Effective development of haptic devices using a model-based and simulation-driven design approach

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Abstract

Virtual reality (VR)-based surgical simulators using haptic devices can increase the effectiveness of surgical training for surgeons when performing surgical procedures in hard tissues such as bones or teeth milling. The realism of virtual surgery through a surgical simulator depends largely on the precision and reliability of the haptic device, which reflects the interaction with the virtual model. The quality of perceptiveness (sensation, force/torque) depends on the design of the haptic device, which presents a complex design space due to its multi-criteria and conflicting character of functional and performance requirements. These requirements include high stiffness, large workspace, high manipulability, small inertia, low friction, high transparency, and cost constraints.

This thesis proposes a design methodology to improve the realism of force/torque feedback from the VR-based surgical simulator while fulfilling end-user requirements.

The main contributions of this thesis are:

1. The development of a model-based and simulation-driven design methodology, where one starts from an abstract, top-level model that is extended via stepwise refinements and design space exploration into a detailed and integrated systems model that can be physically realized.
2. A methodology for creating an analytical and compact model of the quasi-static stiffness of a haptic device, which considers the stiffness of actuation systems, flexible links and passive joints.
3. A robust design optimization approach to find the optimal numerical values for a set of design parameters to maximize the kinematic, dynamic and kinetostatic performances of a 6-degrees of freedom (DOF) haptic device, while minimizing its sensitivity to variations in manufacturing tolerances and cost, and also satisfying the allowed variations in the performance indices.
4. A cost-effective approach for force/torque feedback control using force/torque estimated through a recursive least squares estimation.
5. A model-based control strategy to increase transparency and fidelity of force/torque feedback from the device by compensating for the natural dynamics of the device, friction in joints, gravity of platform, and elastic deformations.

Keywords
Haptic device, model-based design, design optimization

Language
English
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• Paper A
Ahmad, Andersson and Sellgren developed the methodology, and Ahmad verified through experimental test.

• Paper B
Ahmad developed the stiffness model, and developed a methodology for stiffness evaluation with Andersson and Sellgren. Khan helped in experimental verifications.

• Paper C
Ahmad developed the robust design optimization approach, Andersson and Sellgren provided feedback and corrections.

• Paper D
Ahmad evaluated the friction models, Andersson, Sellgren and Boegli provided feedback and corrections.

• Paper E
A. Ahmad, K. Andersson, and U. Sellgren, “Model-based control strategy for 6-DOF haptic devices,” to be submitted to IEEE Transaction on robotics.
Ahmad developed and verified the model-based control strategy, Andersson and Sellgren provided feedback and corrections.
List of additional publications


Chapter 1

Introduction

Haptics-based virtual reality (VR) simulators for teaching and evaluating surgical skills have gained considerable attention in recent years. The virtual reality (VR) based simulators provide a 3D scene of a virtual model and a haptic feedback at the tool handle of a haptic device. A haptic device acts as a communicating bridge to reflect forces and torques to a user from interactions with a virtual environment or teleoperation tasks so that human users can indirectly feel several physical sensations in real situations. The haptic device works on haptic feedback and a haptic collision detection algorithm. The haptic feedback refers to sense and manipulation through touch.

The haptic feedback is active, when the tool center point (TCP) of the end effector of the device is moved and mapped to a position/orientation in a virtual environment. The haptic collision detection algorithm generates force/torque through interaction with a virtual model. The force/torque is generated by the actuators on the haptic device in real-time, so that appropriate reaction forces are applied to the user, leading to haptic perception of virtual objects [1].

1.1 Background

This thesis is part of a research project on “Haptic milling surgery simulator” for bone milling operations. In the earlier part of the research a master-slave for tele-robotic surgery was developed by Flemmer [2], followed by a development of a 6-degrees of freedom (DOF) haptics-based virtual reality (VR) simulator based on Stewart-platform by Khan [3] and Eriksson [4]. The work presented here is an extension of this work, in terms of improving the realism of force/torque feedback of an existing haptic device (Ares haptic device [5]) and development of a new 6-DOF haptic simulator based on TAU configuration.

An evaluation of Ares haptic device using face validity tests were performed by [3] and [4], where it was observed that during manipulation in free space, the motion did not feel free. Many of the participants in the face validity test
had that opinion about the perception of force/torque feedback while moving in free space and during interacting with the virtual environment. The quality of perception of haptic devices is mostly measured by transparency, which quantifies the correspondence between the desired $F_g$ and actually observed values of force/torque feedback $F_T$ as shown in Figure 1.1.

![Figure 1.1: A closed loop between user and virtual rendering environment.](image)

For transparent force/torque feedback, the motion in free space should feel free; while the interaction with a virtual object should result in a feedback of force/torque as close as possible to real physical contact. The quality of perception of free space and force/torque feedback was affected by the friction in the active and passive joints, and inertia of the device.

Apart from the developed simulators in the aforementioned research project, several prototypes of haptic devices as surgical simulators have been developed commercially and in academia for soft and hard tissues over the past couple of decades, but very few have offered a convincing solution for hard tissues. One reason is because of the use of parallel kinematic structures to obtain the wanted high stiffness for interacting with hard tissues. This results in a complex design solution and a need for multi-domain considerations to obtain a realistic force/torque feedback from the device. This thesis proposes a model-based and simulation-driven design approach to deal with this complexity.

Designing a haptic device is a non-trivial task due to its sophisticated performance requirements from users, and the integration of software and hardware. The area of haptic research is an interdisciplinary field and is generally divided into three main fields: computer haptics, machine haptics and human haptics [1].

- Human haptics: the study of how people sense and manipulate the world through touch.
• Machine haptics: the design, construction, and use of machines to replace or augment human touch. Haptic interfaces are devices composed of mechanical components in physical contact with the human body for the purpose of exchanging information with the human nervous system.

• Computer haptics: algorithms and software associated with generating and rendering the touch and feel of virtual objects analogous to computer graphics.

1.2 Problem description

The training of a surgeon is a complex and multi-dimensional process [6] particularly in the case of hard tissues like bone and dental procedures. Surgical students are trained to develop skills by performing surgery using a hand-held mill on real patients, cadavers and plastic models, which are questionable from and ethical, training and cost-effectiveness point of view [4], [7]. The plastic models are expensive to produce and cannot provide a sufficient level of detail and material properties. Also, the repetitive usage of these artificial models is not possible, which is ultimately not cost-effective. The high risk of training on real patients and the high cost have motivated research and development of haptic devices and virtual reality simulators for training surgeons. In contrast to the classical training techniques, training with medical simulators has proved to increase patient safety and reduce risk associated with human errors in hospitals by allowing medical students to develop skills more efficiently and in a shorter time period [7].

Simulators will create new training opportunities for surgical procedures, which are impossible to train with traditional methods. Moving training for surgical procedures from the operating room to a simulator will offer considerable economic advantages. Besides, with the help of virtual simulation environments, we can better assess on the trainee’s performance. It is possible to define performance metrics for a specific surgery in simulations. For instance, during a bone removal operation, simulations are able to figure out the regions that are removed when they are not visible by the user. Furthermore, it is promising to define maximum velocities and forces for some critical anatomic regions and observe whether the user exceeds these thresholds or not. With these metrics, it is also possible to obtain a visual feedback, which can show the bone regions in different colors according to the performance of the user for the tasks on that region.

Although complex and realistic medical simulators are currently being developed by a large number of universities and medical companies, the field of hard tissues interaction like orthopedics and dental surgery has not been exploited yet [7].

Considering the application context of a haptic device in orthopedics and dental surgery, the surgeon needs to perform various tasks like cutting, milling
and drilling, for example, as shown in Figure 1.2.

![Figure 1.2: Typical tasks involved in a surgery of hard tissues, [8],[9].](image)

In order to create a haptically enabled virtual reality simulator to train surgeons for these skills, the main user requirements are given in [10], which are as follows:

- Haptic feedback in 6-DOF to allow both force and torque feedback, as well as translational and rotational capabilities of the virtual tool operating in a (narrow) channel or cavity.

- The whole device should fit in a space of 250 $\times$ 250 $\times$ 300 mm.

- The minimum translational and rotational workspace should be 50 $\times$ 50 $\times$ 50 mm and $\pm40^\circ$, respectively, in all directions at the nominal position, with no singularities in the workspace.

- The tool center point (TCP) should be able to render high force and torque up to at least 50 N and 1 Nm, respectively.

- Low back-drive inertia and friction, and no constraints on motion imposed by the device kinematics, so that free motion feels free.

- Ergonomics and comfort for the user.

- Transparency and stability of the complete system.

Some of the device requirements expressing common desirable characteristics for force/torque feedback of haptic devices include, according to Gogu [11]:

- Isotropic behavior.
1.3 Research objective and questions

The main research objective of this thesis is to develop a 6 DOF haptic device that can provide realistic force/torque feedback from the virtual environment. The focus will be on the investigation of a model-based and simulation-driven design approach as an effective tool for the design of haptic devices.

This main objective can be divided into the following research questions:

• **Q1**: How to accurately estimate stiffness of a 6-DOF haptic device through an analytical model, which is compact and can be used in real-time control?

• **Q2**: How to find a robust optimum design of haptic devices, whose performances are less sensitive to variations in manufacturing tolerances?

• **Q3**: How to estimate friction in haptic devices that can mimic realistic behavior and be used in real-time control?

• **Q4**: How to evaluate force/torque capability of a haptic device without a force/torque sensor?

• **Q5**: How to develop a control strategy that can be used to compensate for unwanted effects and maximize the transparency of a haptic device?

1.4 Research approach

The development of haptic devices is a challenging task because of the multi-criteria design consideration. As stated earlier, the main objective is to provide a realistic force/torque feedback from the virtual environment via a haptic device. This directed the research towards the investigation of how the real
sensation of using the system can be improved when using it in free space (increase transparency) and when in contact (stiffness representation) during surgery can be increased, as shown in Figure 1.3.

![Figure 1.3: Research focus.](image)

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 required performance specifications.
- Elicitation of requirements from the end user and transformation of these requirements together with the performance requirements to design specifications.
- Development of an approach for robust optimization of haptic devices
  - Kinematic models
  - Dynamic model
  - Stiffness model
- Development of a model-based control strategy for haptic devices
  - Compensation for friction
  - Compensation for deflections
  - Compensation for dynamic effects
- Development of a methodology for design of haptic devices
- Experimental verification and validation
1.5 Delimitations

This thesis aims to improve transparency and stability of haptic simulators from the perspective of device performance. Performance of the virtual model and haptic collision detection algorithm has not been considered in this thesis.

This thesis proposes model-based and simulation-driven design approach to develop haptic devices with a model-based control strategy to further improve transparency. In a model-based control strategy, dynamic, stiffness and friction models have been considered for compensating inertial effects, elastic deformations and friction in active joints. However, the friction model is not considered in the multi-objective optimization, as it has only been considered in the control strategy.

1.6 Thesis outline

The thesis is divided into six chapters and a brief overview of each chapter is given below.

Chapter 1 provides an introduction to the thesis, research background, and discusses the problems that have been identified. Furthermore, research questions, research approach, and delimitations of the thesis are given.

Chapter 2 presents state of art in the design of haptic devices. The review includes characteristics of different architectures used for haptic devices.

Chapter 3 presents the model-based and simulation-driven design approach and its verification using both the Ares and TAU 6-DOF haptic devices.

Chapter 4 describes the two haptic devices (Ares and TAU) that have been developed and used as test cases during this thesis work.

Chapter 5 gives a brief summary of the appended papers.

Chapter 6 summarizes the findings, contributions, and conclusions of the thesis work and outlines future work.

1.7 Chapter summary

This chapter summarizes the motives of the thesis and the research frame of the virtual reality-based surgical simulators. The research problem is formulated in the form of research questions followed by the taken research approach, delimitations and thesis outline.
Chapter 2

State of the art

Significant research efforts have been devised in the development of haptic devices, and several studies exist on the design and development in commercial and academic literature. This chapter provides an overview of the current state of the art in design of haptic devices. The review includes an overview of different architectures used for haptic device and its design, optimization, system models, and control design.

2.1 Haptic devices

A state of the art about different commercially available haptic devices and their application areas have been reviewed in [12]. Furthermore, a comparative study has been conducted by Khan [3] in which he compared different haptic devices based on kinematic structure, DOF, workspace, stiffness, maximum force and cost. Currently, there are haptic devices available in the forms of 2, 3, 4, 5, 6, and 7-DOF, reviewed by for example, Gogu [11] and Lee [9]. Lee has compared different haptic devices based on serial and parallel kinematic structures.

Serial haptic devices have a kinematic structure, which consists of a single open-loop chain where the TCP is connected to the fixed based. The kinematic chain is composed of a group of rigid links where each pair of adjacent links is interconnected by an active kinematic pair (controlled joint).

Serial devices have some advantages like a large working volume and high dexterity; however, numerous disadvantages such as low precision, poor force exertion capability, low payload-to-weight ratio, and high inertias tend to limit its use in many applications.

Parallel haptic devices have a kinematic structure, where the TCP is connected to a fixed based through several kinematic chains. In contrast with the open chain serial devices, the parallel devices are composed of closed kinematic chains, and every kinematic chain includes active and passive kinematic pairs.
Parallel devices possess high stiffness, low inertia, high rigidity and accuracy, and high payload-to-weight ratios, which enables the large bandwidth transmission of forces but with some disadvantages like a small workspace, the possibilities of singularity due to link collision, and low dexterity.

Recently, many 6-DOF haptic devices have been developed, some of which have been commercialized, which include both serial and parallel haptic devices. The most widely used haptic devices are PHANTOM\textsuperscript{®} by Massie and Salisbury [13], Omega.3 by Force Dimension [14], Novint Falcon by Novint Technologies [15], Haptic master [16], Virtuose by Haption [17], Freedom 7S by MPB Technologies [18], HD2 by Quanser [19], Xitact HP by Mentice [20] and Meglaev by CAE Healthcare [21]. A performance comparison of these devices is given in Table 2.1.

| Table 2.1: Commercially available force feedback haptic devices [12] |
|---------------------------------|---|---|---|---|---|---|---|---|
| Phantom Omni | Omega 3 | Novint Falcon | Haptic Master | Virtuose | Freedom 7S | HD2 | HHP | Meglaev |
| Structure | Serial | Parallel | Parallel | Serial | Serial | Serial | Parallel | Hybrid |
| Workspace (10\(^{-3}\)m\(^3\)) | 1.3 | 2.2 | 1.1 | 80.0 | 91 | 12 | 70 | 1.9 | 0.01 |
| DOF | 6/3 | 3 | 3 | 3 | 6.0 | 7 | 6/5 | 4 | 6 |
| Position Res (\(\mu m\)) | 55.0 | 10.0 | 60.0 | 4.0 | 6.0 | 2.0 | 51.0 | 57.0 | 2.0 |
| Continuous Force (N) | 0.9 | 12.0 | 9.0 | 100.0 | 10.0 | 0.6 | 10.8 | 20.0 | n/a |
| Peak force (N) | 3.3 | n/a | n/a | 250.0 | 35 | 2.5 | 19.7 | 30.0 | 40.0 |
| Stiffness (N/mm) | 2.0 | 14.5 | n/a | 50.0 | n/a | 2.0 | 3.0 | n/a | 50.0 |
| Stiction (N) | 0.26 | n/a | n/a | n/a | n/a | 0.04 | 0.35 | n/a | 0.0 |
| Force Resolution (N) | n/a | n/a | n/a | 0.01 | n/a | n/a | n/a | n/a | 0.02 |
| Force Bandwidth (Hz) | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | 2000 |

2.2 Haptic device design

As stated in Chapter 1, the design of haptic devices is based on user and device requirements, for example: a large workspace for a human operator, low apparent mass/inertia, low friction, high structural stiffness, backdriveability,
low backlash, high force bandwidth, high force dynamic range, absence of mechanical singularities, compactness, and an even “feel” through the workspace [22]. These requirements reflect considerations of different disciplines such as mechanical, electrical and control design. These considerations benefit from these systems being designed in parallel and are integrated to form the complete system as a mechatronic product.

Fathy et al. [23] identified four different design approaches for the integrated optimization of mechanical and control system design: sequential, iterative, nested, and simultaneous. Khan et al. [24] presented a design methodology for haptic devices based on a combination of the “nested” approach and the general design process by [25]. Another approach for the design of mechatronic systems is to use the V-model [26] in combination with a stage-gate sequential process model (e.g. [27], [28]).

2.2.1 Optimization

Many researchers have addressed the challenge of finding an optimal haptic device design using different approaches depending on specific objectives, for example minimizing or maximizing one or several performance indices such as maximum kinematic dexterity and transmission ability [29], [30], maximum stiffness [31], minimum position error of the movable platform [32], maximum velocities in the platform [33], and maximum required workspace [34], [35], [36].

Many methods and approaches have been proposed to achieve an optimum design that satisfies multi-criteria requirements and constraints. Generally, these approaches can be classified into two types: deterministic design optimization (DDO) and robust design optimization (RDO). A DDO always returns the same result for a specific set of design values, while a non-deterministic optimization may return different results for the same set of design inputs.

Finding an optimal solution using a DDO approach for these devices entails handling a multi-criteria optimal design problem, that is a multi-objective constrained nonlinear optimization problem with no explicit analytical expression. The gradient and Hessian algorithms that generally converge on a local minimum are not suitable for solving this problem. An interval analysis-based approach has recently been used to solve a multi-criteria design problem for parallel manipulators by Hao and Merlet [37]. This approach determines a design parameter space that satisfies all design constraints. However, this approach requires explicitly analytical expressions of all constraints. The performance-chart-based design methodology (PCbDM) proposed by Xin-Jun Liu et al. [38] is an optimal kinematic design methodology for parallel mechanisms with fewer than five linear parameters, which is unsuitable for our optimization problem with its five design parameters. In this regard, the genetic algorithm (GA) [39] approach seems a good option for multi-criteria problems due to its
good convergence property and robustness. Stan et al. [40], Lee et al. [22], Hwang et al. [41], Raza. R et al. [42], and Khan et al. [43] have used a GA approach for the multi-criteria optimization of parallel kinematics machines and parallel haptic devices.

An optimum design using a DDO approach, however, may not always achieve the desired performance due to significant uncertainties that exist in the material and geometrical parameters and the component assembly [44]. Due to variations, uncertainties, and scatter, most real-world designs do not behave in a deterministic manner; rather, they behave stochastically, influenced by chance or probability. Variation is inherent in, for example, geometric properties, manufacturing precision, and actual use of the product. Applying DDO strategies without incorporating uncertainty and measuring its effects leads to designs that cannot be called “optimal”.

A robust optimum design makes the performance minimally sensitive by optimizing mean performance and minimizing its sensitivity to various sources of variation. By accurately assessing the robustness of the design RDO ensures that a product performs its intended function with minimal variation in the performance indices by controlling design parameters without eliminating the cause of the uncertainties [45],[46].

Several authors have contributed to the formulation of robust design problems with the aim of improving the quality of a product whose manufacturing process involves variability [47]. A comprehensive review of the state of art in RDO is presented by Hans et al. [48]. Xiaoping et al. [46] developed a strategy for assessing robustness and synthesizing robust mechanisms when random and interval variables are involved, using a Monte Carlo simulation (MCS) to quantify the variability of the performance. A simulated annealing algorithm was used to maximize robustness by Zhang et al. [49]. A new robust multi-objective GA (RMOGA) that optimizes two objectives, a fitness value and a robustness index, was used by Li et al. [50].

2.2.2 System models

To formulate the performance indices we need to develop a number of focused system models, which include kinematic, dynamic and stiffness models.

For kinematic modeling of haptic devices, both closed loop and open architectures have been studied, for example, [51], [52]. Cui H et al. [53] and Zhu Z et al. [54] have worked on the kinematic analysis, error modeling, and dynamic modeling for real-time control of parallel (TAU) robots.

Most of the different types of haptic devices have been dynamically investigated by researchers using different approaches such as the Newton Euler formulation [55], the Lagrangian formulation [56], the principle of virtual work [57], and the generalized momentum approach [58]. Nguyen et al. [59] used generalized momentum methods to model a Stewart platform with the legs as
point masses. Ahmadi et al. [60] studied dynamic modeling and simulation of a parallel robot Hexa using Lagrangian equations of the first type.

Aiming for high dynamic performance with relatively small actuators and low energy consumption motivates the design of lightweight structures [61]. A light-weight design is a compromise or trade-off between low weight and high stiffness. There are several methods available for computing the stiffness matrix, including the virtual joint method often called the lumped modeling method), finite-element analysis (FEA), and matrix structural analysis (MSA).

Stiffness analysis has been widely investigated in the literature. Several methods exist for computation of the stiffness matrix: the virtual joint method (VJM), which is often called lumped modeling [62], [63], [64], [65], finite element analysis (FEA) [66], [67], and matrix structural analysis (MSA) [68], [69], [70], [71]. Uchiyama [72] has derived an analytical model for the stiffness of a compact 6-DOF haptic device based on static elastic deformation of compliance elements.

Various prototypes have been tested experimentally: Pinto et al. [73] evaluated static stiffness mapping of their Lower Mobility Parallel Manipulator using pre-loading in the experimental testing to eliminate backlash in the system. In experimental testing [74], the static behavior evaluation of a robot was analyzed by norms, for example ANSI/RIA R15.05-1-1990 [75], ISO 9283:1998 [76], which were established for serial manipulators.

2.2.3 Control design

Various control strategies such as open-loop impedance control, impedance control with and without force feedback [77], [78], and admittance control for model-based compensators [79] are employed in haptic interfaces to mask the inertia and friction, and improve transparency and fidelity of force/torque feedback of the system. A force-based impedance control approach has been presented in [80] and [81], and showed that this approach can improve transparency and fidelity of force/torque feedback. A closed-loop impedance control (CLIC) with model-based compensator (MBC) and torque compensator based on motor current (TCBMC) is used by [80] and [81] to improve transparency of haptic devices and mask the parasitic force/torque. These compensators require models, which can accurately predict inertia, stiffness and friction phenomena.

For inertia compensation Carignan et.al [77] used model-based compensation. The dynamic model for inertia compensation should be linear in its parameters. Honegger et.al [82] used dynamic equations in linear form for non-linear adaptive control of a Hexa-glide type parallel robot.

High quality haptic interaction requires compensation of frictional effects, which relies on a friction model that enables accurate prediction of the friction forces. A friction model for friction compensation in real time must also be
computationally efficient. Different friction models exist in the literature, both simple and advanced to predict friction phenomena from simple to complex behavior. These models are investigated in terms of realistic friction phenomena and computational efficiency in a comprehensive survey in [83], where the Smooth Generalized Maxwell slip model (S-GMS) [84] was suggested. Jianjun et.al [85] used a model-based compensation to compensate for robot deflection caused by external forces.

As stated in the previously mentioned literature, there are two types of control structures, as impedance and admittance control are widely used for haptic devices [77], [86], [87]. To implement impedance control an open-loop control structure is traditionally used [88]. It is then assumed that the dynamics of the device, for example time dependent disturbances, friction, inertial and gravitational forces are negligible. However, it is also reported in the aforementioned literature that the quality of haptic feedback (forces/torques) in open-loop is susceptible to environment model errors and time dependent disturbances [81]. Therefore, for high transparency of a device, it is well motivated to compensate for the dynamics and frictional forces of the device using impedance control with force feedback. In these approaches the force is feedback through commercially available force/torque sensors, which are rather bulky and expensive and can increase system inertia. Furthermore, they can increase inertia at the TCP of the platform. An alternative solution for the force feedback is an estimated force/torque using motor torque based on current measurement transformation using the Jacobian matrix to TCP of the end effector. Another solution is the use of dynamic force observers, which estimate external forces using a system dynamic model. For such an approach Van Damme et al. [89] proposed recursive least squares estimation with exponential forgetting to estimate the end-effector force from noisy actuator torque measurement.

2.3 Chapter summary

This chapter describes state of the art for the development of haptic devices. An overview of the characteristics of existing haptic devices is given, followed by an overview of haptic device design, including optimization, system models for performance indices and control design.
Chapter 3

Model-based and simulation-driven design

This chapter presents an overview of a model-based and simulation-driven design approach for 6-DOF haptic devices design in order to have a high transparent force/torque feedback from the virtual environment. Transparency quantifies the correspondence between the desired and actually observed values of force/torque feedback. In an ideal scenario, the force/torque feedback observed at the TCP of the end effector of the haptic device must reflect the actual force/torque generated by interacting with the virtual tool in the virtual environment. Haptic device transparency is restrained by device natural dynamics, gravitational and frictional forces, which can have a significant impact on the kinematic, dynamic and kinetostatic performances. An adequate control system must be implemented for compensation of unwanted effects caused by the mechanical design.

Haptic device transparency depends on the device dynamics and control algorithm, and in this thesis the focus has been to improve transparency by minimizing effects from natural dynamics of the device and by using compensation in the control design. The approach is formulated as a two-stage approach, where a basic level of transparency is achieved during the conceptual design phase and further improved during the detailed design phase. In the conceptual design phase, the suggested approach is to use a model-based and simulation-driven design approach, while in the detailed design, a model-based control strategy is suggested. The approach has been applied to two different case studies to verify its effectiveness. It has been applied on the development of a new haptic device based on the TAU configuration and parts of it have been validated on the Ares device, which is based on a Stewart platform.

Numerous design aspects based on the natural dynamics of haptic devices contribute to the performances. These performances can be described in terms of a large workspace, high manipulability/isotropy torque requirements on an actuator for unit force/torque applied, and high stiffness for precise position-
ing, low inertia and low resonant frequency. Furthermore, these performance are evaluated numerically through performance indices like workspace volume index (VI), kinematic isotropy index (II), quasistatic force/torque requirement index (TRI), dynamic dexterity index (MI), stiffness index (KI), and natural frequency index (NFI) (described in Papers A and C).

The performance requirements are extracted from the requirement specification of the device, and used to identify the main function of the device and basic constraints on the solution space. The main function is described in terms of functional requirements, which are derived from device and user requirements described in section 1.2, and are the basis for generating potential design concept, as shown in Figure 3.1.

The multi-criteria nature of performance requirements of haptic devices motivates the use of a model-based and simulation-driven design approach. Furthermore, the design and development of haptic devices involves a great deal of uncertainties and project risk. This dilemma can be solved by using a process model like the V-model, which focuses on minimizing technical risks by dividing the product development process into a sequence of decomposition stages. This decomposition from abstract idea to realization of the physical product is often referred to as the left leg of the V-model, which is followed by integration stages, that is the right leg.

The decomposition of design tasks for a product with hybrid technological constituents, like a mechatronics product, is not obvious, but one attempt to adapt and formalize the generic V-model for mechatronics development is the German standard VDI 2006 [26]. A coarse representation of VDI 2006 is shown in Figure 3.2. On top of V-model is also represented a stage-gate sequential process model (e.g. [27], [28]), which has as its main purpose to reduce the economical project risks by providing a mechanisms to a company.

Figure 3.1: Dependencies between functional requirements, design concept and models needed for evaluation of product performance.
management to make a go/no-go/wait decision at each main decision gate. In many industrial organizations, the V- and extended stage-gate models are synchronized.

![Diagram](image)

**Figure 3.2: The mechatronics development V-model combined with the stage-gate model.**

The design process is evaluated through an iterative design using a design pyramid as shown in Figure 3.3 (Paper A), which focuses on model-based and simulation-driven (e.g., [90], [91]) design exploration, where one starts from an abstract top-level model, that is extended via stepwise refinement and design space exploration, into a detailed and complete physically realized system.

![Diagram](image)

**Figure 3.3: Design pyramid with different abstraction levels [91].**

The design pyramid is evaluated both at the system and individual model level, where the models were developed using stepwise refinement by adding more details to the models, which are quite coarse in the first instance towards
such a detail that the models can predict the complete behavior of the system and investigate whether it fulfills the required performances or not (Papers A and C). In this thesis, the developed models are presented in the context of the Ares and TAU 6-DOF haptic devices, and a brief overview of these models is given in the coming subsections.

3.1 Model development in the conceptual design phase

The first step of the proposed design approach concerns activities during the conceptual design phase. The activity that has a major impact on device force/torque feedback transparency is the activity that determines the basic kinematic structure parameter and basic shape parameters. This task is addressed by a new RDO approach, which is based on hybrid design optimization, which combines a GA and MCS. This optimization must balance multi-criteria requirements and constraints expressed in the form of design indices. These performance indices are expressed based on a number of behavior models for the studied TAU 6-DOF haptic device. The formulation and verification of these models are given in the coming sections.

3.1.1 Kinematic model

In the kinematic model development, the inverse and velocity kinematics have been considered. Solving the inverse kinematic problem for the 6-DOF TAU configuration as shown in Figure 3.4, determines all orientations (i.e., joint angles) $[\theta_1, \theta_2]$ of all active joints when the pose (i.e., position and orientation) $q = [p_x, p_y, p_z, \alpha, \beta, \gamma]$ of the platform are given.

![Figure 3.4: Kinematic structure of TAU haptic device.](image)
A closed-form solution for the inverse kinematics can be found based on the constrain equations. There are two constrain equations for symmetrical chains according to the kinematic path \((a_i, b_i, c_i)\) and \((a_i, b_i, d_i, e_i)\) shown in Figure 3.4, as given in equation (3.1) and (3.2).

\[
(c_{ix} - b_{ix})^2 + (c_{iy} - b_{iy})^2 + (c_{iz} - b_{iz})^2 = L_2^2 \tag{3.1}
\]

\[
(d_{ix} - e_{ix})^2 + (d_{iy} - e_{iy})^2 + (d_{iz} - e_{iz})^2 = L_2^2 \tag{3.2}
\]

### 3.1.2 Dynamic model

The dynamic model describes the inherent property like inertia of a system. The Lagrange dynamic formulation is used to develop the equation of motion of the form as in (3.3),

\[
M(\theta)\ddot{\theta} + V(\theta, \dot{\theta}) + G(\theta) = \tau_J \tag{3.3}
\]

where the first term \(M(\theta)\) in equation represents inertial forces, while the second term \(V(\theta, \dot{\theta})\) accounts for the Coriolis and centrifugal forces. The last term \(G(\theta)\) on the left side is the gravity force, while \(\tau_J\) is the generalized Cartesian forces/torques at the end-effector. A detailed formulation of dynamics equations is given in (Paper C).

### 3.1.3 Stiffness model

As it has been previously pointed out in Chapter 1, the design of haptic devices is not trivial due to its complex design, multi-domains consideration and in finding the best compromise between several properties such as workspace, dexterity, manipulability, and stiffness. Stiffness is an essential performance measure since it is directly related to the positioning accuracy and payload capability of haptic devices. To make these devices compatible with their applications it is necessary to model, identify and compensate all of the effects that degrade their accuracy. Stiffness can be defined as the capacity of a mechanical system to sustain loads without excessive changes of its geometry, or these produced changes on geometry, due to the applied forces, are known as deformations or compliant displacements [92]. Compliant displacements in a robotic system produce negative effects on static and fatigue strength, wear resistance, efficiency (friction losses), accuracy, and dynamic stability (vibration). In this thesis, a systematic procedure is proposed in order to develop a generalized stiffness model within the workspace of the manipulator and its evaluation with virtual (FEM analysis) and physical experiments. To develop this, a work procedure defined by the flowchart in Figure 3.5 is presented. The procedure established by this chart is outlined below.

This methodology starts with the development of a simplified analytical model. This is verified by a simplified FEM model in an iterative way until
these two models give the same result. Thereafter, a simplified physical experiment is made to validate the analytical model. If the difference between the analytical and the experimental results is not acceptable, in other words it does not validate the analytical model, a more detailed analytical model must be developed.

For the detailed analytical model the passive joints and actuation system are also included. This is further verified using a detailed FEM model with corresponding detailing level in the same way as for the simplified model. Thereafter, this detailed analytical model is validated by means of a detailed physical experiment. After validating the proposed model, a sensitivity analysis is performed to map the variation of static stiffness in the workspace. In these maps, the engineering stiffness is visualized as a function of the generalized coordinates of the workspace. A detailed description of this methodology is given in Paper B.
For the case of $N$ number of serially connected compliant elements with local stiffness $i^{-1}K_i$, a general stiffness $0K_N$ of the TCP of the end-effector can be obtained by force/displacement transformation Jacobian $i^{-1}J_i$, which can be expressed in the base frame 0, as given in equation (3.4):

\[
0K_N = 0J_{N-1}N^{-1}S_N0J^T_{N-1} + \ldots \\
0N_{N-1,\text{disp}}(0J_{N-2}N^{-2}S_{N-1}0J^T_{N-2})0G_{N-1,\text{force}} + \ldots \\
+ 0N_{J_1,\text{disp}}(0J_{i-1}i^{-1}S_i0J^T_{i-1})0J_{N,\text{force}} + \ldots \\
+ 0N_{J_1,\text{disp}}(0J_10S_10J^T_1)0J_{1,\text{disp}} \tag{3.4}
\]

### 3.1.4 Model verification and validation

To verify the developed kinematic, dynamics and stiffness models, the first two models were verified in MapleSim [93], while the third model was verified by FEM analysis (ANSYS [94]) and validated by physical experiments. The MapleSim model is shown in Figure 3.6.

![MapleSim model](image)
Kinematic model

In order to verify the inverse kinematic model, an input trajectory of was applied in the rotational degree of freedom along the x-axis. The results from both the analytical and MapleSim models are shown in Figure 3.7.

![Figure 3.7: Comparison of Inverse kinematics by analytical and MapleSim](image)

By comparing these results, we can verify the inverse kinematics calculation approach. These results show that the analytical model agrees with the MapleSim model, which verifies the model.

Dynamic model

The dynamic model was verified using the same trajectory $\sin(\omega t)$ on the actuators, and the required torques on the actuators were calculated based on the analytical dynamic model of section of 3.1.2 and MapleSim model. The results from these analyses are shown in Figure 3.8, where we can conclude that the results from the analytical model agree with the MapleSim model, which verifies the model.

Stiffness model

The stiffness model developed in section 3.1.4 was verified through simulation using ANSYS and validated by physical experiments. In this verification and validation the Ares 6-DOF haptic device was used. A detailed description of
the validation is given in Paper C and some of the results are shown in Figure 3.9.

Figure 3.9: Deflections of platform in (a) X-, (b) Y-, and (c) Z-directions, given by the analytical model, ANSYS model, and experimental tests, respectively.

3.1.5 Robust optimum design

Transparency of a haptic device can be improved through design, which is optimum and whose performance are less sensitive to variations in manufacturing
tolerances of optimum numerical value of design parameters. The haptic device that has been used as a basis for developing this approach is the TAU 6-DOF device and the optimization formulation in equation 3.6 is specific for this device. However, the stepwise approach outlined below is general for any haptic device. The steps proposed to achieve a robust optimum design, as shown in Figure 3.10, are outlined as follows:

- Normalize the performance indices by finding the maximum and minimum bounds of the performance indices under the given constraints, and also find the bounds of the design parameters using Monte Carlo simulations.

- Perform RDO using a GA to find optimum robust values for the design parameters using robustness criteria on the performance indices. This is to ensure that the optimum design parameters are robust to tolerance variations.
• Perform sensitivity analysis of the performance indices using Monte Carlo simulations based on the variations in the optimum numerical values of the design parameters obtained from the RDO in step 2. Perform design optimization to find optimum tolerances that minimize manufacturing cost and satisfy the allowed variations in the performance indices.

The proposed RDO approach seeks to find numerical values of optimum design parameter by maximizing volume index (VI), global kinematic isotropy index (GII), global stiffness index (GKI), and global natural frequency index (GNFI), while minimizing the global quasistatic force/torque requirement index (GTRI) and dynamic dexterity index (MI). The design optimization is evaluated in a dexterous workspace (Paper C) along with the robustness criteria defined in equation 3.5, which tries to minimize the objective function $GDI_R$.

$$\mu_{GI_n} + 3\sigma_{GI_n} \leq 1$$

(3.5)

where $\mu_{GI_n}$ and $\sigma_{GI_n}$ is the mean value and standard deviation of normalized performance indices (Paper C). The robust design approach can be formulated in the form of an optimization as given in equation 3.6:

minimize $\frac{1}{GDI_R(x)}$

over $x = [L_1, R_1, t_1, L_2, R_2, b_L, t_3, h_L, R_p, \theta_p, t_p, \theta_{32_{nom}}, ln]$

subject to $\min(\theta_{ii}) \leq \theta_{ii} \leq \max(\theta_{ii})$

$\min(\phi_{ik}) \leq \phi_{ik} \leq \max(\phi_{ik})$

$x_{lb} \leq x_j \leq x_{up}$

$\det(J) > 0$

$\det(K) > 0$

$\det(M) > 0$

$\mu_{GI_n} + 3\sigma_{GI_n} \leq 1$

$$N_{uvw} = \begin{cases} 
1 & \text{if } P_{uvw} \in W(X,Y,Z,\alpha,\beta,\zeta) \\
0 & \text{if } P_{uvw} \notin W(X,Y,Z,\alpha,\beta,\zeta) 
\end{cases}$$

(3.6)

where variable $x$ is a vector of design parameters, $x_{lb}$ and $x_{up}$ are the lower and upper bounds of the design parameters, respectively, while $\min(\phi_{ik})$, $\min(\theta_{ij})$, $\max(\phi_{ik})$ and $\max(\theta_{ij})$ are the minimum and maximum bounds of the active and passive joints, $\det(J) > 0; \det(K) > 0$ and $\det(M) > 0$ are singularity conditions in the workspace. The term $J$, $K$, and $K$ defines the Jacobian matrix, stiffness matrix and inertia matrix, while $P_{uvw}$ and $N_{uvw}$ defines the grid point in the workspace and binary flag, a grid point is a reachable point when $N_{uvw} = 1$; otherwise not when $N_{uvw} = 0$. The variation
The design parameters is assumed to be normally distributed and $\pm 3\sigma_{x_j}$ covers the tolerance interval.

### 3.2 Control design in the detailed design phase

The second step of the proposed design approach concerns activities during the detail design phase. In this phase, we focused on improving the force/torque transparency by compensating for unwanted effects in the device, which reduces transparency. We developed a model-based control strategy to compensate for the natural dynamics of the device, friction between joints, gravity of platform, and elastic deformation. For this strategy, we used the Ares 6-DOF haptic device as a test case for the development, testing and verification of the control strategy. The objective of this strategy is to minimize the problems with the existing approaches, and make it cost effective. The proposed approach is based on closed-loop impedance control (CLIC) with model based compensation and force/torque feedback, where the force/torque at TCP of the platform is to be estimated using recursive least squares estimation with exponential forgetting [89]. The disturbance torque to compensate for the parasitic effects was estimated by their corresponding models, and added to the torque applied by the feed forward of the reference force $F_d$ and feedback of estimated force $F_{est}$, where $K_p$ is the gain of force feedback controller, and $J$ denotes the Jacobian matrix. The proposed control structure is shown in Figure 3.11.

![Figure 3.11: Control design of 6-DOF haptic device.](image-url)
3.2. CONTROL DESIGN IN THE DETAILED DESIGN PHASE

3.2.1 Friction estimation

In this thesis, different friction models were investigated to determine how well these models are suited for performance simulation and control of a 6-DOF haptic device. The studied models include the Dahl model, LuGre model, Generalized Maxwell slip model (GMS), smooth Generalized Maxwell slip model (S-GMS), and Differential Algebraic Multi-state (DAM) friction model. These models were evaluated both numerically and experimentally with a 6-DOF Ares haptic device. To evaluate these models, we used criteria based on fidelity to predict realistic friction phenomena, ease of implementation, computational efficiency, and ease of estimating the model parameters. A detailed overview of evaluation is described in Paper D.

In this investigation, the S-GMS was identified as the best candidate for the real-time friction compensation. A brief description of the selected model is given below:

The analytical multi-state S-GMS model according to [95] is given as in (3.7);

$$\frac{dF_i}{dt} = k_i(\dot{l} - \eta_i(F_i, \dot{l}) \left| \dot{l} \right| \frac{F_i}{\alpha_i g(\dot{l})})$$  \hspace{1cm} (3.7)

where \( \eta_i(F_i, \dot{l}) \) is a smoothed transition function between presiding (\( \eta_i \approx 0 \)) and sliding regime (\( \eta_i \approx 1 \)), while \( k_i \) is the stiffness of element \( i \). The transition function \( \eta_i(F_i, \dot{l}) \) consists of two multiplicative terms given in equation (3.8), the transition function (3.9) and the reset function (3.10)

$$\eta_i(F_i, \dot{l}) = \eta_{A_i}(F_i, \dot{l})\eta_{B_i}(F_i, \dot{l})$$  \hspace{1cm} (3.8)

$$\eta_{A_i}(F_i, \dot{l}) = 1 - \frac{1}{2} \tanh \left[ \lambda \left( \frac{F_i}{\alpha_i g(\dot{l})} + \varsigma \right) \right] + \frac{1}{2} \tanh \left[ \lambda \left( \frac{F_i}{\alpha_i g(\dot{l})} - \varsigma \right) \right]$$  \hspace{1cm} (3.9)

$$\eta_{B_i}(F_i, \dot{l}) = \frac{1}{2} + \frac{1}{2} \tanh \left[ \gamma \left( \frac{F_i}{\alpha_i g(\dot{l})} \right) \right]$$  \hspace{1cm} (3.10)

Where \( \varsigma \in [0.9, 1] \) is a factor to avoid ringing in sliding regime and set the frictional lag, the factor \( \lambda \) sets the transition sharpness of (3.9). The reset function (3.10) vanishes as the velocity reverse its direction. The factor \( \gamma \) sets the transition sharpness of (3.10). The function \( g(\dot{l}) \) describes the Stribeck effect, which is defined as

$$g(\dot{l}) = (f_C + (f_S - f_C)e^{-(\frac{\dot{l}}{\nu_s})^2})$$
Where $f_S$ and $f_C$ are static and Coulomb friction force, $\nu_s$ the Striebeck velocity, while

$$\alpha_i = \frac{F_i}{\sum_{i=1}^{N} F_i}$$

The resulting friction force is the summation of $N$ number of stiffness forces $F_i$ plus a viscous $\sigma v \dot{l}$ term as given in equation (3.11).

$$\tau_f(\dot{l}) = \sum_{i=1}^{N} F_i + \sigma v \dot{l} \quad (3.11)$$

### 3.2.2 Force torque estimation

As an alternative to using a force/torque sensor, we developed an approach to estimate the force/torque feedback at the TCP of the end effector. For this purpose, the filtered dynamic equation proposed by Van Damme et al. [89] was used. A solution of the dynamic equation for the haptic device, which shows the torques on actuators in the joint space, when an external force/torque acting on the TCP of the end effector is given in 3.12 as,

$$H(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + G(\theta) = \tau + J^T(q)f_e - \tau_f(\dot{\theta}) \quad (3.12)$$

here $\theta$ is the vector of joint variable, $H(\theta)$ is the inertia matrix, $C(\theta, \dot{\theta})$ is the centrifugal matrix comprised of Centrifugal and Coriolis forces. $G(\theta)$ is a vector that contains gravitational torque on the joints, $\tau_f(\dot{\theta})$ is a vector containing friction torques, and the $\tau$ is the vector representing the actuator torques.

The dynamic equation defined in (3.12) was filtered with a low-pass filter to remove the acceleration term $\ddot{\theta}$, then a recursive least square estimation was used to estimate the force/torque at TCP of the platform. A detailed description of the proposed approach is given in Paper E.

### 3.2.3 Transparency measurement

Transparency $G_T$ of the haptic device can be defined according to [96], as the ratio of actual transmitted force to the user $F_t$, to the desired virtual force generated in the virtual environment $F_g$ as in equation 3.13.

$$G_T = \frac{F_t}{F_g} \quad (3.13)$$

According to equation 3.13 for high transparency the ratio should be close to unity. A comparison of transparency for uncompensated and compensated interaction in x, y and z-directions are shown in Figure 3.12. The results from
this comparison show a significant transparency improvement of the proposed approach.

Figure 3.12: Transparency for uncompensated and compensated forces while interacting with a virtual object in (a) X-, (b) Y-, and (c) Z-directions.

3.3 Chapter summary

This chapter presents an overview of a model-based and simulation-driven design approach for design of 6-DOF haptic devices with a high transparency in the force/torque feedback from the virtual environment. The first step of the approach is applied during the conceptual design phase and focuses on RDO to find basic kinematic structure parameters and basic shape parameters. The second step is applied during detail design phase, where the goal is to further improve the transparency in the control design by compensating for unwanted effects.
Chapter 4

Prototypes

Research dealing with design and development of physical products has a great need for prototypes to use as test cases in the virtual world and for experimental testing. In this work two physical 6-DOF haptic devices were used for development and testing of theories and methods. The first device, Ares, is based on a Stewart platform and was initially developed and manufactured during an earlier project. The second device is named TAU because of the kinematic structure (TAU) that it is based on and has been developed and manufactured during this project.

4.1 The Ares haptic device

A physical prototype and schematic of the 6-DOF Ares haptic device is shown in Figure 4.2. The schematic structure consists of a fixed base, a moving platform and six identical kinematic chains connecting the platform to the base. Each kinematic chain consists of an active actuator fixed to the base to actuate a linear guideway of length $L_1$ using cable transmissions to provide linear motion to each linear guideway, a spherical joint, a constant length proximal link of length $L_2$, and a universal joint. The joint attachment point pairs are symmetrically separated by $120^\circ$, and lie on a circle, both on the base and platform. The platform attachment points are rotated $60^\circ$ clockwise from the base attachment points. The 6-PSU (active prismatic, passive spherical and universal) joint’s configuration is used to get 6-DOF motion at TCP.

4.1.1 Model development and analysis based on the Ares haptic device

The Ares haptic device was developed during an earlier research project (see for example Khan et al. [3]). In this work, this device was used for the development of the stiffness modeling methodology, where the verification of the approach was made with measurements on this device. It has also been utilized for the evaluation of friction models as discussed in section 3.2.1, as well as for the development and verification of the proposed model-based
strategy in Paper E. It has also been used in the formulation of the model-based and simulation driven design approach for haptic devices.

4.2 The TAU haptic device

The TAU haptic device was designed and implemented within the timeframe of this thesis work. Based on a deterministic optimization of the kinematic structure in the early parts of the project, a mechanical prototype system was designed and developed and physically realized during a capstone course project in machine design at Kungliga Tekniska Högskolan (KTH). This structure was slightly modified later in the project when the RDO approach [97] was developed and applied to find optimum numerical values of design parameters of the kinematic structure of the 6-DOF TAU haptic device, as shown in Figure 4.2. Based on these slightly adjusted optimum numerical values of design parameters, the prototype was changed accordingly. A brief overview of the prototype is given in this paper.

The TAU schematic consists of a fixed I column, made from steel, a moving platform, and three kinematic chains $i = 1, 2, 3$, where the two chains $i = 1, 2$ are symmetrical, while the third chain $i = 3$ is asymmetrical. These three chains have two active revolute joints with angles $\theta_{ij}$, where $i = 1, 2$. Furthermore, the two symmetrical chains have two passive universal joints with angles $\phi_{ik}$ where $k = 4$, while the third chain has a passive revolute joint with angle $\phi_{31}$. The three kinematic chains connect the base coordinate $N$ to the moving platform.

The size of the prototype is $250 \times 250 \times 300$ mm. Six Maxon [98] DC motors (model-339152, RE 25 mm, Graphite Brushes, 20 watt) coupled with a HEDL 5540 encoder with a resolution of 500 counts per revolution along with 4-Q-DC Servo Amplifier were selected. Three of the motors with rotation angles

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Figure 4.1: (a) Physical prototype, and (b) schematic of 6-DOF haptic device.
4.2. THE TAU HAPTIC DEVICE

\[ \theta_{11}, \theta_{21}, \theta_{31} \] are fixed to the I column, while the motors with \[ \theta_{12}, \theta_{22}, \theta_{32} \] are attached to \[ \theta_{11}, \theta_{21}, \theta_{31} \] through a kinematic link close to the I column, thus reducing the moving inertia of the device. The active and proximal links with length \( L_1 \) and \( L_2 \), respectively, are made of carbon fiber reinforced polymer, while the platform is made from ABS plastic. Therefore, the overall moving weight and inertia of the device are small.

4.2.1 Transmission system

A cable transmission mechanism with a pulley was used for the gear ratio, as shown in Figure 4.3, which has a small contact area as compared to the transmission with a linear guideway in a 6-PSU joint-based configuration like a Stewart platform [99]. A similar cable transmission mechanism is also used in the Phantom haptic device [100] to make it back-drivable. This characteristic improves the transparency of the overall haptic system and simplifies the control of the device.

4.2.2 Spherical joint design

The proposed parallel mechanism has five spherical joints. However, a conventional ball-and-socket type spherical joint has rotational limitations and large friction. Therefore, it is necessary to design a spherical joint that allows for the largest possible rotations with less friction. A combination of universal and revolute joints was used to provide rotations in 3-DOF.
4.2.3 Model development and analysis based on the TAU haptic device

The TAU haptic device was developed during this project, wherein the knowledge of kinematic modeling and optimization of the Ares device was further developed and applied during the design of this device. In this thesis work, the device was used for developing kinematic, dynamic and stiffness models that were used during the development of the RDO approach described in section 3.1. It has also been used in the formulation of the model-based and simulation-driven design approach for haptic devices.

4.2.4 Performance evaluation of the TAU haptic device

An evaluation of the main characteristics of the TAU haptic device has been made in order to investigate how well the stated requirements in Chapter 1 have been fulfilled.

Workspace of a 6-DOF TAU haptic device

The physical prototype of a 6-DOF TAU haptic device was developed based on the optimum numerical values of the design parameters of [97]. The reachable workspace based on these design parameters is shown in Figure 4.4 and is free from singularities within that space.

Force/torque capability

In order to measure the force and torque capability of the developed prototype, we used the force/torque estimation technique described in Chapter 3. The estimated maximum forces/torques capabilities at TCP are shown in Table
4.2. THE TAU HAPTIC DEVICE

4.1. The peak forces and torques capabilities of the device, measured at each corner of the cube within the workspace shown in Figure 4.4, are fulfilling the stated force and torque requirements in Chapter 1.

Table 4.1: Force/torque capability of a 6-DOF TAU haptic device.

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<td>3</td>
<td>56.8</td>
<td>56.2</td>
<td>61.2</td>
<td>1.4</td>
<td>1.34</td>
<td>1.39</td>
</tr>
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<td>4</td>
<td>55.4</td>
<td>53.8</td>
<td>60.0</td>
<td>1.29</td>
<td>1.21</td>
<td>1.11</td>
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<tr>
<td>5</td>
<td>52.5</td>
<td>49.1</td>
<td>54.6</td>
<td>1.18</td>
<td>1.24</td>
<td>1.09</td>
</tr>
<tr>
<td>6</td>
<td>53.0</td>
<td>50.2</td>
<td>53.5</td>
<td>1.13</td>
<td>1.12</td>
<td>1.23</td>
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<tr>
<td>7</td>
<td>52.3</td>
<td>53.9</td>
<td>52.8</td>
<td>1.04</td>
<td>1.21</td>
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<td>1.23</td>
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<tr>
<td>9</td>
<td>49.98</td>
<td>51.7</td>
<td>52.9</td>
<td>1.13</td>
<td>1.31</td>
<td>1.4</td>
</tr>
</tbody>
</table>

**Stiffness capability**

In order to verify the stiffness of the developed device, the TCP of 6-DOF TAU haptic device was positioned at the center (point 0, nominal position) and at eight corner points, 1-8, of a cube of 50 × 50 × 50 mm within the reachable workspace of the haptic device, as shown in Figure 4.5. The inverse kinematic model was used to calculate the active joint angles for the required position of TCP. At each position the deflection was measured for some given loads and an average stiffness was calculated.

4.2.5 Performance characteristics

The performance characteristics of the developed TAU 6-DOF haptic device are summarized in Table 4.2.
Figure 4.5: Stiffness measurement of a 6-DOF TAU haptic device.

Table 4.2: Performance characteristics of a 6-DOF TAU haptic device and mapping between requirements.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Required values</th>
<th>Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOF</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Device footprint [mm]</td>
<td>250 × 25 × 300</td>
<td>250 × 25 × 300</td>
</tr>
<tr>
<td>Workspace</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Translation [mm]</td>
<td>50 × 50 × 50</td>
<td>70 × 80 × 100</td>
</tr>
<tr>
<td>Roll</td>
<td>±40°</td>
<td>±45°</td>
</tr>
<tr>
<td>Pitch</td>
<td>±40°</td>
<td>±45°</td>
</tr>
<tr>
<td>Yaw</td>
<td>±40°</td>
<td>±45°</td>
</tr>
<tr>
<td>Minimum stiffness [N/mm]</td>
<td>50 (x)</td>
<td>60 (x)</td>
</tr>
<tr>
<td></td>
<td>50 (y)</td>
<td>70 (y)</td>
</tr>
<tr>
<td></td>
<td>50 (z)</td>
<td>55 (z)</td>
</tr>
<tr>
<td>Maximum force [N]</td>
<td>-</td>
<td>62 (x)</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>57 (y)</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>48 (z)</td>
</tr>
<tr>
<td>Continuous force [N]</td>
<td>-</td>
<td>35</td>
</tr>
<tr>
<td>Sampling time [ms]</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

In summary, the stated requirements given in Chapter 1 on a haptic device for surgical applications with interactions with hard tissue have been fulfilled by the developed TAU device.
4.3 Chapter summary

This chapter presents the physically realized haptic devices that have been utilized in this thesis work. Firstly, the Ares 6-DOF haptic device is briefly described along with the developed models and research activities. Thereafter, the TAU 6-DOF haptic device, which is realized based on the research results in this project, is described. The developed models and proposed methods based on this device are given, and finally a performance evaluation of the characteristics of the TAU haptic device is given.
Chapter 5

Summary of appended papers

This chapter gives a brief review of the appended papers.

5.1 Paper A: a model-based and simulation-driven methodology for design of haptic devices

In this paper a systematic step-by-step model-based and simulation-driven design methodology has been developed for high precision and reliable haptic devices. Design of these devices is based on functional and performance requirements, such devices as high stiffness, low Inertia, large workspace; high manipulability, low friction, high transparency, as well as they must satisfy cost constraints. These requirements are conflicting which ask for a systematic usage of kinematic, dynamic, stiffness, friction and control models.

The methodology is based on V-model along with a stage-gate model, and evaluated through a test case where a haptic device, based on a Stewart platform, is designed and realized as a surgical simulator for training on hard tissues including bone and teeth. The objective of the presented approach is to minimize technical risks by dividing the product development process from abstract ideas to realization of the physical product into a sequence of decomposition stages with go/no-go/wait decision at each stage.

In the model-based and simulation-driven design approach, the design starts from an abstract top-level model, which is extended via stepwise refinements through a design space exploration phase into a complete realization of the system. The transparency performance of the device was improved with a friction compensation strategy. We can conclude both from simulations and results from physical experiments that the performance of the designed haptic device satisfies the stated requirements. Experiences from this case indicate that the methodology is capable of supporting effective and efficient development of high performing haptic devices.
5.2 Paper B: a stiffness modeling methodology for simulation-driven design of haptic devices

This work proposes a new methodology for creating an analytical and compact model for quasi-static stiffness analysis of a haptic device, which considers the stiffness of an actuation system, flexible links and passive joints. For the modeling of passive joints, a Hertzian contact model is introduced for both spherical and universal joints, and a simply supported beam model for universal joints. The verification and validation process is presented as a systematic guideline to evaluate the stiffness parameters using both parametric FEM modeling and physical experiments. Pre-loading has been used to consider the clearances and possible assembling errors during manufacturing. A haptic device based on a Stewart platform is used as an example to illustrate the modeling and validation methodology.

The approach used in this methodology is to start with a simplified analytical model, which is verified by a simplified FEM model in an iterative way until these two models give the same results. Thereafter, a simplified physical experiment is made to validate the analytical model. If the difference between the analytical and experimental results is not acceptable, that is it does not validate the analytical model, a more detailed analytical model must be developed. For the detailed analytical model the passive joints and actuation system are also included. This is then verified with a detailed FEM model with a corresponding detailing level in the same way as for the simplified model. Thereafter, this detailed analytical model is validated by means of a detailed physical experiment. After validating the proposed model, a sensitivity analysis is performed to map the variation of static stiffness in the workspace. In these maps, the stiffness is visualized as a function of the generalized coordinates of the workspace.

5.3 Paper C: an optimization approach towards a robust design of 6-DOF haptic devices

In this paper a robust design optimization approach is proposed for the design of haptic devices. The objective is to find optimal numerical values for a set of design parameters of haptic devices, which enable to its performance less sensitive to parameters variations and allows active trade-off decisions between device-performance variations and parameter tolerances.

The presented approach is verified through a test case to design a 6-DOF haptic device based on TAU configuration to maximize its kinematic, dynamic, and kinetostatic performance indices of a 6-DOF haptic device while minimizing its sensitivity to variations in manufacturing tolerances. These indices were defined through kinematic, dynamic, and stiffness models. During design evaluation global indices were defined such as workspace volume,
quasi-static torque requirements of the actuators, kinematic isotropy, dynamic isotropy, stiffness isotropy, and natural frequency of the device.

A new approach used to normalize the performance indices to find the minimum and maximum performance indices within the bounds of the design parameters using Monte Carlo Simulations (MCS). For design optimization, a new hybrid optimization approach was used, that combines GA and MCS including a robustness criterion for the 6-sigma principle. The effectiveness of the proposed approach is verified through a comparative analysis with a deterministic design optimization, it has been shown that the proposed approach can find the numerical values of the design parameters that are both optimal and robust (i.e., less sensitive to variation and thus to uncertainties in the design parameters). Further on a set of optimum tolerances is determined that minimizes manufacturing cost and also satisfies the allowed variations in the performance indices. The presented approach can thus enable the designer to evaluate trade-offs between allowed performance variations and tolerance cost.

5.4 Paper D: evaluation of friction models for haptic devices

In this paper the classical old models like Dahl, LuGre and more recent advanced models like Generalized Maxwell slip model (GMS), the smooth Generalized Maxwell slip model (SGMS) and the Differential Algebraic Multistate (DAM) friction models have been investigated to determine how these models are suited for performance simulation and control of a 6-DOF haptic device.

To evaluate the friction models, we use criterion based on: fidelity to predict realistic friction phenomena, easiness to implementation and easiness to estimate model parameters for online parameter estimation. These models are evaluated both numerically and experimentally with an existing 6-DOF haptic device that is based on a Stewart platform.

In order to evaluate how well these models can compensate for friction, a model-based feedback friction compensation strategy along with a PID controller was used for position tracking accuracy. The accuracies of the friction compensation models were examined separately for both low-velocity and high-velocity motions of the system. To evaluate these models, we used criteria based on fidelity to predict realistic friction phenomena, ease of implementation, computational efficiency and ease of estimating the model parameters. Experimental results show that friction compensated with GMS, S-GMS and DAM models give better accuracy in terms of standard deviation, Root Mean Square Error, and maximum error between a reference and measured trajectory. Based on the criteria of fidelity, ease of implementation and ease of estimating model parameters, the S-GMS model, which represents a smooth transition between sliding and pre-sliding regimes through an analytical set of differential equations, is suggested.
5.5 Paper E: model-based control strategy for 6-DOF haptic devices

In this work, a new model-based control strategy is proposed for improving transparency and fidelity of force/torque feedback from a 6-DOF haptic device used for hard tissues interactions. The presented approach is evaluated experimentally with an existing 6-DOF haptic device that is based on a Stewart platform. The model-based design is driven through dynamic, stiffness and friction models in order to compensate inertia, gravitational forces, elastic deformations, and friction effects in the active joints. Parameters of the 6-DOF haptic device were identified using a new approach. The effectiveness of the approach is verified in free space and while interacting with the virtual object. The comparison is made between force/torque generated and force/torque estimated using sensor-less force/torque estimation using recursive least squares estimation with exponential forgetting. The experimental results show that the proposed approach can increase transparency of the haptic devices, thereby increasing the realism of the simulation.
Chapter 6

Discussion, conclusions and future work

This chapter gives a brief discussion, conclusions and contributions of this work along with an outline of promising future research directions enabled by this work.

6.1 Discussion

The training of a surgeon is a complex and multi-dimensional process particularly in the case of hard tissues like bone and dental procedures. Simulators will create new training opportunities for surgical procedures, which are impossible to train with traditional methods. Moving training for surgical procedures from the operating room to a simulator will offer considerable economic advantages. In this context, a haptic device is one of the key components to enable realistic force/torque feedback in a virtual environment. Development of a haptic device for this type of application is a challenging task because of the multi-criteria design consideration and a successful design requires that it is able to provide a sufficient level of realistic feedback.

The focus of this thesis work has been to provide a realistic force/torque feedback from the virtual environment via a haptic device. This has included development of methods on a high level such as the model-based and simulation driven design approach as well as a more specific level such as friction estimation and compensation.

During this work, which is dealing with design and development of physical products it has been a great advantage to have prototypes to use as test cases for model development as well as for experimental testing. In this work two physical 6-DOF haptic devices have been used for development and testing of theories and methods. Having access to two prototypes, being developed from the same set of requirements has also been used to show and claim that the results developed in this work can be generalized.
6.2 Conclusions

The overall research objective in this thesis is to find a methodology that can support the development of haptic devices with realistic force/torque feedback from the virtual environment. This objective is addressed through the development of a model-based and simulation-driven methodology for the design of haptic devices (Paper A). This overall objective was divided into more specific research questions, which are answered below.

- **Q1**: How to accurately estimate stiffness of a 6-DOF haptic device through an analytical model, which is compact and can be used in real-time control?

  A stiffness modeling methodology has been developed to create an analytically compact and computationally efficient (Paper C) stiffness model of a 6-DOF haptic device. This model is obtained in a step-by-step modeling manner starting with a simplified model considering the stiffness of the compliant element within the system. It also considers the stiffness of the actuation system, linear guideways, proximal links, and passive joints. The force acting at the TCP of the platform is decomposed into individual link forces, thereafter individual link deflections are computed from the link stiffness properties. Finally, all these displacements are transformed and added to obtain the final global compliance matrix.

- **Q2**: How to find a robust optimum design of haptic devices, whose performances are less sensitive to variations in manufacturing tolerances?

  A hybrid design optimization approach has been developed, which combines a genetic algorithm (GA) and Monte Carlo simulation (MCS), and can find the numerical values of the design parameters that are both optimal and robust (i.e., less sensitive to variation and thus to uncertainties in the design parameters) (Paper B).

- **Q3**: How to estimate friction in haptic devices that can mimic realistic behavior and be used in real-time control?

  Different friction models like classical old models such as Dahl, LuGre and more recently advanced models like Generalized Maxwell slip model (GMS), the smooth Generalized Maxwell slip model (S-GMS) and the Differential Algebraic Multistate (DAM) friction models have been investigated to determine if these models are suited for performance simulation and control of a 6-DOF haptic device (Paper D). These models are evaluated both numerically and experimentally with an existing 6-DOF haptic device that is based on a Stewart platform. Experimental results show that friction compensated with GMS, S-GMS and DAM models give better accuracy in terms of standard deviation, Root Mean Squared Error, and maximum error between a reference and measured trajectory.
Based on the criteria of fidelity, ease of implementation and ease of estimating model parameters, the S-GMS model, which represents a smooth transition between sliding and pre-sliding regimes through an analytical set of differential equations, is suggested.

- **Q4: How to evaluate force/torque capability of a haptic device without a force/torque sensor?**

  The developed approach evaluates the force/torque capability of the device by estimating a vector of force/torque of six degrees in x-, y- and z-directions using a linearized form of a dynamic equation along with least squares estimation with exponential forgetting.

- **Q5: How to develop a control strategy that can be used to compensate for unwanted effects and maximize the transparency of a haptic device?**

  A model-based control strategy has been developed that compensates for the natural dynamics of the device, friction between joints, gravity of platform, and elastic deformation (Paper E). The developed approach is based on a closed-loop impedance control (CLIC) with model-based compensation and an estimated force/torque feedback.

### 6.3 Contributions

This thesis makes the following key contributions to the design of haptic devices used for interaction with hard tissues.

- A model-based and simulation-driven design methodology is developed, where one starts from an abstract, top-level model that is extended via stepwise refinements and design space exploration into a detailed and integrated systems model that can be physically realized.

- A methodology for the development of an analytical stiffness model of a 6-DOF haptic device, which is compact, can capture realistic stiffness and is computationally efficient to be used in real-time stiffness compensation of elastic deformation.

- An optimization approach is presented towards a robust design of 6-DOF haptic devices that maximize the kinematic, dynamic, and kineto-static performances of a 6-DOF haptic device, while minimizing its sensitivity to variations in manufacturing tolerances.

- A cost-effective approach is presented for force/torque feedback control using force/torque estimated through a recursive least squares estimation.

- A model-based control strategy has been proposed based on a CLIC with model-based compensation in order to improve the transparency and fidelity of force/torque feedback of a 6-DOF haptic device.
6.4 Future work

Future research can be directed into a number of interesting areas, which can extend this thesis work, for example:

- Stability of control system.
- Evaluation of velocity and acceleration capability of the TAU haptic device.
- Face validation study of 6-DOF TAU haptic device.
- Backlash compensation in joints.
- Compensation for passive joints friction.
- Evaluation of the proposed control strategy in Sim-Mechanics.
- Verification and validation of the proposed control strategy through a force/torque sensor.
References


[82] M. Honegger, A. Codourey, and E. Burdet, “Adaptive control of the hexaglide, a 6 dof parallel manipulator,” in Robotics and Automation,

friction models for haptic devices,” in In proceeding of: DSCC 2013
ASME Dynamic Systems and Control Conference October 21-23, 2013,
Stanford university, Munger Centre, Palo Alto, CA, USA.

friction model suited for gradient-based friction state and parameter es-
timation,” Mechatronics, IEEE/ASME Transactions on, vol. PP, no. 99,
pp. 1–10, 2013.

with robot deformation compensation,” in Intelligent Robots and Sys-

[86] M. J. Puerto, E. Sanchez, and J. J. Gil, “Control strategies applied to
kinesthetic haptic devices,” in Robotic Intelligence in Informationally
Structured Space, 2009. RIISS’09. IEEE Workshop on. IEEE, 2009,
pp. 137–144.

to virtual reality,” Control Systems Technology, IEEE Transactions on,

[88] J. J. Gil and E. Sanchez, “Control algorithms for haptic interaction and
modifying the dynamical behavior of the interface,” in 2nd international

[89] M. Van Damme, P. Beyl, B. Vanderborght, V. Grosu, R. Van Ham,
I. Vanderniepen, A. Matthys, and D. Lefeber, “Estimating robot end-
effector force from noisy actuator torque measurements,” in Robotics and
Automation (ICRA), 2011 IEEE International Conference on. IEEE,
2011, pp. 1108–1113.

[90] U. Sellgren, “Simulation-driven design: motives, means, and opportuni-

[91] J. F. Broeink, Y. Ni, and M. A. Groothuis, “On model-driven design of
robot software using co-simulation,” SIMPAR, Workshop on Simulation

[92] Rivin, E.I, Stiffness and Damping in Mechanical Design. New York:

com


A model-based and simulation-driven methodology for design of haptic devices

Aftab Ahmad, Kjell Andersson and Ulf Sellgren

Journal of Mechatronics, Jan 2014.
A stiffness modeling methodology for simulation-driven design of haptic devices

Aftab Ahmad, Kjell Andersson, Ulf Sellgren and Suleman Khan

An optimization approach towards a robust design of 6-DOF haptic devices

Aftab Ahmad, Kjell Andersson and Ulf Sellgren

Submitted to Journal of Mechanical Design, Jan 2014.
Evaluation of friction models for haptic devices

Aftab Ahmad, Kjell Andersson, Ulf Sellgren, and Max Boegli

In proceeding of DSCC 2013
ASME Dynamic Systems and Control Conference
October 21-23, 2013, Stanford university,
Munger Centre, Palo Alto, CA, USA.
Model-based control strategy for 6-DOF haptic devices

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To be submitted to IEEE Transaction on Robotics.