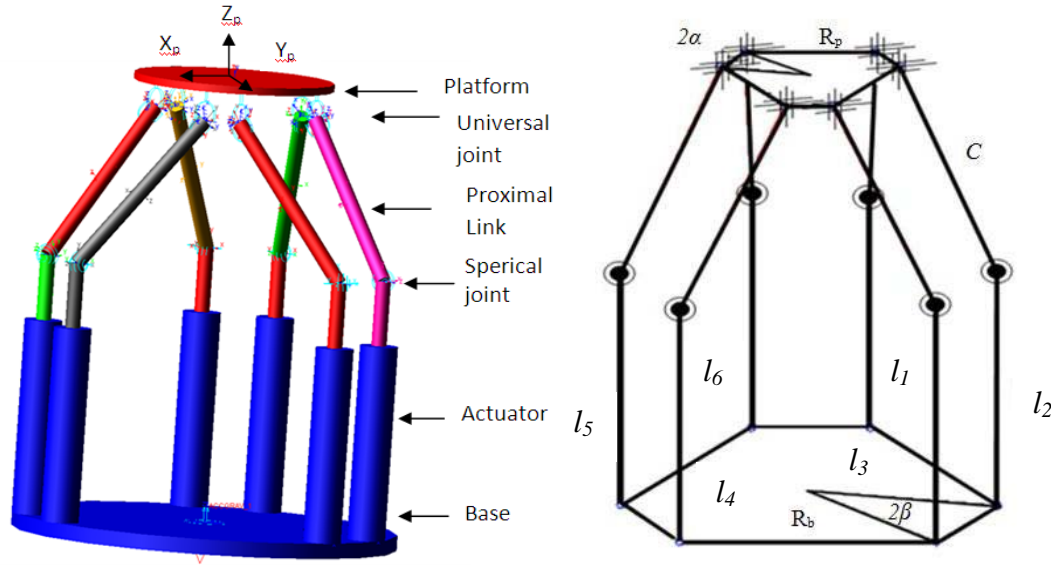
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Figure 3.1a) Conceptual model of concept 1 in Adams View® [43] b) Kinematic structure of concept 1.

In the selected concept each leg consists of an active linear actuator fixed to the base, a spherical joint, a constant length proximal link and a universal joint. This 6-PSU (active Prismatic, Spherical and Universal) joint configuration was used to achieve 6-DOF.

For parametric design of this structure, six design parameters are considered: range of actuators' motion (l_{i_min}, l_{i_max}), length of proximal link C_i, radius of base R_b, radius of platform R_p, angle between the base pair of joints 2α and angle between the platform pair of joints 2β, see Figure 3.1b. The pairs of attachment points are symmetrically separated 120° and lie on a circle, both on the base and the platform. The platform attachment points are rotated 60° clockwise from the base attachment points.

 The second concept (concept 2) is based on a hybrid parallel kinematic structure called TAU [63][64], shown in Figure 3.2a. This concept consists of a fixed I-column, a moving platform and three parallel chains (1, 2 and 3) which connect the base frame to the moving platform. In this structure, chain 1 and chain 2 are symmetrical, while chain 3 is unsymmetrical, as shown in Figure 3.2. Each symmetrical chain has two active rotational actuators: one attached to the I-column while the other is mounted on the upper link U_1, U_2. Furthermore, chains 1 and 2 have two extra proximal links connecting the platform to upper links U_1 and U_2, to increase the structural stiffness. The third chain, chain 3, also has two active rotational actuators, one attached to the I-column and the other mounted to the top of the device.

For the parametric design of this structure, five design parameters are considered: position d of each parallel chain with respect to the base coordinate system, length L_1 of the upper arm, length L_2 of the proximal links, radius of the platform R_p and the elevation angle, $\theta_{32\ nom}$, of the upper arm U_3.
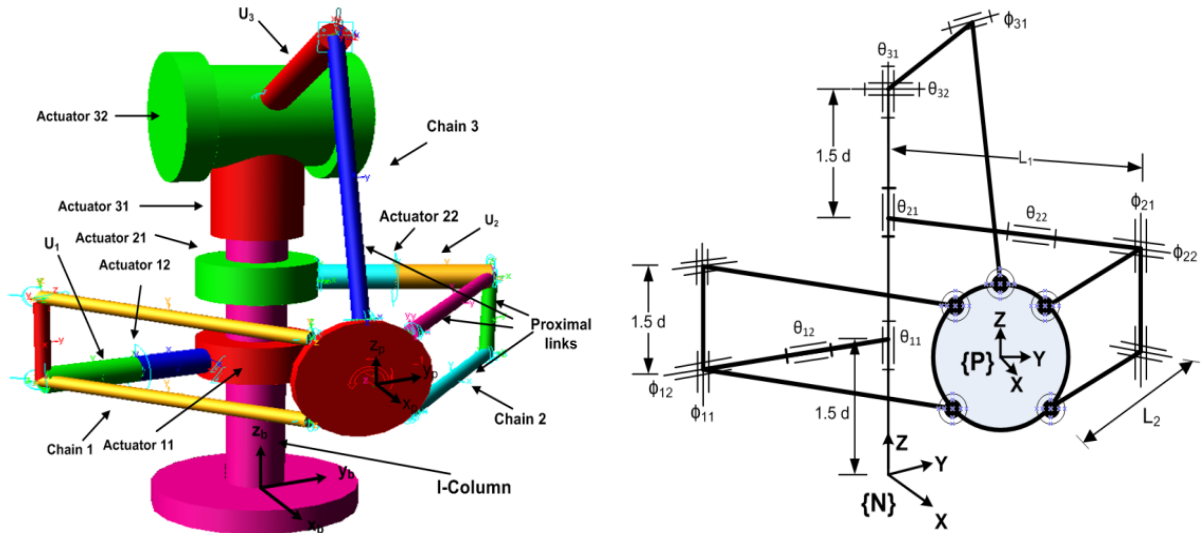
Figure 3.2a) Conceptual model of concept 2 in Adams View® [43] b) Kinematic structure of concept 2.

3.1.1 Preliminary analysis

At this stage in the conceptual design, the number of DOF, workspace (translational and rotational) and actuators' forces/torque requirements are the main focus of investigation. The concept evaluation process (section 2.1) is used in the conceptual phase for these investigations. Three main properties are investigated (see Figure 3.3), these are:

- What is the number of DOF?
- What is the device workspace?
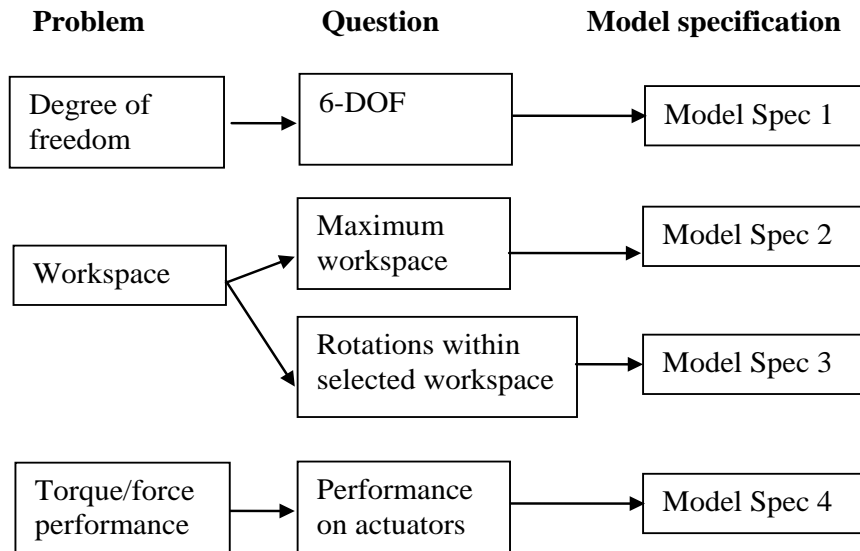- What is the force/torque performance around the TCP?

Figure 3.3 problems to investigate during the initial analysis.

The two selected concepts were modeled and analyzed using MBS software Adams View® [43]. For modeling and analysis at this stage, we assume rigid bodies, ideal joints (no friction) and free motion without dynamic effects. Also, we do not consider the actuator's inertia and transmission mechanism at this point. Modeling of the two concepts follows the same principle steps. The following steps were performed in the concept evaluation process:

- Create a parameterized Adams model of the concepts based on preliminary dimensions (see Figure 3.1a and 3.2a).

- Scale the model to fit in the same virtual box with the size (footprint) of 250 x 250 x 300 [mm] in the modeled normal position.

- Determine the number of DOF.

- Analyze the outer boundary of the workspace.

- Select a suitable position for an assumed required workspace of 50 x 50 x 50 [mm].

- Analyze how much the TCP can rotate in all eight corners of the cubic workspace (applying a torque or rotation at the TCP).

- Analyze what force or torque is needed by the actuators for a required force or torque performance at the TCP in all 6-DOF (by applying a force or a torque at the TCP) at each corner of the cube.

- Analyze what force or torque is needed by the actuators for a required force or torque performance at the TCP in all 6-DOF (by applying a force or a torque at the TCP in opposite direction to the motion) while moving the TCP along a specified trajectory.

The concept modeling, analysis and results are presented in detail in appended Paper A and in [45]. The reachable workspace, with preliminary dimensions for these concepts, is shown in figure 3.4. The required cubic workspace is shown in Figure 3.4a.
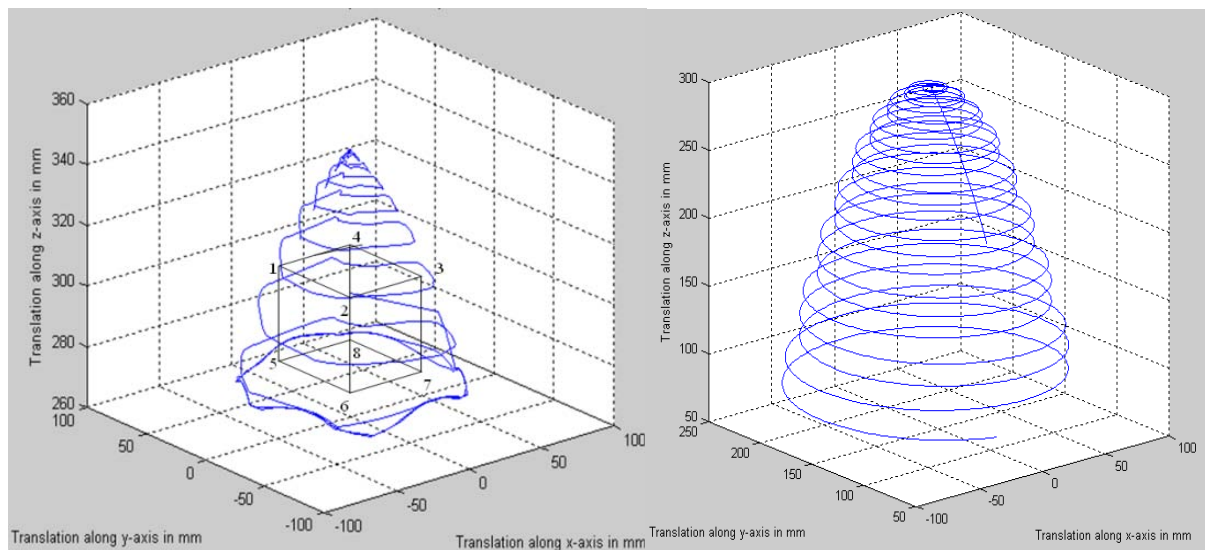

Figure 3.4 a) Boundary of workspace for concept 1 and b) for concept 2 in 3-D space.

The approach used to measure the force/torque requirements on actuators, was to move the TCP in the x-z plane along a circular path enlarged in diameter with steps of 10 [mm] through the workspace, starting in the middle of the bottom of the cylinder. In order to span the whole workspace, this motion pattern was applied at five equally spaced layers along the y-axis while we applied a specified force of 50 [N] on TCP, acting opposite to the motion. The force/torque actuator requirements for these concepts are given in figures 3.5 and 3.6.
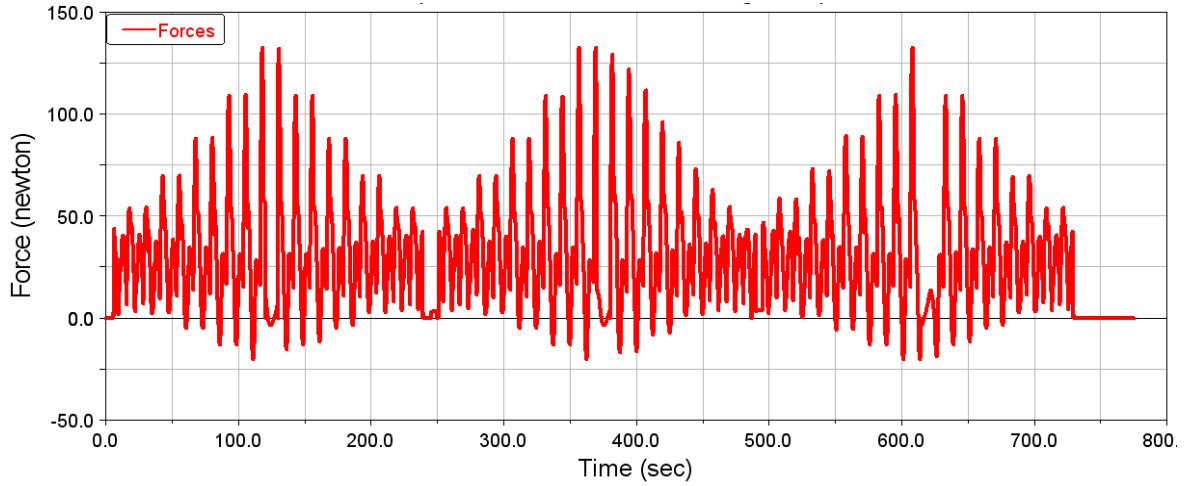
Figure 3.5 Maximum actuator force requirements for 50 [N] applied force on TCP along specified path in the workspace (concept 1).
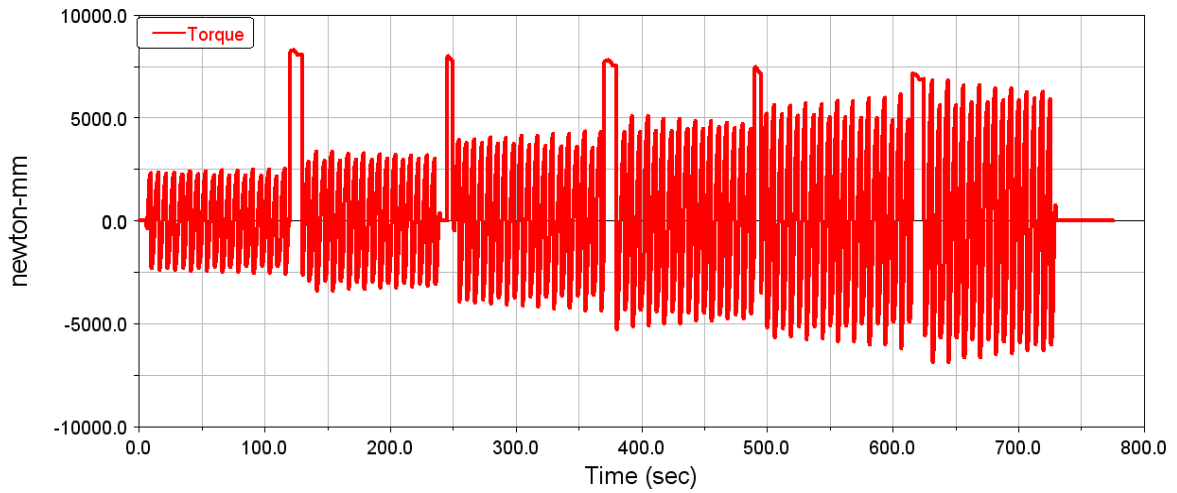

Figure 3.6 Maximum actuator torque requirements for 50 [N] applied force on TCP along specified path in the workspace (concept 2).

The force/torque requirements in figures 3.5–3.6 correspond to the actuator having maximum force/torque requirements for the applied load. The peak force/torque requirements for both concepts occur when the TCP has motion in 3-DOF (combined motion in xyz directions) at the outer circle of the specified trajectory.

3.1.2 Performance indices and optimization

The outcome of the above preliminary analyses is used as a decision basis to select the mechanism that we will consider further for design optimization. Based on the force/torque analysis and the property of low inertia due to the fixed motors, concept 1 was selected. For the following optimization, kinematic and dynamic models of this concept were derived (Paper B and D) and implemented in Matlab® [44]. The stiffness model for the device was developed and verified using finite elements methods FEM [65].

In order to verify the kinematic and dynamic mathematical models of the selected concept, a MBS model of the concept is developed and simulated using the MBS software Adams View® [43]. The same input parameters (preliminary dimension, masses and inertia) and

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trajectories were used for simulation of both models (mathematical model in Matlab® and the MBS model in Adams View®). A trigonometric trajectory is applied in Cartesian space for each degree of freedom of the platform, using the following equations

$$\begin{bmatrix} x = -a\cos(\beta + \omega) \\ y = a\sin(\beta + \omega) \\ z = (\beta + \varpi) * b / 2 \\ \theta_z = (2 * b / 3 * (\beta + \varpi)) pi / 180 \\ \theta_y = (b / 4 * (\beta + \varpi)) pi / 180 \\ \theta_x = -(b / 4 * (\beta + \varpi)) pi / 180 \end{bmatrix}$$

(3.1)

Where *a, b, ω and ϖ* are scalar constants and the first two terms have units of length and the last two terms are dimensionless. While β is a trajectory parameter that varies with time (t) according to a (5th order) quintic polynomial, which gives a smooth motion without any jerks. The trajectory parameter β is calculated as

$$\beta = \sum_{k=0}^{5} a^k t^k, \quad \beta_0 = 0, \quad \beta_f = 10, \quad \omega = 0, \varpi = 0, \ a = 6 \text{ and } b = 3.$$

(3.2)

It is assumed that the device motion starts at time *t = 0* and ends at time *t = t_f*. Using these initial and final motion conditions and constants, the coefficients of the above quintic polynomial can be determined. For simplicity, it is assumed that the motion of TCP starts with zero initial velocity and acceleration. Also, the motion of platform ends with zero final velocity and acceleration. The position and orientation trajectories for 6-DOF platform motion are shown in Figure 3.7.
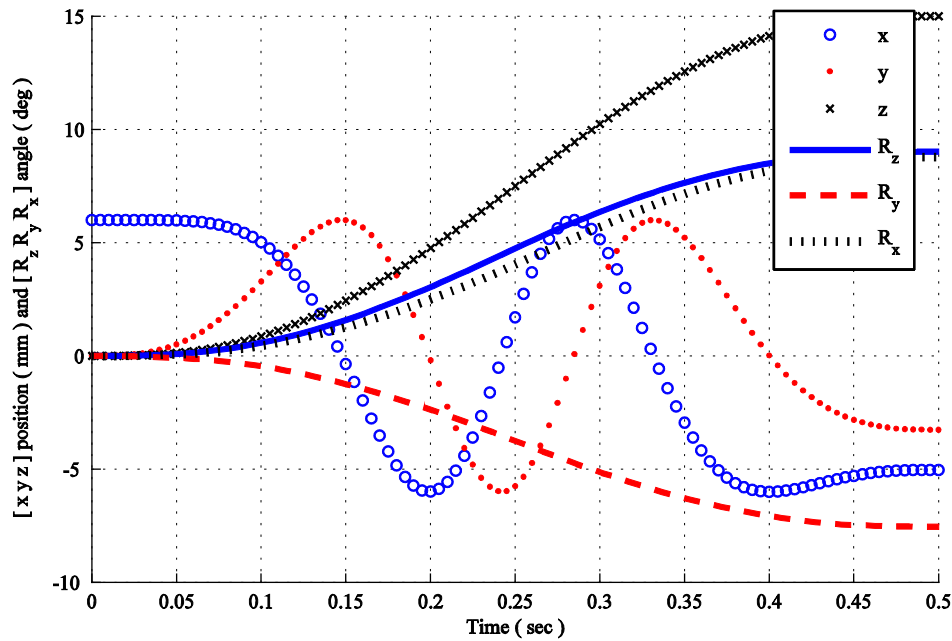

Figure 3.7 Position and orientation trajectory of the TCP, used both in Matlab® and Adams View®.
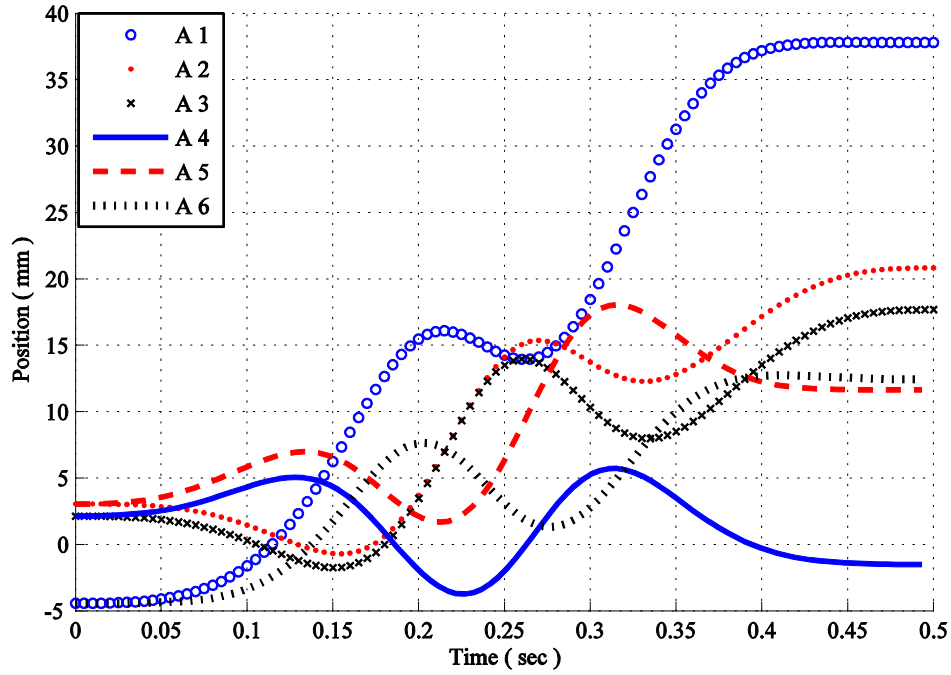
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Figure 3.8 Actuator trajectories resulting from Matlab® simulation corresponding to the TCP trajectories in Figure 3.7.
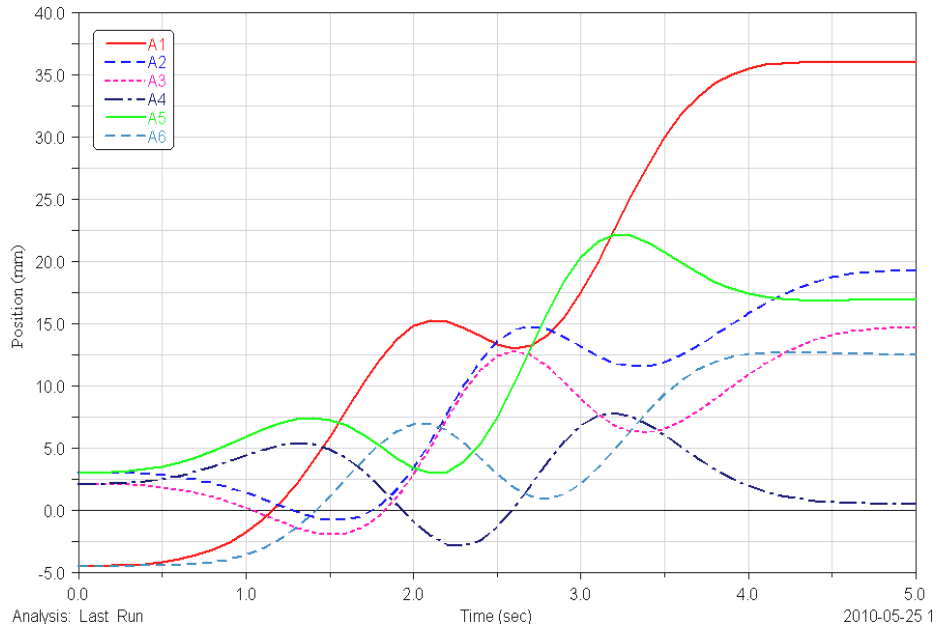

Figure 3.9 Actuator trajectories resulting from Adams simulation corresponding to the TCP trajectories in Figure 3.7.

Actuator trajectories resulting from simulation of the mathematical model in Matlab® are presented in Figure 3.8, and the corresponding trajectories from simulation of the Adams model are shown in Figure 3.9.

Similarly, the trajectories of the force requirements on each actuator, corresponding to the defined 6-DOF motion of the platform, are shown in Figure 3.10 (Matlab®) and Figure 3.11 (Adams). The starting forces are approximately 1.8 N, and this initial force is due to the gravitational force. The difference in forces between the legs is a result of the initial device configuration (the x-coordinate of the platform is deviated 6 mm from nominal position).
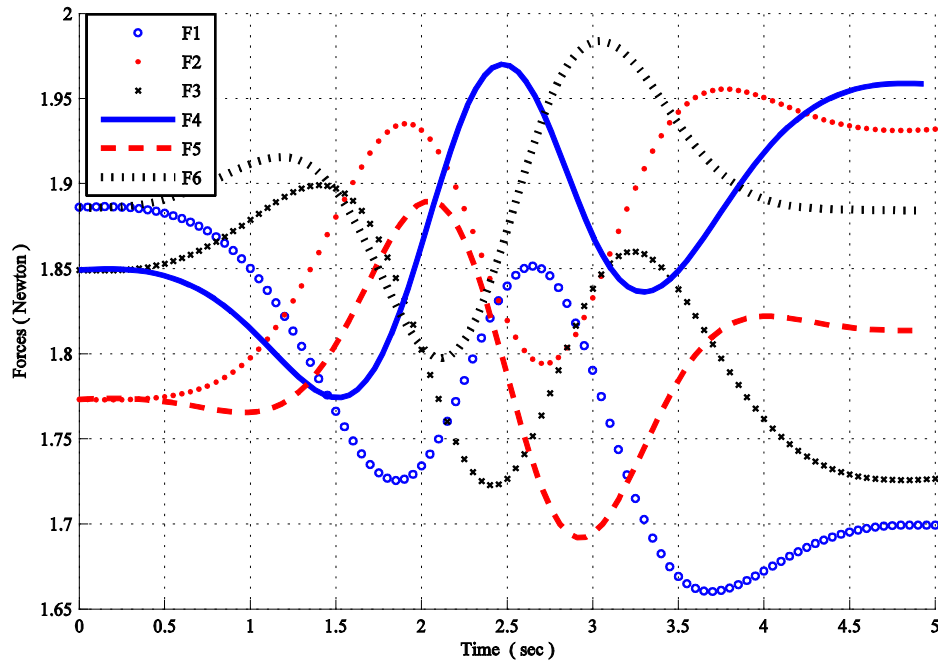
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Figure 3.10 Force requirements on actuators calculated using Matlab® to achieve motion corresponding to TCP trajectories in Figure 3.7.
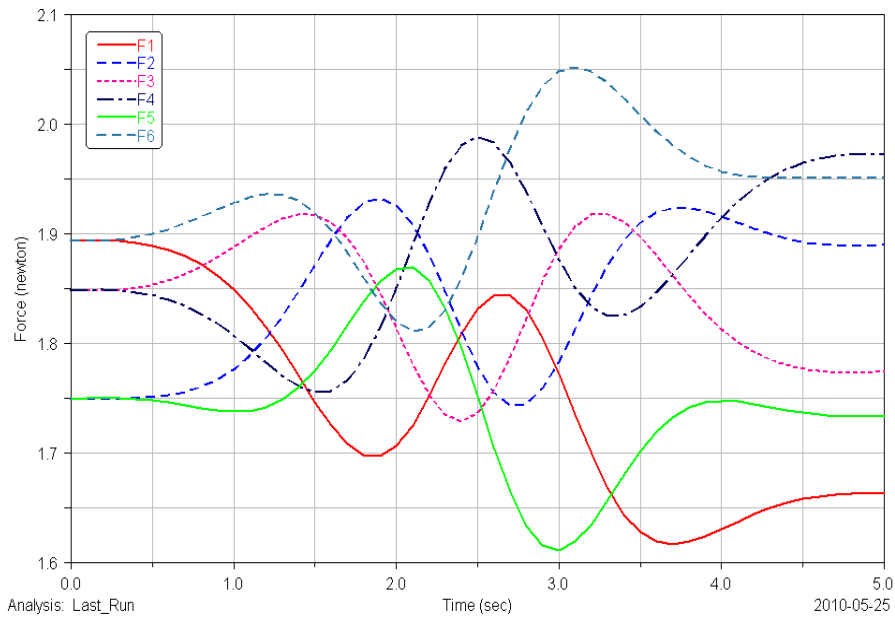

Figure 3.11 Force requirements on actuators calculated using Adams to achieve motion corresponding to the TCP trajectories in Figure 3.7.

The above results show that the developed kinematic and dynamic models are correct. The resultant force trajectories are almost the same from both models for the given motion. Additional simulations were performed on different trajectories with different velocities and acceleration in order to further verify the mathematical model and its results.

The kinematic, dynamic and stiffness models are used to define the performance indices used for optimization. We consider performance indices for properties such as device workspace-to-footprint ratio (workspace volume), kinematic isotropy, static actuator force requirements, stiffness and inertia. Kinematic isotropy and actuator force requirement indices are defined based on a Jacobian matrix, which relates the actuator velocities in joint space to the TCP velocities in task space. For the selected concept, the Jacobian is a 6 x 6 matrix, which is

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dimensionally inconsistent due to that the linear actuators provide both translation and orientation at the TCP. Performance indices that are defined based on a Jacobian matrix having non-uniform physical units are of little practical use [66]. Thus, Jacobian normalization techniques should be used prior to defining the performance indices.

Different methods have been proposed in the literature for defining a scaling factor used to normalize the Jacobian. We conclude (Paper C) that it is better to have the scaling factor as a design variable subject to the multi objective optimization. However, a new scaling factor is also proposed and defined as the ratio of a maximum actuator motion in joint space to the maximum required rotational motion in the task space as

$$SF = \frac{l_{ia}}{R_{max}}. \tag{3.3}$$

Where actuator motion range (l_{ia}) may be defined as a design parameter and where the rotational motion (R_{max}) is defined as the sum of the required maximum TCP rotations (roll, pitch, yaw). The scaled form of the Jacobian is achieved by multiplying the rotational entries of the original Jacobian with *SF*. A scaling factor according to this definition proved to give good device performance in this particular case study. However, more test cases are needed to draw more general conclusions.

The normalized Jacobian matrix is used to define the kinematic performance indices. The performance indices, optimization problem and the results from optimization are presented in appended Paper B.

The main requirements and design constraints on the particular haptic device studied in this thesis, and which must be adhered to during the optimization process are:

- The whole device (footprint) should fit within the space of 250 x 250 x 300 mm.

- Required workspace:

    o Translational: 50 x 50 x 50 mm

    o Rotational: 40 degrees about all three axes.

- Singularity-free workspace.

- Constraints on joints motions.

The footprint and minimum workspace requirements determine the bounds for the design variables. The boundaries of the workspace are calculated using inverse kinematics. In a haptic device the user is controlling the TCP motion, hence the avoidance of singular points cannot be guaranteed. In the current implementation of the controller the Jacobian determinant is used to continuously check closeness to singularities and if such a region is entered the Jacobian of the previous sampling instant is instead used for the forward kinematics calculations.

In our case, all the actuator transmissions/linkages are identical, and thus have the same stiffness. Thus, the stiffness matrix K reduces to a diagonal matrix $K = kJ^TJ$ in task space (TCP). Thus, the condition number or singular value of the matrix J^TJ should be optimized [67], this corresponds to minimizing the maximum singular value of the Jacobian matrix, and this is the same criterion as for the force isotropy index. In addition, striving to minimize the maximum singular value of the Jacobian works in the same direction as optimizing on the index applied for optimizing kinematic isotropy (See paper B for details). Thus, we effectively reduce this MOO problem to three main indices (workspace, isotropy and inertia).

The MOO approaches presented in Chapter 2 were used to find the optimal structural parameters. The optimal design parameter values and the corresponding normalized performance indices are given in Table 3.1. The optimization results are presented in detail in appended papers B and C.

Table 3.1 Optimized design parameters and performance indices.

GA Parameters	WSA	NSGA-II	MOGA
l_a [mm]	130.41	128.52	132.0159
C [mm]	129.45	132.15	135.4555
R_{b} [mm]	108.62	110.17	108.56
R_{p} [mm]	52.99	48.11	47.19
β [deg]	16.15	16.91	13.16
α [deg]	13.94	12.85	12.5
Volume index, VI	1.032	1.040	1.085
Global isotropy index	0.998	0.998	1.093
Global inertial index	1.10	1.10	1.092

3.1.3 Control design

In parallel to mechanical design, a control strategy for a stable and transparent haptic system was also investigated. The control strategy shown in Figure 3.12 is developed for the selected 6-DOF concept. This control strategy is of impedance type and is based on computed torques, similar to the method used in [57]. The controller is based on sensing of motor currents and rotor angles. The current measurement is used to estimate actuator force and thus indirectly torques and forces produced by the haptic device (using a constant K_t (capturing the static gain of motor and transmission) and the Jacobian matrix J). The force/torque error in task space is formed by subtracting this estimated task space force/torque from the force/torque references produced by the haptic VR system. This error then serves as input to a PI/H-infinity force/torque controller.
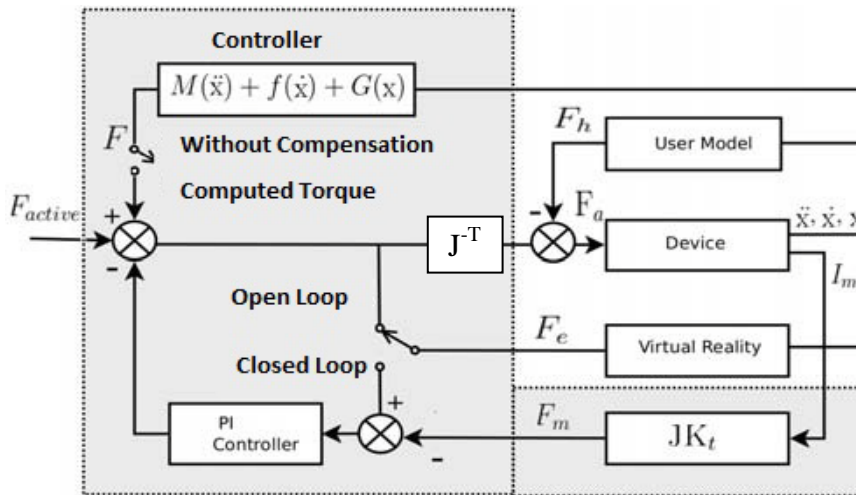

Figure 3.12 Control strategy for haptic interaction.

The rotor angle measurements are used both as input to the haptic algorithms (for collision detection and contact force calculations) and to the dynamic feed forward compensator. The influence F of the device dynamics itself is added to the control signal as a feed-forward term. The aim of this feed-forward term is to increase the transparency of the device, i.e. the user should not feel the inertia and friction of the device itself, only the inertia of the tool and its

interaction with the virtual environment. For this purpose, the dynamic model presented in Paper D is used to calculate the required feed forward forces *F*. The simplified dynamics equation used for control design is

$$F = M(X)\ddot{X} + f_f(\dot{X}) + G(X)$$

(3.4)

Where $f_f(\dot{X})$ represents velocity-dependent compensation terms (friction in motor and joints, and back-Emf in the motor), *M* is the mass matrix, and *G* contains gravity terms. For simulation purposes a user hand model is also included and briefly described paper D.

In the context of control design, we also focused on the optimal selection of gear ratio and simplification of the dynamic model as discussed below.

- **Selection of gear ratio (transmission system) and motor**

  The gearing from motor rotation to actuator translation is realized through a cable/pulley transmission. In this section, we discuss the selection of motor and optimal gear ratio (pulley radius) for the transmission. For the calculated actuator force requirements (see section 3.1.1), one can choose between many combinations of motor and gear ratio. However, inertia of both components plays an important role in this selection process. At this stage, we selected two different motors with two choices of gear ratio (Table 3.2) and performed dynamic simulation, using trajectories shown in figure 3.7. The purpose of this simulation was to select a motor and pulley radius which would give low effective inertia but which would also fulfill the force/torque requirements on each actuator. The dynamic effects are shown in figures 3.13–3.16.

Table 3.2 Motor characteristics for the selection of gear ratio.

	Motor 1*	Motor1	Motor 2**	Motor 2
Inertia (gcm^2)	10.5	10.5	65.5	65.5
Friction No. load (mN)	0.8805	0.8805	4	4
Stall torque (Nmm)	280	280	493	493
Continuous torque (Nmm)	28.4	28.4	105	105
Pulley radius (mm)	12	8	12	8
Inertia of Pulley (Kgm^2)	4.5e-6	3.0005e-6	4.5e-6	3.0005e-6
Mass of pulley and motor rotor (Kg)	0.0394	0.0633	0.0785	0.1492
Dynamic effects	Figure 3.13	Figure 3.14	Figure 3.15	Figure 3.16

*DC motor model-118755, RE 25 mm, Graphite Brushes, 20 watt.
**DC motor model-273759, RE 35 mm, Graphite Brushes, 90 watt.

Figure 3.13 Motor torques due to device dynamics for motor 1 with a 12 [mm] pulley radius.

Figure 3.14 Motor torques due to device dynamics for motor 1 with an 8

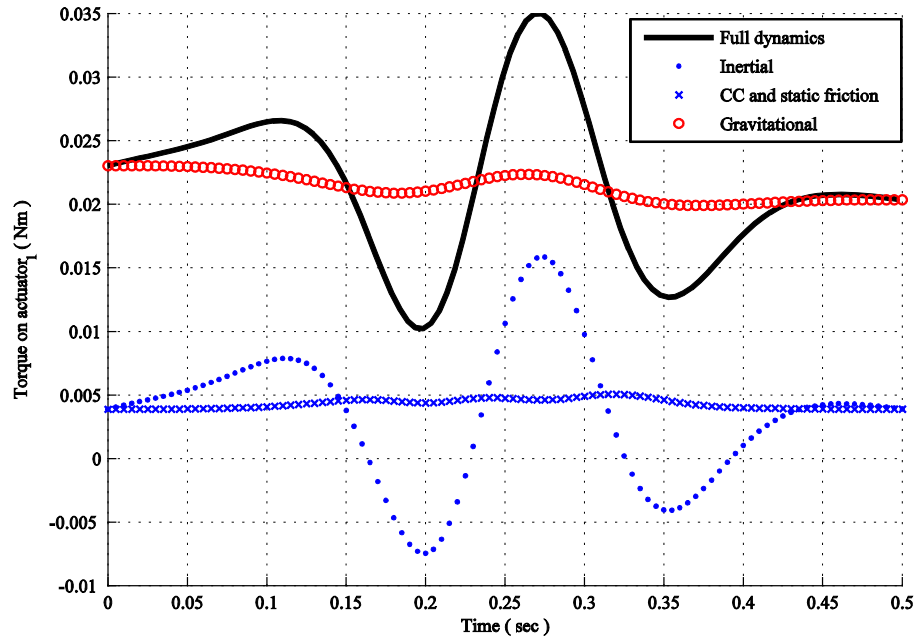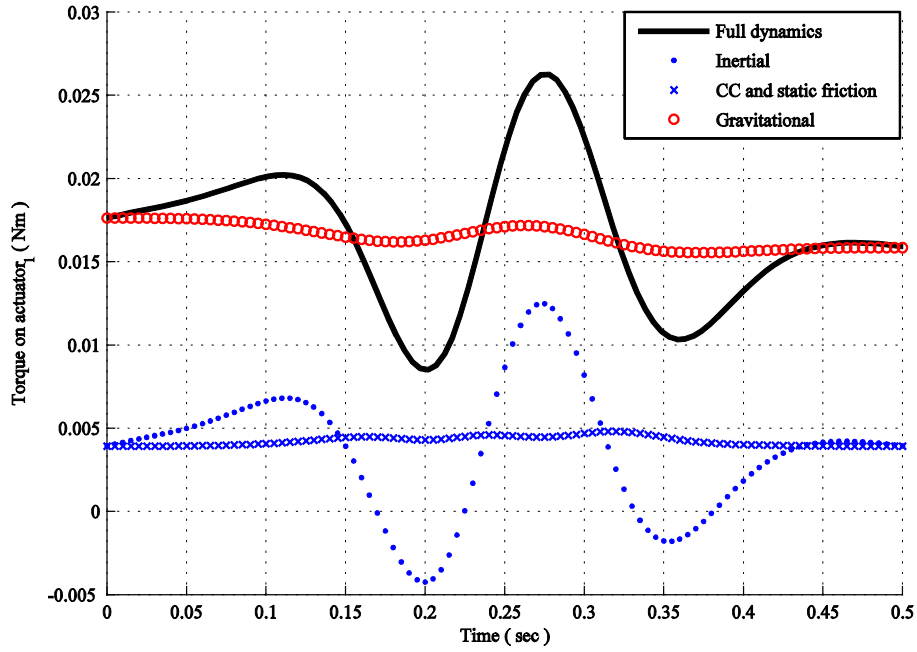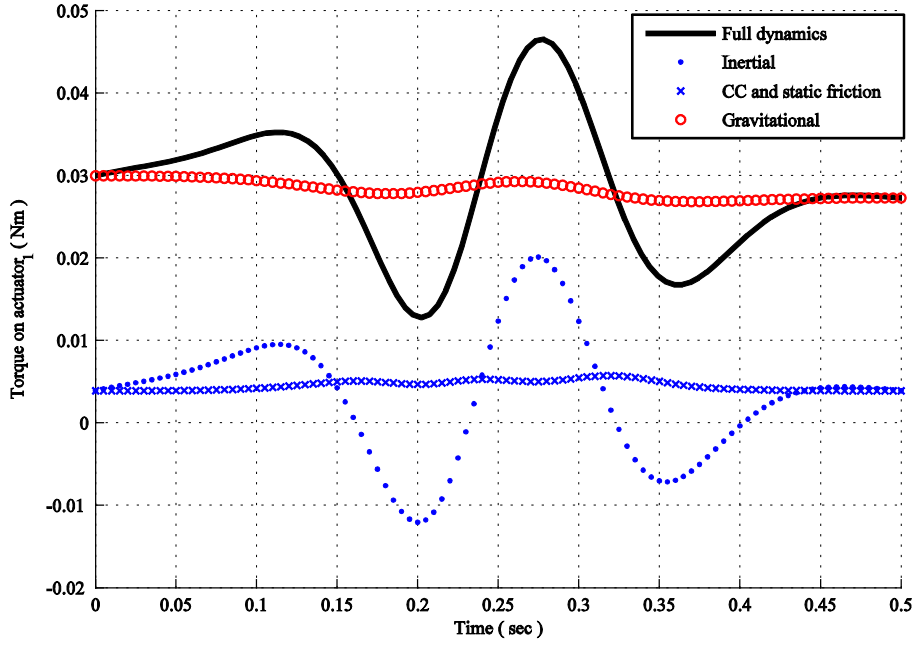[mm] pulley radius.

Figure 3.15 Motor torques due to device dynamics for motor 2 with a 12 [mm] pulley radius.
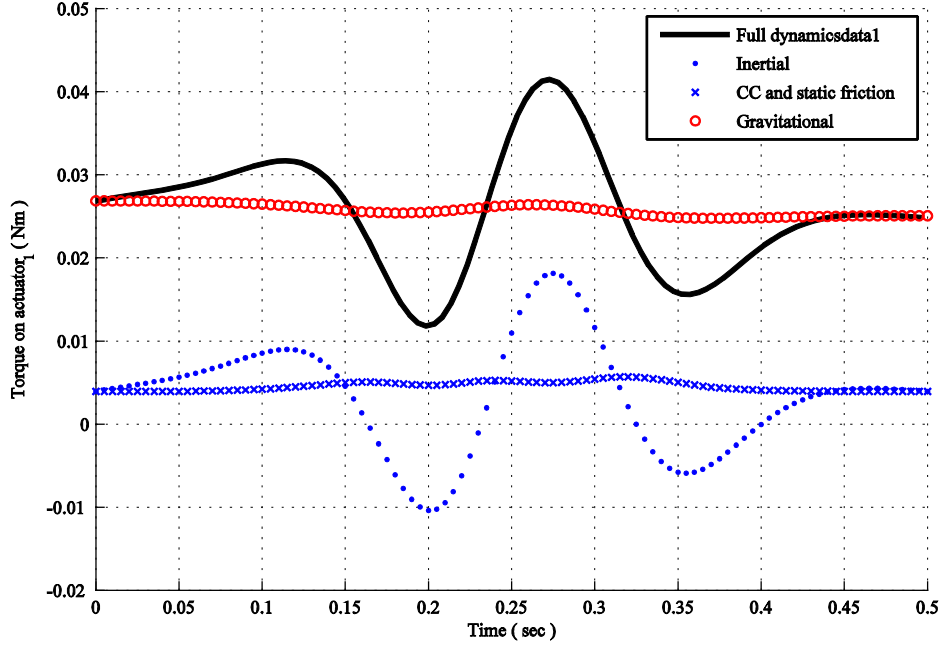

Figure 3.16 Motor torques due to device dynamics for motor 2 with an 8 [mm] pulley radius.

On the basis of the above simulations, we selected motor 1 with a pulley radius r = 8 mm. To confirm that the selected motor and gear ratio can provide the force/ torque requirements shown in figure 3.5, we performed the same analysis (section 3.1) again. With this selection, the stall torque requirement on each motor is 96 Nmm for a 50 N force on the TCP in nominal position. Continuous loading torque was calculated for the case of loading the TCP with two different force levels (20 and 10 N respectively), while simulating motion of the device along a circular path (see section 3.1.1). This resulted in continuous motor torque requirements of 72 and 46 Nmm respectively. Even the lower of these two values is beyond what the selected motor can provide. The smaller motor was still selected due to its lower inertia and based on the reasoning that in a real milling scenario such high forces as those used in the simulations will not be applied continuously.

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- **Simplification of the dynamic model for control design**

    As mentioned in section 3.1.3, we use dynamic compensation in control to achieve high transparency. However, dynamics-based control imposes hard requirements on the real-time implementation of the controller due to the complex and nonlinear dynamics of the selected parallel structure. We simplified the dynamic model by ignoring the effects of the proximal link, coriolis and centrifugal forces. This simplification is based on the simulations in figures 3.13–3.17. The simulations were repeated with different input velocities and accelerations, but with the same position trajectories to study the contributions from different components of the dynamic equation. It was concluded that the major components of the total torque (roughly 95%) on each motor is due to the gravitational and inertial effects. The effect of coriolis and centrifugal forces is very small (less than 5%), as shown in figures 3.13–3.16. Similarly, from the simulation, it is also clear that the force contribution from the proximal link is very small compared with the other components, see Figure 3.17.
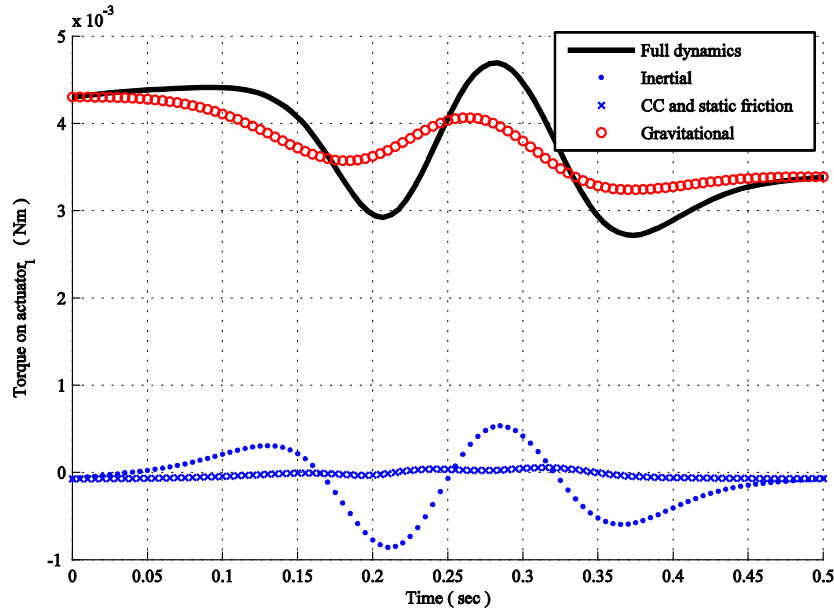

Figure 3.17 Force requirements on actuators due to proximal link only.

Thus, we added the mass of the proximal link to the actuator mass and tuned the combined mass to get approximately the same dynamic results as with full dynamics.

3.2 Detail design and prototype development

A 3D-CAD assembly of the mechanical design developed using Solid Edge is given in Figure 3.18. Dimensions of the components were selected on the basis of optimization results and sensitivity analysis of the design parameters (appended Paper B). A prototype of the designed 6-DOF haptic device was manufactured and assembled, see Figure 3.20. Six DC motors (model-118755, RE 25 mm, Graphite Brushes, 20 watt) [68] integrated with an encoder (model HEDS 5540, 500 Counts per turn, 3 Channels) were selected. Six 4-Q-DC servo amplifiers ADS 50/5 were selected as drivers for the DC motors. All motors are fixed at the base, so that they do not add inertia to the moving part of the mechanism. The proximal links are made of carbon fiber reinforced polymer, and thus the overall moving weight and inertia of the device is small. This characteristic improves the transparency of the overall haptic system and simplifies the control of the device. In this prototype, a cable transmission mechanism with a pulley was used to convert angular motor motion to linear actuator motion.
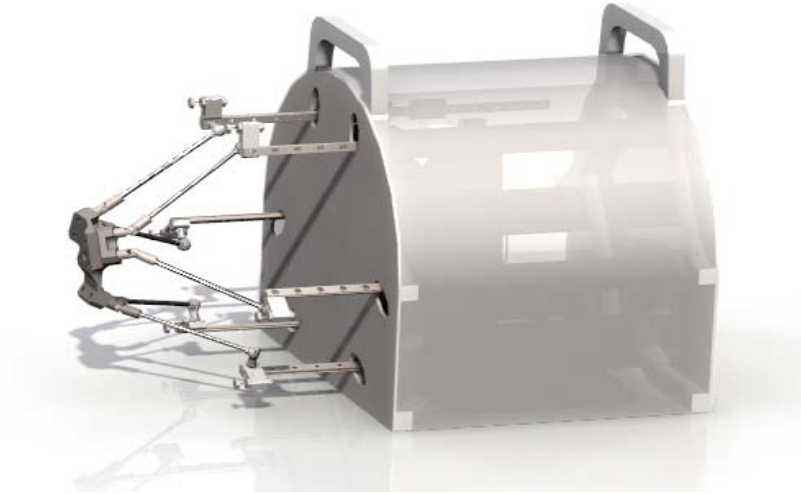
Figure 3.18 Assembly of the 6-DOF haptic device developed using Solid Edge.

3.3 Prototype characteristics and performance verification

The developed 6-DOF haptic device is connected to a personal computer using a dSpace 1103 board [59] and Simulink [44], shown in Figure 3.19.
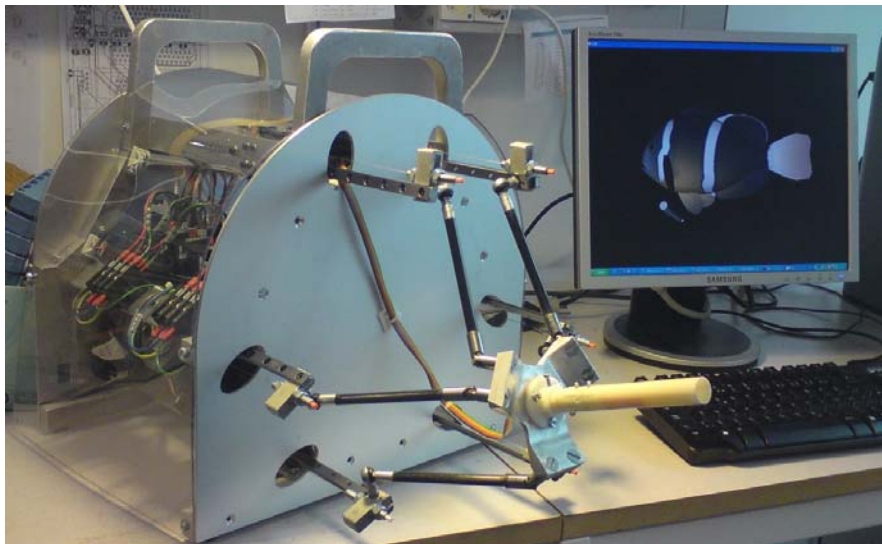
Figure 3.19 Prototype of the designed 6-DOF haptic device.

3.3.1 Position measurement and resolution

To calculate the pose (position and orientation) of the TCP, incremental encoders mounted on the shaft of the motors are used. These encoders are two-phase encoders with a resolution of 500 pulses per revolution. A DSpace 1103 board uses a two-phase reading of the encoder, and thus the resolution of $2*pi/2000 = 0.00314$ rad is available for pose calculation.

3.3.2 Singularity free workspace

A singularity-free workspace is important in the case of a haptic application, because the user is controlling the motion of the device and hence any existing singular point cannot be

avoided by control. In the specified workspace (50x50x50 mm) there are no singular points. Outside this space, singular points may be entered and as mentioned previously, the controller continuously uses the Jacobian determinant to check if such a region is entered, and if so the Jacobian of the previous sampling instant is instead used for the kinematics calculations.

The basic characteristics of the prototype are presented in Table 3.3.

Table 3.3 Basic characteristics of the prototype.

Characteristics of the haptic device	Values
Number of DOF	6
Footprint of the device (mm)	250 x 250 x 300
Workspace: Reachable translational (mm)	75 x 75 x 100
Rotational at nominal position (deg)	± 40
Resolutions: linear (mm)	± 0.01
angular (deg)	± 0.05
Control sampling time (ms)	1

3.3.3 Force/torque capabilities and stiffness measurements

Device performance in terms of structural stiffness and maximum and continuous forces/torques has been investigated, including the variation of forces and stiffness within the selected cubic workspace, i.e. the isotropic characteristics of the device. These experiments are presented in detail in appended Paper B.

As the device force/torque capability in the task space is directly related to the motor torque, we used motor current measurement and position control for this measurement. The TCP was positioned in a specific point by a PD position controller for each actuator in joint space. A load vector was applied to the TCP and gradually increased while measuring motor current. The load was increased until reaching the maximum continuous and maximum peak current limits of the motors. The continuous force and torque capabilities of the device are 20 N and 1 Nm in each direction respectively (Paper B). Using a slightly different setup the maximum force and torque capabilities were estimated to 58 N and 1.4 Nm respectively (Paper B).

The structural stiffness of the device was measured at each corner of the cubic workspace. The TCP was positioned at each point by mechanically locking all actuators. Then a known load was gradually applied in the specific direction (x, y, z), at the TCP, from 0 to 50 N. The deflection of the TCP from the reference position was measured using a CMM (Coordinate Measuring Machine). For each experiment, measurements showing the position of the TCP were taken in a sequence: no load position, position after loading and position after unloading. The deflections were calculated on the basis of the latter two measurements in order to exclude the backlash in the joints. The average maximum and minimum structural stiffness of the device was approximately 55 N/mm and 35 N/mm respectively (Paper B).

3.3.3 Transparency and stability measurements

The transparency of the device including the control strategy discussed in section 3.1.3 was also investigated. The current signal was used to measure the forces and torques that the device provides at TCP while the device was operated by a human user, as shown in Figure 3.20, with the corresponding controller implementation depicted in Figure 3.21. The response from the system follows the reference forces from a simple virtual environment (implemented in Matlab®) quite closely and in a quite stable manner. The current signal contains some noise which partly explains some of the high frequency fluctuations in the force.
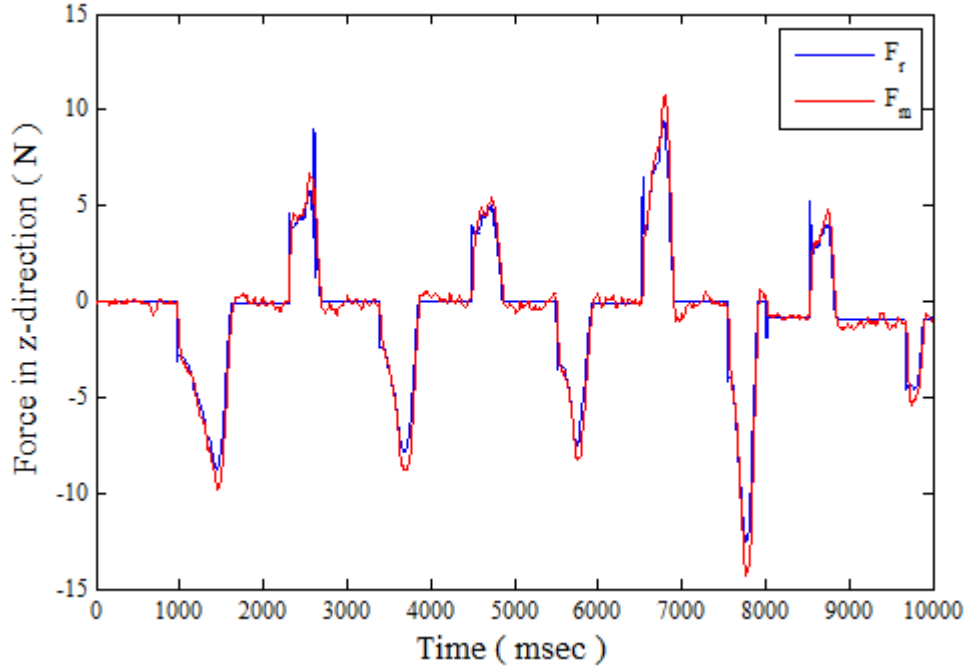
Figure 3.20 Comparison of the references force (F_r) from the virtual environment and the force (F_m) reflected by the device.
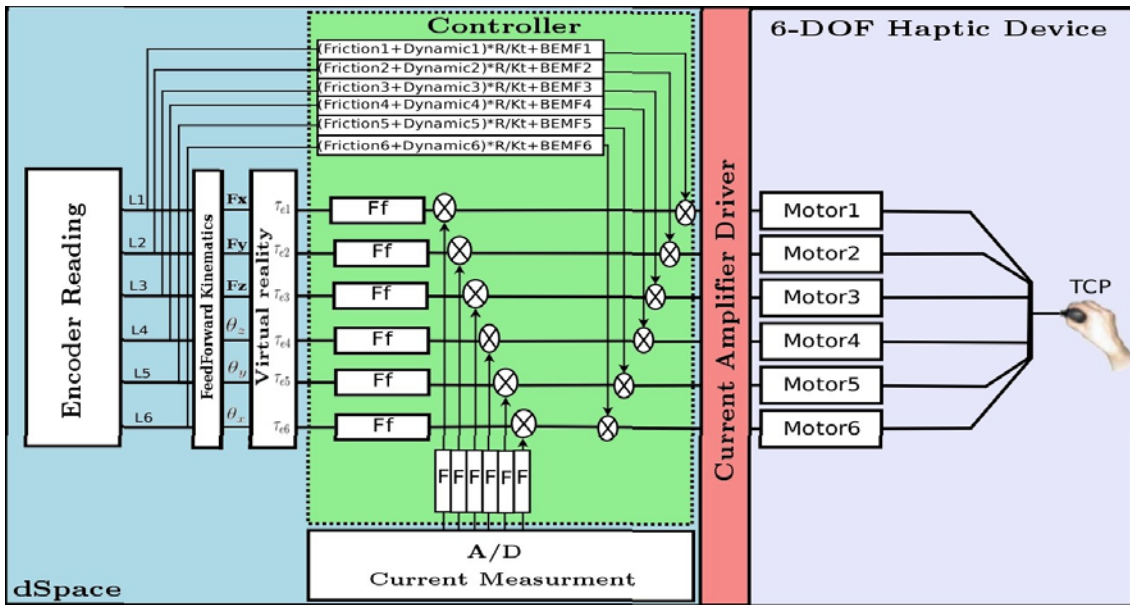
Figure 3.21 The impedance based control architecture of the haptic device implemented in Simulink.

3.4 Summary

A case study where the design methodology is applied to the design of a parallel haptic device is presented in this chapter. Different candidate structures are modeled and analyzed through a concept verification process. A final concept is selected for further design optimization and control design. MOO techniques are used to optimize the selected structure. A control strategy based on inverse dynamics compensation is designed and analyzed. On the basis of optimization results and sensitivity analysis of performance indices with respect to changes in design variables, a prototype has been built and verified.

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4. Integration of a haptic device to VR: (Haptic milling simulator)

This chapter focuses on the integration of the haptic device with a computer system containing a VR-system including haptic collision detection and force/torque rendering algorithms for 6-DOF haptic rendering. The integrated system constitutes a complete VR simulator with visual and haptic feedback. The chapter also briefly covers testing and performance evaluation of the device and of the integrated system – the haptic milling simulator.

4.1 Communication between the haptic device and H3DAPI

The VR system is implemented using H3DAPI which is an open-source library for communication, haptic collision detection and haptic force/torque rendering, developed using VC++ [69]. The developed prototype is connected to the VR computer system via a dSpace board 1103 [59], as shown in Figure 4.1. A serial communication link RS432 is used to establish the communication between H3DAPI and the device. The complete haptic control loop including device control, serial communication and haptic rendering must meet the real-time requirements of this kind of haptic interaction. It is commonly accepted that a sample rate of about 1 KHz is required to achieve good haptic performance [70].
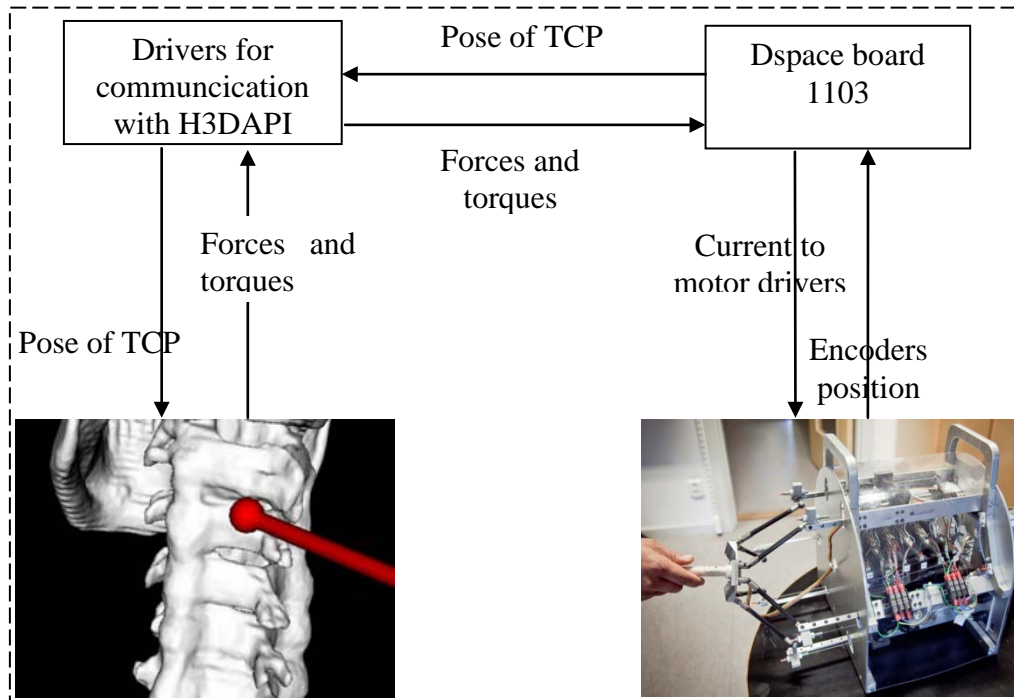
Figure 4.1 Illustration of the communication system in the haptic milling surgery simulator.

The integration according to Figure 4.1 is implemented through drivers for the haptic device written in VC++ using the H3DAPI interface. On the device side, the communication is implemented in Simulink [44] and executed on the dSpace board. Via this communication the TCP pose and the rendered force and torque references are effectively communicated between the VR environment and the device. On the serial communication link the data exchanged

correspond to task space, i.e. transformation from task space to joint space and vice versa is performed on the device side.

As depicted in Figure 4.2 the user controls a virtual tool – in this case a mill – which is visualized in the virtual environment. The user can manipulate the objects – with or without milling – and move the tool in free space within the virtual environment. A 6-DOF collision detection algorithm detects multiple-point contacts between the virtual tool and the virtual object. Based on these contacts the motion of the virtual tool is constrained and the collision contact forces are calculated and the feedback forces and torques are rendered [71] and communicated to the device. On the device side, these feedback forces and torques are then converted to joint space and in turn to motor current signals. Ideally, the device will finally produce feedback forces and torques to the users that resembles the contact forces and torques which were calculated in the virtual world.
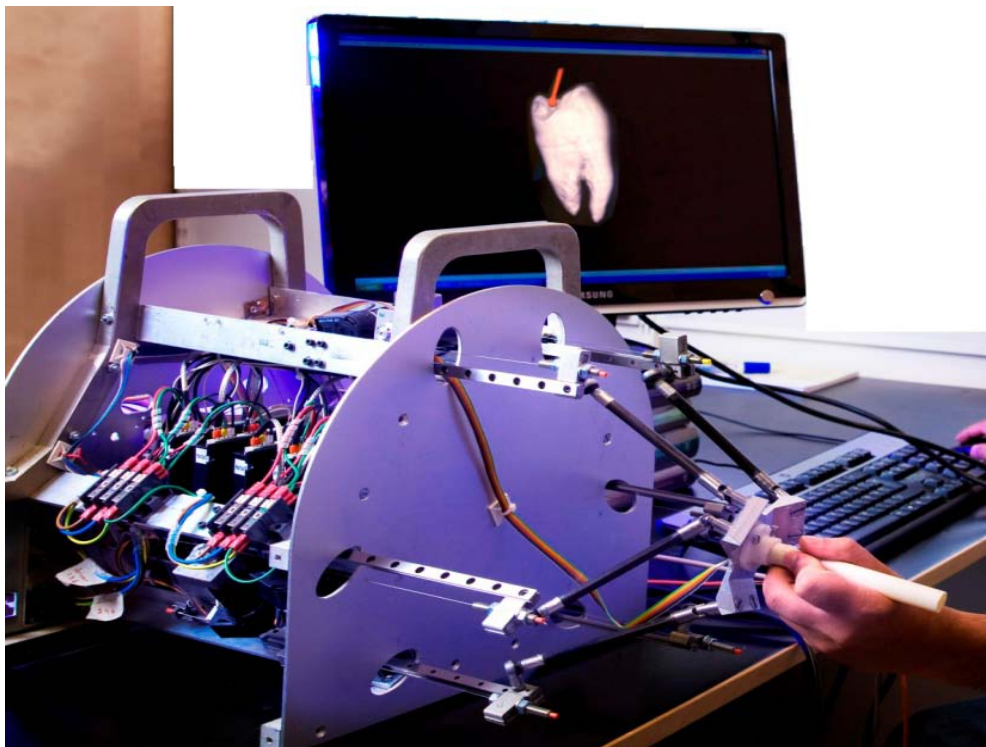

Figure 4.2 User interacting with a virtual environment using a 6-DOF prototype.

4.2 Performance Evaluation of the device using a haptic simulator

Typical evaluation methods that have been applied to haptic devices, haptic interactions, the virtual environment, and to the human operator are illustrated in Figure 4.3 [71].
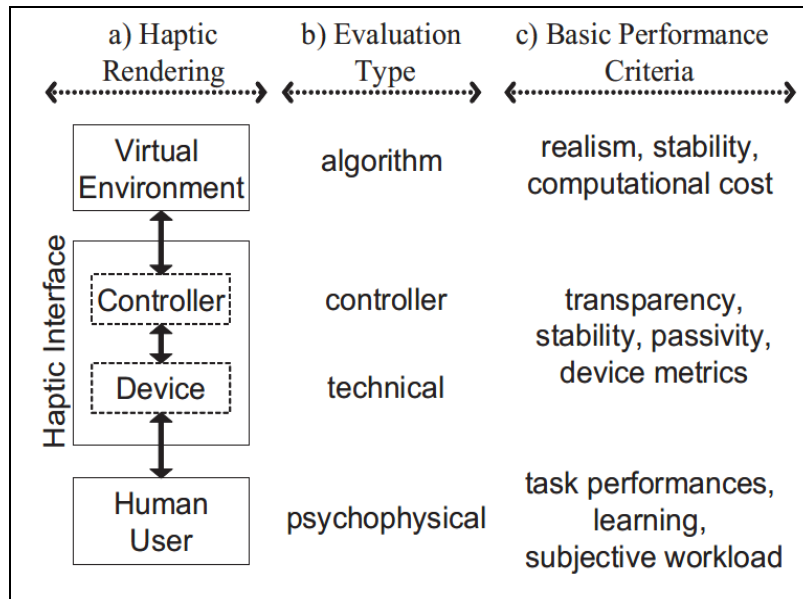
Figure 4.3 Various techniques of haptic system evaluation [71].

A brief evaluation of the haptic interface in terms of transparency and stability is given below. Good transparency means that the user should feel motion in free space as unconstrained, that is, ideally the dynamics of the device itself should not be felt. Motion constrained by interacting virtual objects should on the other hand render realistic feedback, and this is particularly challenging for the case of stiff interactions. An experiment is performed where the user makes a free space motion with a stiff tool in the virtual environment, followed by entering into contact with a stiff object, then leaving contact and again entering into contact in another direction (see figure 4.4).

Figure 4.4 Illustration of the VR visualization and the dSpace user interface.

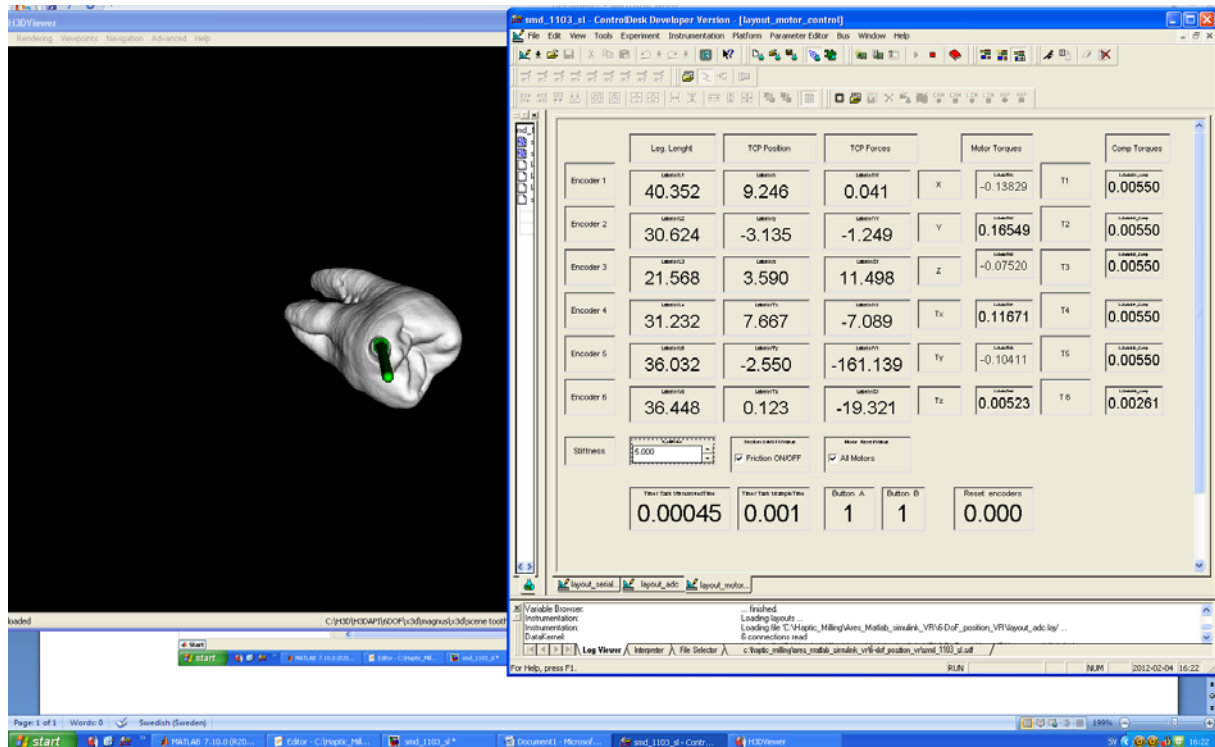The rendered response from the virtual environment and the force (estimated via motor currents) generated by the haptic device are logged as depicted in Figure 4.5. The figure shows that the device response follows the reference force quite closely. The high frequency fluctuations in the produced feedback force are partly due to a noisy current signal. The device response shows that it is stable while it is in contact with a virtual object. However, there are small vibrations when the probe comes out of virtual contact.
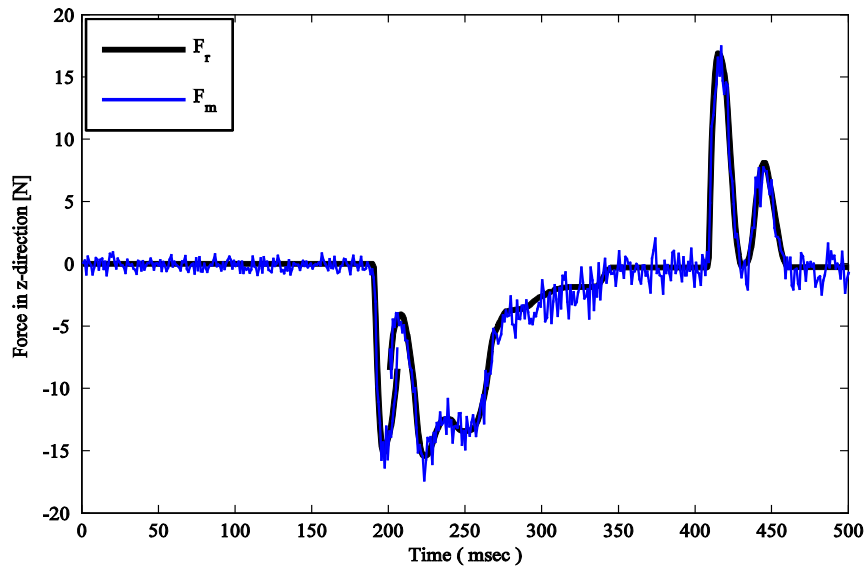

Figure 4.5 Response (F_m) from the haptic device while reflecting a rendered force (F_r) due object contacts in the virtual world.

To further evaluate the performance of the haptic milling surgery simulator, a face validity test was performed in collaboration with the Division of Orthopedics at the Karolinska University Hospital, in November 2011. The aim of the face validity test was to determine: can we simulate real interaction with hard tissue using the simulator, or, in other words, can the simulator mimic the real environment? The test procedure in the simulator prototype was focused on milling in bone tissue, not on a specific milling case operation scenario.

Twenty-one volunteer participants from the Division of Orthopedics in the Karolinska University Hospital were recruited to the study. Thirteen (61.9%) orthopedists and eight (38.1%) residents participated. Eleven (85%) of the orthopedists had more than 10 years' work experience, and 10 (77%) of the same group had performed more than 1,000 orthopedic operations each. Five (63%) of the residents had observed more than 200 orthopedic operations. One of the participants (4.7%) had tried a haptic milling surgery simulator before, but none of the others had. The mean ages of orthopedists and residents were 55.6 (range 39–68) and 31.7 (range 29–36) years respectively.

The results from the face validity test are based on the participants' response to a questionnaire, which included questions of the overall system performance. Good face validity would mean that both the haptic device and the other parts of the system work properly. All but two of the questions in the questionnaire were to be answered using a five-point Likert scale (1 = not at all realistic/poor, 2 = not very realistic/fair, 3 = somewhat realistic/good, 4 = realistic/very good, 5 = very realistic/excellent). In this kind of test, a threshold for acceptable realism is a scoring ≥ 3.0.

The test procedure consisted of three different cases, described below. In all cases, the same virtual environment was used. The scene was built up with a 3-D rendered tooth taken from a

high-resolution CT image, representing the medical object to be milled, and a 3-D rendered approximated mill, representing the tool maneuvered by the user.

In the first case of the test procedure, the user manipulated and explored the tooth without milling. The user was instructed to move the tool in free space and also to interact with the tooth's surface, utilizing the reachable workspace and using the full size of the tool's shape to interact with interesting parts of the tooth, see Figure 4.6. The idea with this task was to make the user familiar with the virtual environment in terms of navigation, depth perception and basic 6-DOF collision detection and haptic feedback. The task also gives the participants time to experience both free motion and constrained motion and the transition between those two modes. For those aspects, the performance of the haptic device is critical.
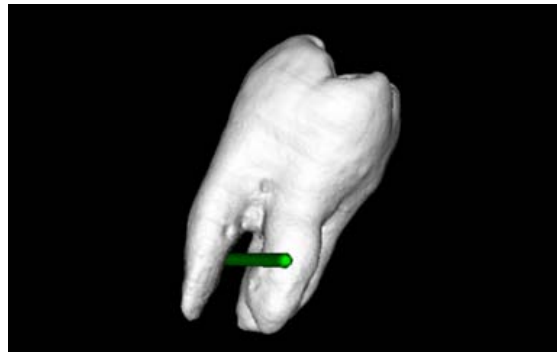

Figure 4.6 The first case, where the user explored the surface.

In the second case of the test procedure, the user was instructed to mill a straight channel, located at the center of one side of the tooth, to a depth of half the width of the tooth, see Figure 4.7 (left). Then, the user was asked to mill a straight channel from the dental crown down to where the first channel was made, such that the channels met each other, see Figure 4.7 (right). The aim of this case was to emphasize the aspects of stability and force/torque feedback capabilities while interacting and milling in a narrow channel or cavity, i.e. interaction which involves multiple-point contacts and hence requiring at least 5 DOF force and torque feedback.

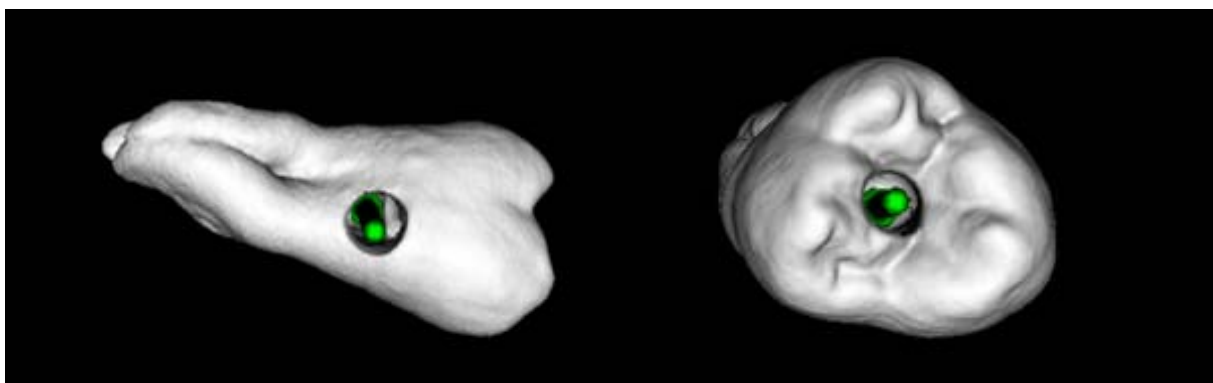Figure 4.7 The second case, where the user milled inside the object.

In the third case of the test procedure, the user was required to position the mill at the point where the dental crown meets the side of the tooth. Here, the user created a channel that was half the length of the mill's shaft. Once the channel was created, the operator was told to mill a cavity inside the tooth, see Figure 4.8.
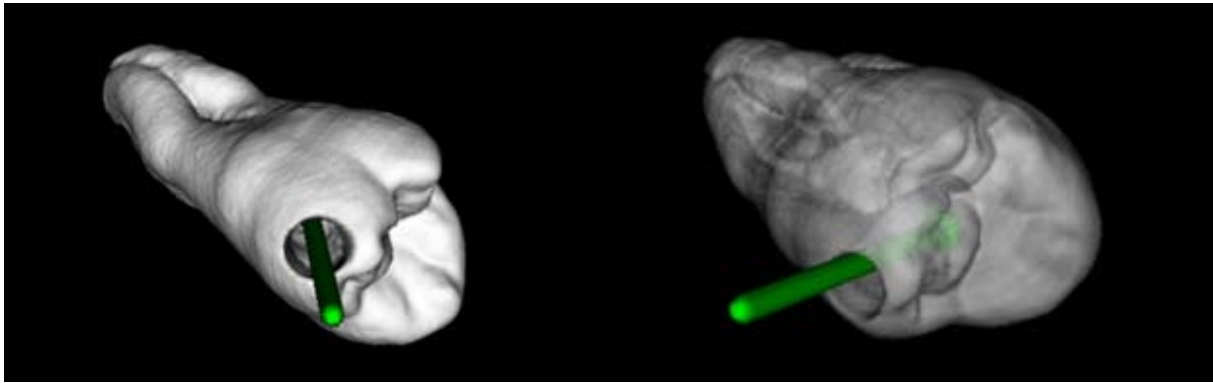
Figure 4.8 The third case, where the user made a cavity inside the object.

Figure 4.9 presents the results from the first test case of the face validity study (figures are taken from the appended Paper F). From the results, we can see that the participants' overall opinions when exploring the surface were good or very good. Looking at all of the participants, the average scores for all of the questions were > 3.0.

For two questions there was a difference between the two groups of participants. The experienced orthopedists thought that the surface felt real in a very good way and that the navigation in free space was very realistic, but the inexperienced residents were a bit more restrictive on these two questions (the difference was however not statistically significant).

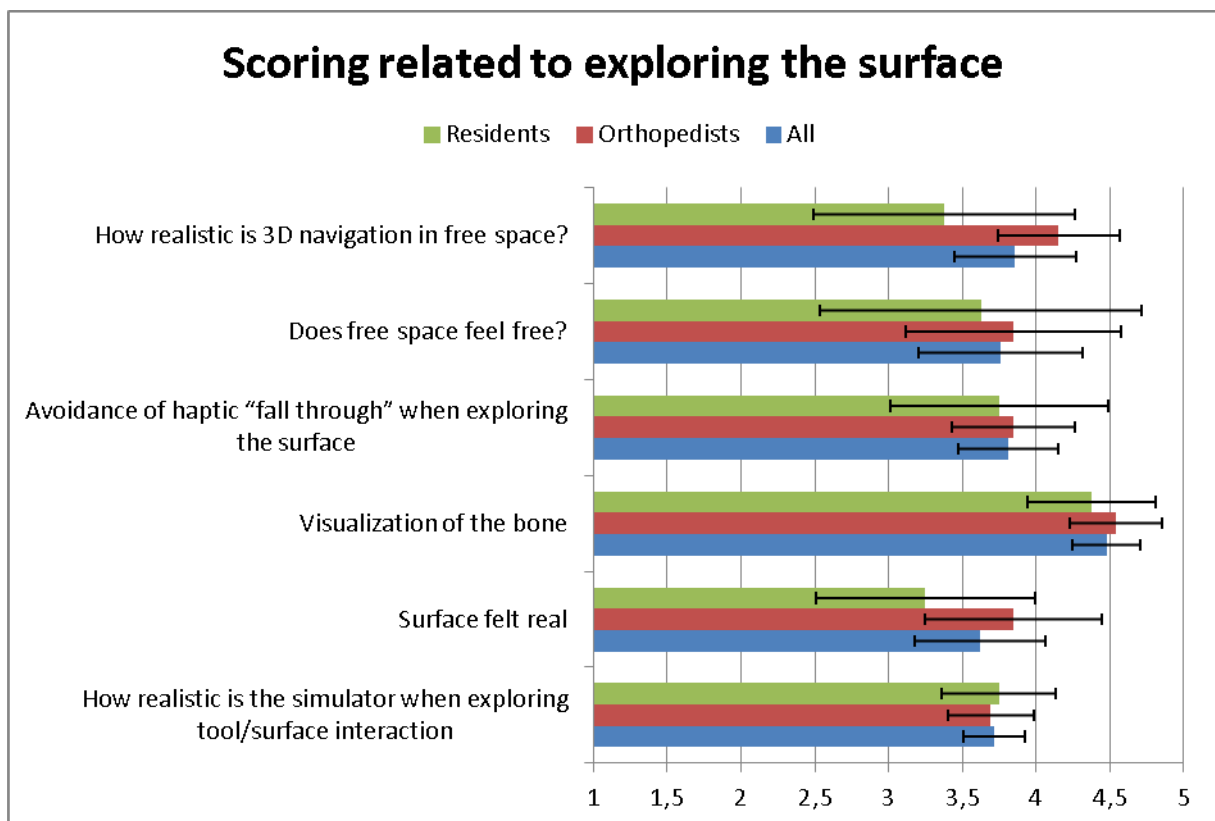Figure 4.9 Scoring related to the first case, where the user explored the workspace and the surface of the object.

Figure 4.10 presents the results from the second test case. From the results, we can see that the participants' overall opinions when milling were good or very good, as for the non-milling case. Looking at all of the participants, the average scores for all of the questions were > 3.0.

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Scoring related to the milling process

Figure 4.10 Scoring related to the second case, where the milling process was performed.

Figure 4.11 depicts scoring from the fourth part of the questionnaire: the participants' opinions about the simulator's usefulness as an educational tool. The first and second questions were answered on 1-3 scale, and most of the participants answered useful/very useful and "yes", they think the simulator would be useful as an educational tool.

From the face validity study it is concluded that the haptic simulator can provide sufficient realism for simulation of real bone milling surgery. This conclusion is backed up by the fact that the participants graded the overall realism of the bone milling simulator to 3.8 on a 1-5 scoring scale. This in turn means that the new haptic device enables high performance force- and torque feedback for stiff interactions, and that the developed 6-DOF haptic milling algorithm enables realistic force- and torque feedback when milling in a virtual environment.
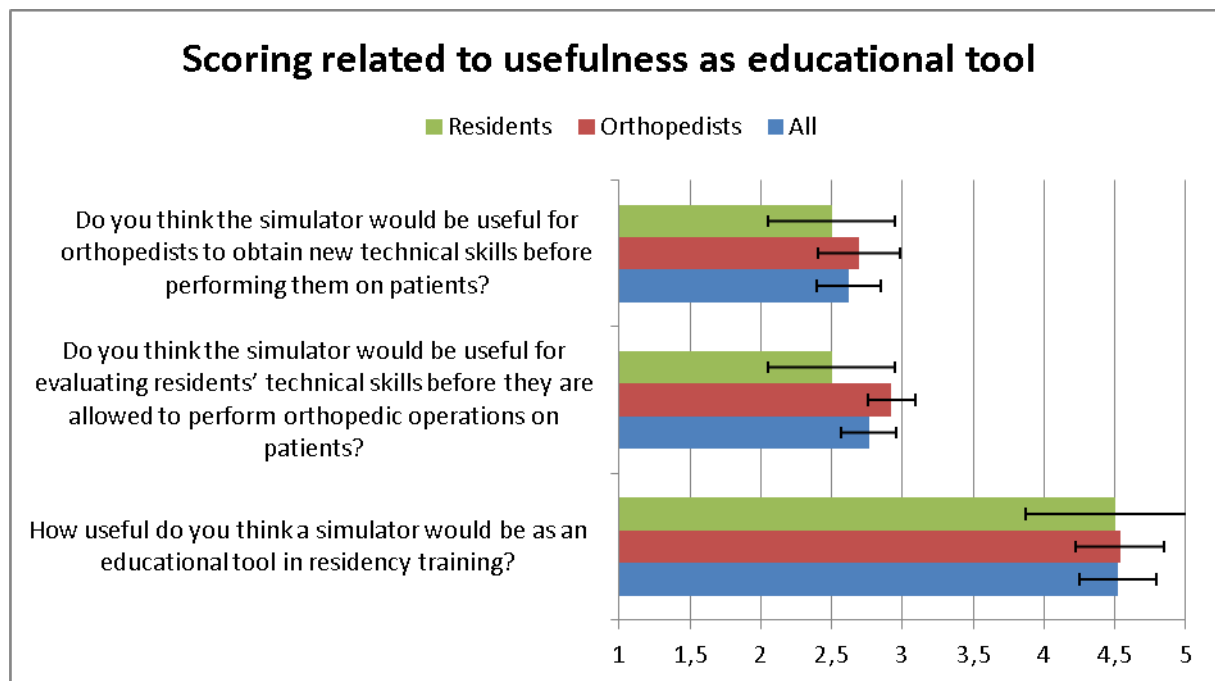
Figure 4.11 Results related to having the simulator as an educational tool.

4.3 Summary

This chapter gives an overview of the haptic milling surgery simulator and an evaluation of the complete system, including the developed 6-DOF haptic device. For the evaluation, an experimental setup was realized and a face validity test was performed at the Division of Orthopedics at the Karolinska University Hospital. Twenty-one volunteer participants performed the test and answered a questionnaire. Based on laboratory experiments and on the face validity test, it is concluded that the simulator can mimic a real milling process in hard tissue.

5. Summary of appended papers

5.1 Paper A: A Design Approach for a New 6-DOF Haptic Device Based on Parallel Kinematics

This paper deals with design requirements, conceptual modeling and preliminary analysis for haptic devices in the concept phase of the design methodology. The application area of the 6-DOF haptic device is introduced. Based on the application of the device, three concepts are modeled and analyzed to select a final structure for the 6-DOF haptic device to be designed. The performance aspects analyzed in this preliminary analysis are DOF, workspace size and force/torque requirements to fulfill the specified TCP force/torque performance. The MBS tool Adams View® [43] is used for the simulation and analysis.

Performance indices are defined to compare different structures and to facilitate selection of a candidate structure for further design.

5.2 Paper B: Design Optimization and Performance Evaluation of a 6-DOF Haptic Device

In this paper, we present a design optimization of the 6-DOF haptic device. The design optimization/dimension synthesis of the selected 6-DOF parallel structure is a MOO problem. Basic performance indices such as workspace-to-footprint ratio (workspace), static force/torque capacities, stiffness and inertial index are considered for optimization. These are defined based on the kinematic, dynamic and stiffness models of the selected concept. To perform the optimization, a new MOO function is introduced, which is then resolved using GAs. Three multi-objective approaches are used; weighted-sum, MOGA [31] and non-dominated sorting based genetic algorithm (NSGA-II) [50].

As a basis for prototype development based on optimization results we performed a sensitivity analysis of the performance indices against each design parameter, to guide the selection of a final set of design parameters.

Prototype performance is evaluated based on experiments. We measured the structural stiffness of the prototype using a CMM machine, and also the force and torque capabilities and transparency of the device at different points in the workspace. Both simulation and experimental results verify that the developed device fulfills the stated requirements for the particular application.

5.3 Paper C: Multi-objective Optimal Design of a 6-DOF Haptic Device Based on Jacobian Normalization

This paper investigates optimization of parallel kinematic devices, focusing on performance effects depending on the Jacobian normalization technique used and depending on the

kinematic performance index used. Jacobian normalization becomes an issue when the Jacobian contains elements having non-homogenous physical units, i.e. representing both translational and rotational motions. In multi objective optimization, using the full Jacobian for deriving device performance indices, normalization is necessary. Different methods have been proposed in the literature for defining a scaling factor used to normalize the Jacobian. Based on comparison of a few of those methods, we conclude that it is better to have the scaling factor as a design variable subject to the multi objective optimization. However, a new scaling factor is also proposed based on a relation between linear actuator motion range in joint space and rotational end effector motion in task space. The selection of this scaling factor is underpinned by simulation, analysis and comparison of optimization results using existing normalization techniques.

For optimization, performance indices for workspace, kinematic sensitivity, device isotropy and inertia are considered. To deal with the multi-objective optimization problem, genetic algorithms are employed, together with a normalized multi-objective optimization function. The performance of different device structures depending on normalization method used and depending on the global isotropy index used, are finally presented.

5.4 Paper D: Dynamic Based Control Strategy for Haptic Devices

This paper focuses on the investigation of different control strategies for haptic devices in order to achieve high transparency and stability while interacting with stiff tissues such as bone. The requirement on transparency means that motion in free space should feel free while motion in contact with a virtual or remote object should result in feedback forces and torques as close as possible to those that would appear due to real physical contacts. In free space motion, transparency is affected by the dynamics (moving inertia, friction) of the device. Dynamic effects of the device itself must, therefore, passively be kept low or actively be compensated for, in control of the system.

A control strategy is proposed, which is based on careful analysis of the dynamics of the haptic device, computed torque feed-forward control and motor current based force control. The inverse dynamic equation of motion for the device is derived using Lagrangian formalism and the dominating terms are identified for some representative motion trajectories. The user contact dynamic model is identified using experiments on the device with different users. A PI controller using motor current measurements is used to follow the reference force from the virtual environment. Experimental results on the developed prototype are presented in the last section of the paper to illustrate the effectiveness of the control strategy.

5.5 Paper E: A Design Methodology for Haptic Devices

A design methodology is proposed for a more systematic design of e.g. haptic devices. The design methodology captures how to design a complex mechatronic product while considering aspects from all involved subjects in parallel. It consists of the five main process steps; requirements specification, conceptual design, detail design, industrialization and production. The design methodology is based on parametric modeling with an iterative and integrated design approach that leads to easier design space exploration for optimal design and initial verification in the conceptual design phase. A generic verification model is used in each iteration to investigate the problem and provide a basis for the decisions. The focus is on the conceptual phase.

For design optimization, performance indices such as workspace volume, isotropy, stiffness, and inertia of the device are considered. A case study, where the methodology has been applied to develop a parallel haptic device, is presented in detail in this paper. The simulation and experimental results obtained from this test case are discussed in detail; the results show significant improvements in the performance of the designed device.

5.6 Paper F: Face Validity Tests of a Haptic Bone Milling Surgery Simulator Prototype

Today, the training of bone surgery is mostly performed on real patients and in some cases on cadavers, which – if there are alternatives – is ethically, qualitatively and economically questionable. Hence, we present a haptic milling surgery simulator prototype that is intended for further development towards a new training opportunity to improve the conditions of surgery training.

The complete system consists of the new 6-DOF haptic device connected to a recently developed haptic milling surgery simulator program, including 6-DOF haptic milling algorithms and software for 3-D graphic rendering of medical bone objects. In the simulator, the operator can interact with a virtual environment by manipulation using a virtual milling tool. Collision between the virtual object and the virtual tool generates force and torque feedback to the hand-held haptic device.

In this paper, we first focus on giving an overview of the complete haptic milling surgery simulator system. Second, we investigate the research question: "Can we mimic a real milling process of hard tissue in the simulator?" The investigation is performed through a face validity user study of the simulator prototype. The paper concludes with a positive answer to the research question by means of analyzing the results of the face validity study which was conducted in collaboration with the Karolinska University Hospital in Stockholm.

6. Discussion, conclusion and future work

The product related aim of this thesis was to develop a 6-DOF haptic device for use in a haptic milling surgery simulator. The targeted simulator is intended for use in bone surgery training which involves virtual interaction with stiff objects. Design of a haptic device of this type is a rather challenging problem, both in terms of finding the right concept for a particular application and in terms of a dimensional synthesis of the selected concept. Several, often conflicting design objectives must be handled concurrently in the design process. For this purpose modeling, simulation and optimization become central issues. Hence, the scientific aim of this thesis was to propose, apply and demonstrate a systematic model-based development methodology for designing haptic devices. A key part of this methodology is the multi-objective optimization method that has been used.

Key parts of the research work and of the proposed methodology as it has been applied to the specific 6-DOF haptic device are as follows.

- A related state-of-the-art review was performed to create a database of the 6-DOF haptic devices available commercially or in research literature. Information was gathered about the electro-mechanical design, the performance and other characteristics, as well as any optimization methods used.

- Model-based analysis and simulation were performed on different design concepts as a basis for selecting a candidate concept for further development. Here, a generic concept verification process was applied. Performance indices such as workspace volume, number of DOF and actuator force requirements were used to underpin decisions about the concept for further development (*Appended Paper A*).

- For dimensional synthesis through design optimization, performance indices such as workspace, global kinematic isotropy, global force requirements, global inertial and global stiffness indices were defined based on Jacobian, inertial and stiffness matrices respectively. To cope with the problem of non-uniform units of the Jacobian matrix, different normalization techniques based on Jacobian scaling have been investigated. Hence, it is concluded that it is beneficial to have also this scaling as a design variable subject to optimization.

- To solve the optimization problem, MOO tools with a new proposed optimization function were used to obtain an optimal solution (*Appended Paper B and Paper C*). Sensitivity analysis of the performance indices as a function of the design variables was performed, to gain further understanding for the final dimension synthesis.

- A control strategy was developed for desired performance, where the key points of consideration were transparency and stability of the device (*Appended Paper D*). In the control strategy, device dynamics is compensated through computed torque control in order to increase transparency.

- A prototype was developed based on the optimal dimension synthesis. Experiments have been performed to evaluate the performance of the device, and these have been presented in detail in appended *Paper B, Paper D and Paper F*. The evaluation includes integration of the device in a complete simulator system.

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From the research performed in this thesis, it is concluded that:

- The use of optimization algorithms suitable for multi-objective optimization is essential for efficient design and to achieve high performance of haptic devices for more advanced applications. Formulating relevant objective functions requires kinematic modeling and Jacobian normalization.

- Global performance indices which reflect the performance of a device over the whole workspace of interest should be used. This requires modeling and simulation tools such that the formulated global performance indices can be evaluated over the whole workspace.

- Different researchers have used different formulations of the performance indices and different means for handling Jacobian normalization. It is concluded that the optimization results are substantially affected depending on which approaches are taken.

- Analyzing the sensitivity of the performance indices with respect to changes in design variable around the optimally selected values gives additional insight which can be useful before deciding on the final design variable selection.

- The work clearly indicates that the genetic algorithm optimization techniques result in a device with improved performance than those that could be achieved using model based design and simulation in MBS software.

- In the case study, the combination of model based design, advanced simulation tools and optimization toolboxes were demonstrated to result in a final design that met the main application requirements that were initially formulated. It is also demonstrated that the variation in performance over the specified workspace is acceptable.

- Dynamic modeling of the device was necessary to enable computed torque control in order to increase transparency of the device. The influence of various dynamic effect where analyzed and compared. Some effects (e.g. coriolis) have very small influence and could be neglected to reduce execution time of the controller.

The developed haptic milling surgery simulator prototype has been validated in a face validity study at the Division of Orthopedics at the Karolinska University Hospital. The investigated research question was: "*Can we mimic a real milling process of hard tissue in the simulator?*" Test data were collected through a questionnaire logging the participants' opinions about the performance and qualities of the simulator. From the face validity study, we conclude that the haptic milling surgery simulator can provide sufficient realism for simulation of real bone milling surgery. The results from the face validity study verify that the new haptic device enables high-performance force and torque feedback for stiff interactions.

Suggestions for future work include:

- A detailed structural stiffness modeling, analysis and verification of the device would be useful. Through such a model the optimization with respect to stiffness might be more effective.

- Friction modeling and compensation is important for improving device transparency. In this thesis, friction is considered only in active joints, while friction modeling of passive joints and means for control compensation of such friction would lead to improvements.

- The quite successful face validation study leads us to the conclusion that there might be a commercial opportunity for the overall simulator. This leads to the need for more testing to gain more user feedback and to entering into a product development phase.

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Section – 2