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Model-based design of haptic devices

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| <i>Abstract</i> <p>Efficient engineering design and development of high precision and reliable surgical simulators, like haptic devices for surgical training benefits from model-based and simulation driven design. The complexity of the design space, multi-domains, multi-criteria requirements and multi-physics character of the behavior of such a product ask for a model based systematic approach for creating and validating compact and computationally efficient simulation models to be used for the design process.</p> <p>The research presented in this thesis describes a model-based design approach towards the design of haptic devices for simulation of surgical procedures, in case of hard tissues such as bone or teeth milling. The proposed approach is applied to a new haptic device based on TAU configuration.</p> <p>The main contributions of this thesis are:</p> <ul style="list-style-type: none">• Development and verification of kinematic and dynamic models of the TAU haptic device.• Multi-objective optimization (MOO) approach for optimum design of the TAU haptic device by optimizing kinematic performance indices, like workspace volume, kinematic isotropy and torque requirement of actuators.• A methodology for creating an analytical and compact model of the quasi-static stiffness of haptic devices, which considers the stiffness of; actuation system; flexible links and passive joints. | | | |
| <i>Keywords</i> Haptic device, model-based design, stiffness | | <i>Language</i> English | |

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Aftab Ahmad Stockholm, June 2012

Contents

| | |
|--|-----------|
| Acknowledgements | v |
| Contents | vii |
| List of appended publications | ix |
| Other publications | xi |
| 1 Introduction | 1 |
| 1.1 Background | 1 |
| 1.2 Problem description | 2 |
| 1.3 Research objective and questions | 4 |
| 1.4 Research approach | 4 |
| 1.5 Delimitation | 5 |
| 1.6 Thesis outline | 5 |
| 2 State of the art | 7 |
| 2.1 Serial, parallel and hybrid haptic devices | 8 |
| 2.2 Optimization | 9 |
| 2.3 Stiffness modelling | 10 |
| 3 Model-based design | 11 |
| 3.1 Degrees of freedom | 12 |
| 3.2 Workspace | 12 |
| 3.2.1 Kinematic model | 13 |
| 3.2.2 Workspace analysis | 15 |
| 3.3 Multi-objective design optimization | 17 |
| 3.3.1 Optimization objectives | 19 |
| 3.4 Dynamic model | 20 |
| 3.4.1 Lagrange equation in joint space | 20 |
| 3.5 Stiffness model | 21 |
| 3.6 Model verification | 23 |
| 3.6.1 Kinematic model | 24 |
| 3.6.2 Dynamic model | 24 |
| 3.6.3 Stiffness model | 24 |

| | |
|--|-----------|
| 4 Summary of appended papers | 29 |
| 4.1 Paper A: Kinematics and dynamics of a novel 6-DOF TAU haptic device | 29 |
| 4.2 Paper B: Design Optimization of the TAU haptic device | 29 |
| 4.3 Paper C: Stiffness modeling methodology for simulation-driven design of haptic devices | 30 |
| 5 Discussion, conclusions and future work | 31 |
| 5.1 Discussion | 31 |
| 5.2 Conclusions | 32 |
| 5.3 Future work | 33 |
| References | 35 |
| Paper A Kinematics and dynamics of a novel 6-DOF TAU haptic device | 43 |
| Paper B Design optimization of the TAU haptic device | 55 |
| Paper C Stiffness modeling methodology for simulation-driven design of haptic devices | 67 |

List of appended publications

- **Paper A**

Ahmad, A.; Khan, S.; Andersson, K.; “Kinematics and dynamics of a novel 6-DOF TAU haptic device”, IEEE International Conference on Mechatronics (ICM), 2011, pp.719-724, 13-15 April 2011.

Aftab developed the kinematic and dynamic models and the verifications of these models, Suleman and Kjell provided feedback and correction.

- **Paper B**

Khan, S.; Ahmad, A.; Andersson, K.; “Design optimization of the TAU haptic device”, 3rd International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2011, pp.1-8, 5-7 Oct. 2011.

Suleman and Aftab developed the optimization approach for the TAU haptic device and Kjell provided feedback and correction.

- **Paper C**

Aftab Ahmad, Kjell Andersson, Ulf Sellgren and Suleman Khan, “A stiffness modeling methodology for simulation-driven design of haptic devices”, submitted to Journal of Engineering with Computers.

Aftab developed the stiffness model, developed a methodology for stiffness evaluation with Kjell and Ulf , Suleman helped in experimental verifications.

Other publications

- Ahmad, A.; Andersson, K.; Sellgren, U.; “An approach to stiffness analysis methodology for haptic devices”, 3rd International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2011, pp.1-8, 5-7 Oct. 2011.

Chapter 1

Introduction

Haptics refers to sense and manipulation through touch, which is a rapidly growing field that draws upon multidisciplinary fields like cognitive science, electrical engineering and mechanical engineering. Design of high precision and reliable surgical simulators, like haptic devices is not trivial, because of the many conflicting constraints due to multi-domain considerations. Some of the major domains are biomechanics, psychophysics, neuroscience, robot design and control, mathematical modeling and simulation, and software engineering. This thesis presents a model-based design approach to consider different models based on multi-domain design specifications.

1.1 Background

A haptic device act as a communicating bridge to reflect forces and torques to a user resulting from interactions with virtual environment or tele-operation tasks, so that human users can indirectly feel several physical sensations in real situations. The haptic device works based on haptic feedback and haptic collision detection algorithm. The haptic feedback works when manipulating the end-effector in the virtual environment; The position of the end-effector is calculated based on the measurement by position sensors on the device and conveyed to the computer. The haptic collision detection algorithm in the computer calculates the torque to 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].

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 subdivided into three main fields, such as 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 [2] particular in the case of hard tissues like bone and dental procedures. The surgical students are trained by performing operations with open surgery using a hand-held mill. These trainings are sometimes performed on real patients and in some cases on cadavers, which is questionable from both ethical and training effectiveness point of view [3]. Also training on real patients are not effective due to an unpredictable flow of patients into surgery, fewer opportunities to practice on more unique cases and cost of training [2].

The high risk of training on real patients and the high cost have motivated to research and development haptic devices and virtual reality simulators for training surgeons. 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 would offer considerable economic advantages.

In most of the medical fields, the apprenticeship models; first see, then do and then teach has been used as a traditional method for the training of surgeons. However, the usage of simulation-based systems, coupled with haptic technology, has become widespread in the medical field. After force feedback has been adapted in virtual simulations by the widely extended usage of haptic devices, the surgery simulations have provided various features, which cannot be achieved by the current classical training techniques.

Plastic models are used for surgical training of hard tissue, which can't provide the level of detail and material properties of a real system. Since repetitive usage of these artificial models is not possible, it is not cost-effective for the repetitive usage. However virtual simulation environments provide not only the possibility to use different material properties and level of details but also the ability of creating several challenging scenarios, which can be faced through real life.

Besides, by the help of virtual simulation environments we can get a better assessment on the trainee's performance. It is possible to define performance metrics for a specific surgery in simulations. For instance, during bone removal operation, simulations are able to figure out the regions which are removed when they are not visible by the user. Also it is promising to define maximum

velocities and forces for some critical anatomic regions and observe whether the user exceeded these thresholds. 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.

Considering the application context of a haptic device in orthopaedic and dental surgery, the surgeon needs to perform various tasks like cutting, milling and drilling as shown in Fig.1.1.

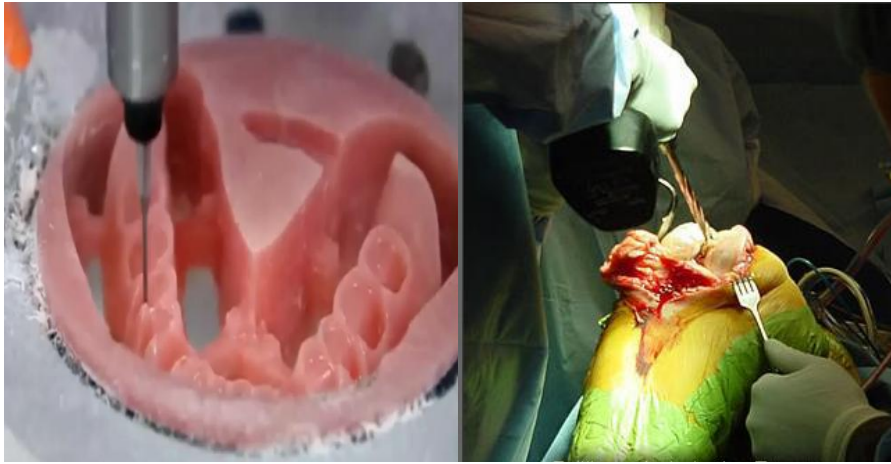


Fig. 1.1 – Typical tasks involved in a surgery of hard tissues, [4],[5].

In order to create a haptically-enabled virtual reality simulator to train surgeons for these skills, the main requirements are given in [6], which are as follows.

- Haptic feedback in 6-DOF, to allow both force and torque feedback as well 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 $\pm 40^\circ$ 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 common characteristics which are considered desirable for force/torque feedback haptic devices include according to [7]:

- Isotropic behaviour
- Large workspace
- Low effective mass
- Symmetric inertia, friction, stiffness, and resonate frequency properties thereby regularizing the device so users don't have to compensate for these forces
- Robustness
- Balanced range, resolution, and bandwidth of position sensing and force reflection
- Proper ergonomics that eliminate pain and discomfort when manipulating the haptic interface

Ideally, these design specifications can be transformed into quantitative performance measures like workspace, manipulability, payload, inertia and stiffness, where it is desirable to obtain a parametric relationship to critical design parameters of the device.

1.3 Research objective and questions

The main objective of this research has been to investigate, if model-based design can be an efficient tool to develop haptic devices that can be used for simulation of surgical procedures of hard tissues. We have chosen to focus on investigating the following questions:

- What is the available number of degrees of freedom, and what is the actual workspace of the concept being studied?
- How can we optimize haptic devices for optimal performance?
- How should we model the stiffness of haptic devices?

1.4 Research approach

Development of haptic devices is a challenging task because of the multi-criteria design consideration. The approach used in this thesis is to apply a model-based design approach on some relevant evaluations that are needed.

First, existing literature was reviewed to identify the main design requirements, which have considerable effects on the overall performance of haptic devices. Thereafter, the focus was set to evaluate some of these requirements,

e.g. workspace, isotropy and stiffness. Then the model-base approach was used and models necessary for these evaluations were developed. The approach that has been used here is shown in the top part of Fig.1.2.

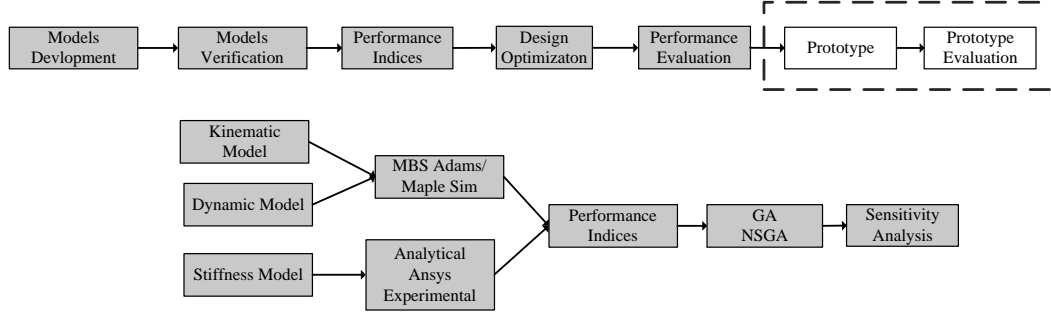


Fig. 1.2 – Research approach.

First models for the specific evaluations are developed and verified (*first two boxes*), then based on the situation these models can also be used for formulation of performance indices and later in the multi-objective optimization. The lower part of Fig.1.2 shows the models that have been developed in this work to investigate the model-base design approach.

1.5 Delimitation

The research presented in this thesis mainly focuses on model-based design of haptic devices. This has been applied on the current ongoing project at the System and Component Design division and Mechatronics division, at KTH[3],[8]. In this model-based design approach we have only considered kinematic, dynamic and stiffness models for design evaluation. The friction and joint clearance models are not treated.

1.6 Thesis outline

The thesis is organized in five chapters including the introductory chapter. The thesis is outlined as follows, chapter 2 presents the state of the art of haptic devices. Chapter 3 presents model-based design. Chapter 4 presents a summary of the appended papers and finally Chapter 5 presents discussion, conclusions and future work.

Chapter 2

State of the art

Several studies exist on design and devolvement of haptic devices in commercial and academic literature. In this chapter, a brief review is given about comparison of different haptic devices, design and modelling approaches. A comparative study has been conducted by S.Khan [8], in which he compared different haptic devices based on configuration, DOF, workspace, stiffness, maximum force and cost. Currently, there are haptic devices available in form of 2, 3, 4, 5, 6, 7-DOF reviewed by e.g. G. Gogu [7] and F.Lee [5]. F.Lee has compared different haptic devices based on serial and parallel configurations as shown in Fig.2.1 and Fig.2.2. An overview of this comparison is made in the next section.

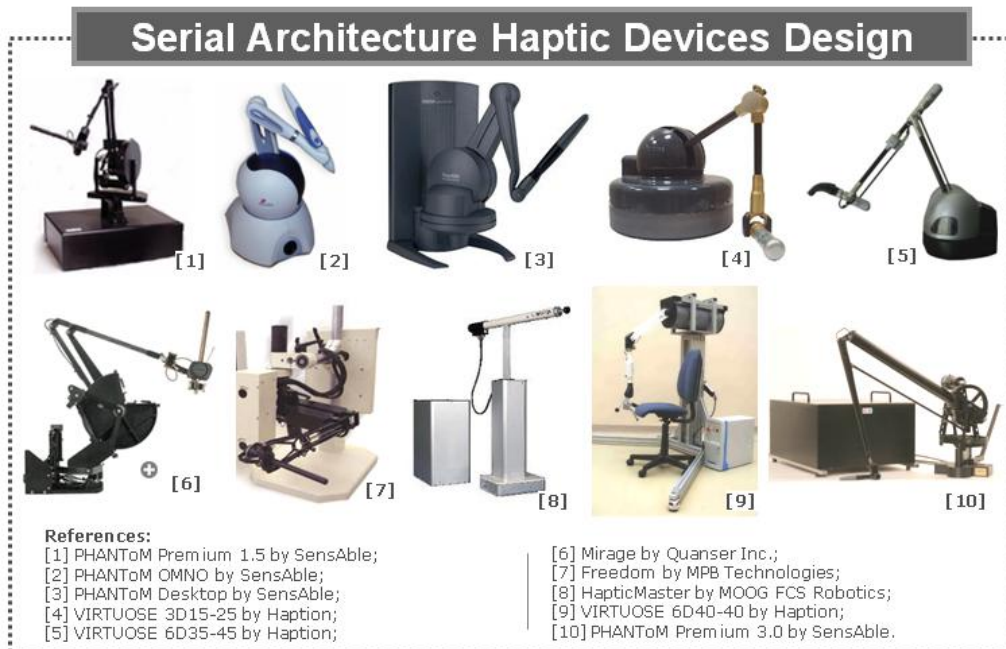


Fig. 2.1 – Haptic devices based on serial configuration [5].

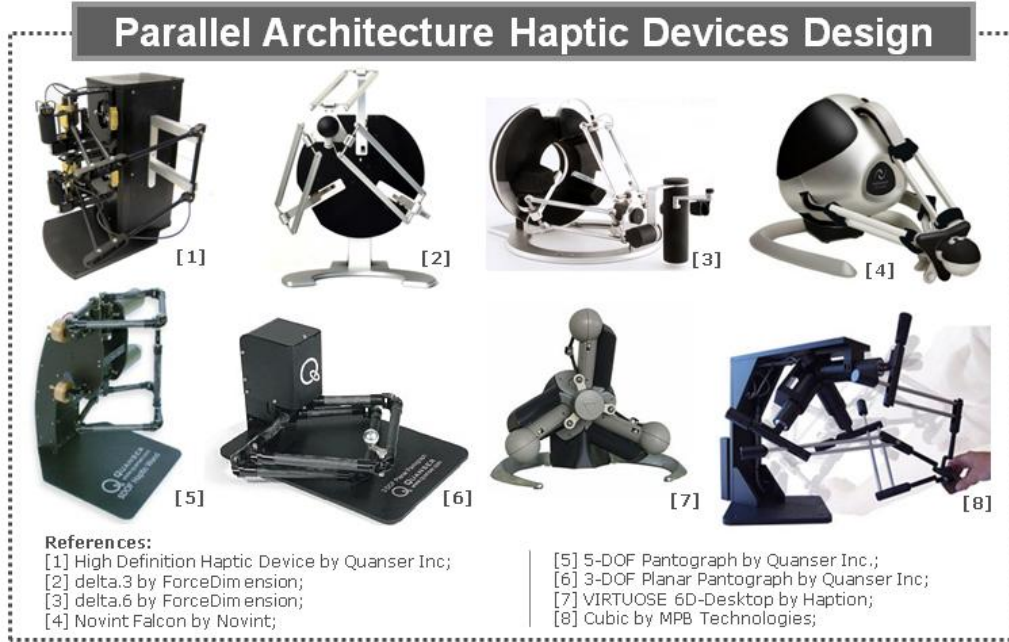


Fig. 2.2 – Haptic devices based on parallel configuration [5].

2.1 Serial, parallel and hybrid haptic devices

Serial devices adopt a design by connecting arms one by one in series by various types of joints, especially revolute and prismatic. One end of the manipulator is connected to the ground, and the other end is free to move in space. For this reason, a serial manipulator is also referred as an open-loop manipulator. Serial devices possess some advantages like 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 devices in contrast to serial one are closed-loop mechanism where the end-effector is connected to the base by at least two independent kinematic chains. Parallel devices possess high stiffness, low inertia, high rigidity and accuracy, and high payload-to-weight ratios, which enable large bandwidth transmission of forces but with some disadvantages like small workspace, possibilities of singularity due to link collision and low dexterity.

Recently, many six degrees of freedom (DOF) haptic devices have been developed, some of which have been commercialized [9]. These include serial-mechanism-based devices, such as the PHANTOM Desktop and PHANTOM Omni by SensAble technologies [10] that provide a large workspace of $160 \times 120 \times 120$ mm, with a stiffness of 2.35 N mm^{-1} and a force of 7.9 N for stiff contacts; similarly, the HAPTION [11] Virtuose 6D35-45 and Virtuose 3D15-25 provide a workspace of 450 mm and a maximum force of 35 N. These devices

provide insufficient stiffness and force/torque capacity for stiff contacts and are not suitable in case of interaction with hard tissues. Many researchers have proposed parallel-mechanism based haptic devices due to their high stiffness and accuracy. Six-DOF Delta and Omega haptic devices from Force Dimension [12], a modified Delta device and Haptic master developed by Tsumaki et al. [13], a 6-URS parallel haptic device developed by J.M. Sabater et al. [14], and a new 6-DOF haptic device developed at CEA-LIST [15], all for desktop applications, are some examples of parallel mechanisms. However, all these devices have the drawback of having either a small workspace or low stiffness.

Research is therefore focusing on hybrid mechanisms that combine the advantages of parallel and serial mechanisms to obtain sufficient stiffness, enough workspace, and a compact design. Hybrid devices aim to combine the best characteristics of a serial and parallel device, with large workspace, high dexterity, high stiffness and high payload-to-weight ratios and high precision. Hongliang Cui et al. [16] have worked on the kinematic analysis and error modeling of a new 3-DOF mechanism based on a serial-parallel mechanism, called 3-DOF TAU parallel robot. Zhenqi Zhu et al. [17] have developed kinematic and dynamic modeling for real-time control of TAU parallel robot. However, no effort has been made to develop the kinematics of 6-DOF TAU devices. Various models of 6-DOF TAU devices have been developed and analyzed by Khan et al. [6] to identify their best characteristics.

2.2 Optimization

The performances of these devices are highly dependent on optimum structural and geometric parameters of the device. Furthermore, numerous design aspects contribute to the performance, and an efficient design will be one that takes into account all or most of these design aspects. This is an iterative process, and an efficient design requires a lot of computational efforts and capabilities for mapping the design parameters into design criteria, and hence into a form of multi-objective design optimization problem [18]. In the optimization, multiple criteria such as, for example, workspace; kinematic performance indices like kinematic isotropy; static force transmission capability; stiffness; and dynamic performance needed to be considered [8].

Finding an optimal solution 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 to 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 [19]. 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. [20] 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) [21], approach seems a good option for multi-criteria problems due to its good convergence property and robustness. Stan et al. [22], J.H. Lee et al. [23], S.S. Lee and J.M. Lee [24], Hwang et al. [25], Raza.R et al. [26] and Khan et al. [9] have used a GA approach for the multi-criteria optimization of parallel kinematics machines and parallel haptic devices.

2.3 Stiffness modelling

Mechanical stiffness is one of the most important indicators in performance evaluation of robotic systems [27, 28, 29]. In particular, for haptic devices, where the primary target is the precise manipulation of a tool centre point, precise stiffness identification and compensation play an important role during the design process.

Stiffness analysis has been widely investigated in the literature. Several methods exist for computation of the stiffness matrix: the virtual joint method (VJM), that is often called the lumped modeling [30, 31, 32, 33, 34], finite element analysis (FEA) [34, 35, 36] and matrix structural analysis (MSA) [37, 38, 39, 40]. Uchiyama [41] has derived an analytical model for the stiffness of a compact 6-DOF haptic device based on static elastic deformation of compliance elements.

Moreover, in order to obtain a more realistic stiffness model the existing stiffness models should be complemented with more complex effects such as joint stiffness, that also degrade the positioning accuracy. When it comes to the compliance of joints, they are mostly modeled as a constant stiffness and applied only for active joints. Bonnemains et al. [42] e.g. have considered the stiffness of spherical joints in the stiffness computation and identification of kinematic machine tools.

Common to all the described modeling methods is that they all need a practical validation by means of experimental testing of a prototype. Charles Pinto et al. [43] have evaluated static stiffness mapping of their Lower Mobility Parallel Manipulator. They used pre-loading in the experimental testing to eliminate backlash in the system. In experimental testing [44], the static behavior evaluation of a robot was analyzed by norms, e.g. ANSI/RIA R15.05-1-1990 [45], ISO 9283:1998 [46], which were established for serial manipulators.

Chapter 3

Model-based design

This chapter presents a model-based design approach for design of haptic devices. The basic objective of this approach is to develop a haptic device, which has high stiffness, large workspace, high manipulability, small inertia, low friction and high transparency. The functional requirements are derived from the user and device requirements, described in section 1.2, and are the basis for generating the design concept as shown in Fig.3.1. The properties of this concept are then evaluated using a model based design, as shown on the right side of Fig.3.1. The overall objectives of the haptic device is to resemble a real situation, when manipulating objects in a remote or virtual world.

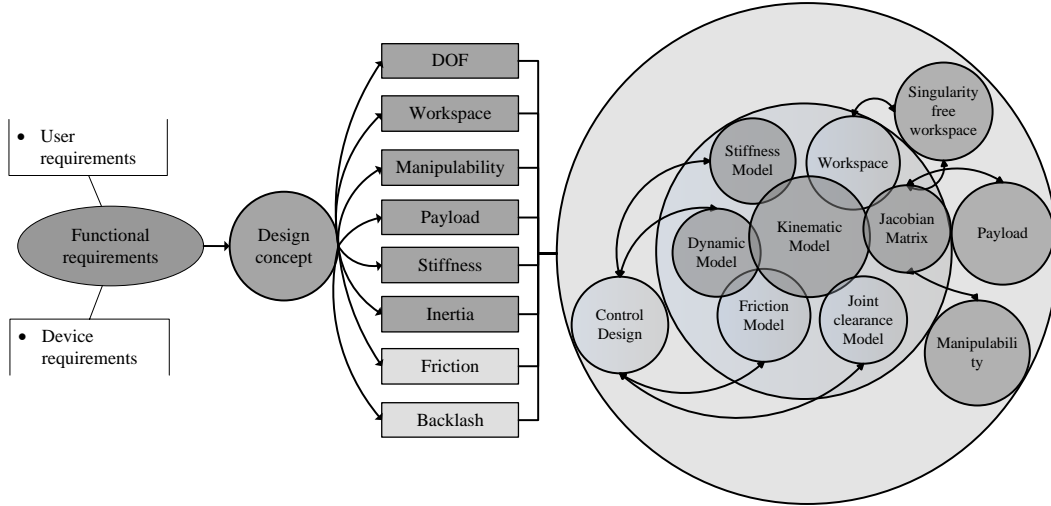


Fig. 3.1 – Dependencies between functional requirements, design concept and models needed for evaluation of product properties.

Carbone Giuseppe et al. [47] have used model-based design approach and multi-criteria requirements for multi-objectives optimization of CaPaMan (Cassino Parallel Manipulator). He considered kinematic, static, dynamic,

friction, stiffness and joint clearance models for formulating the optimization problem, but due to computational complexity, he managed to include only kinematic and stiffness models in the optimization.

Furthermore, numerous design aspects/attributes contribute to the performance of haptic devices, like large workspace, high manipulability/isotropy, torque requirements on an actuator for unit force/torque applied, high stiffness for precise positioning, low inertia and low resonant frequency. This turns out to be a multi-criteria problem, which is addressed by a model-based design approach for evaluating concept properties. In Fig.3.1, a selection of these required properties and models needed to evaluate them are illustrated.

The main requirements considered in this thesis are DOF, workspace, manipulability/isotropy, torque requirements on actuators, structural stiffness and dynamics. The models which are needed to evaluate these requirements are the kinematic, stiffness and dynamic models. The friction and joint clearance models are not considered in this thesis. Some of these models are mutually dependent, thus leading to a computationally complex evaluation. In the coming sections a case study is used to illustrate the evaluation of the above discussed requirements.

3.1 Degrees of freedom

The first concern in the study of kinematics of a mechanism is the number of degrees of freedom. The degrees of freedom of a mechanism are the number of independent parameters or inputs needed to specify the configuration of the mechanism completely. The Grübler criterion was used to find the number of independent coordinates of the system by using equation (3.1).

$$F = \lambda(n - j - 1) \sum_i f_i \quad (3.1)$$

Where

F : Degrees of freedom of the mechanism.

λ : Degrees of freedom of the space in which a mechanism is intended to function.

n : Numbers of links in mechanism including fixed link.

j : No of joints in a mechanism, assuming that all the joints are binary.

f_i : Degrees of relative motion permitted by joint i .

3.2 Workspace

The workspace is one of the most important kinematic properties of manipulators, because of its impact on manipulator design and location within a workspace. Different types of workspace are defined by G. Castelli et al. [48], such as reachable workspace, dexterous workspace and constant orientation workspace. The kinematic model is the basis for the workspace analysis,

because the workspace depends upon the constraints on active and passive joints, collision avoidance between the links and platform (end effector) and kinematic singularity.

In order to take into account the above-mentioned constraints and to determine the workspace, we need a kinematic model of the device. In the coming section, the kinematic model of a new 6-DOF haptic device based on TAU configuration is presented.

3.2.1 Kinematic model

Kinematics is the basis to the analysis of any robotic system. Once this model is developed, the designer can evaluate the performance of the system. The kinematic model is the core for other dependent models like dynamic and stiffness models, etc. A schematic model of kinematics of 6-DOF TAU is shown Fig.3.2. The schematic model consist of three 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 $[\theta_{i1}, \theta_{i2}]$, Further the two symmetrical chains have two passive universal joints with angles $[\phi_{i1}, \phi_{i2}, \phi_{i3}, \phi_{i4}]$ for $i = 1, 2$, while the third chain has a passive revolute joint with angle ϕ_{31} . The kinematic model consist of two sub-models i.e., the inverse kinematic and forward kinematic model.

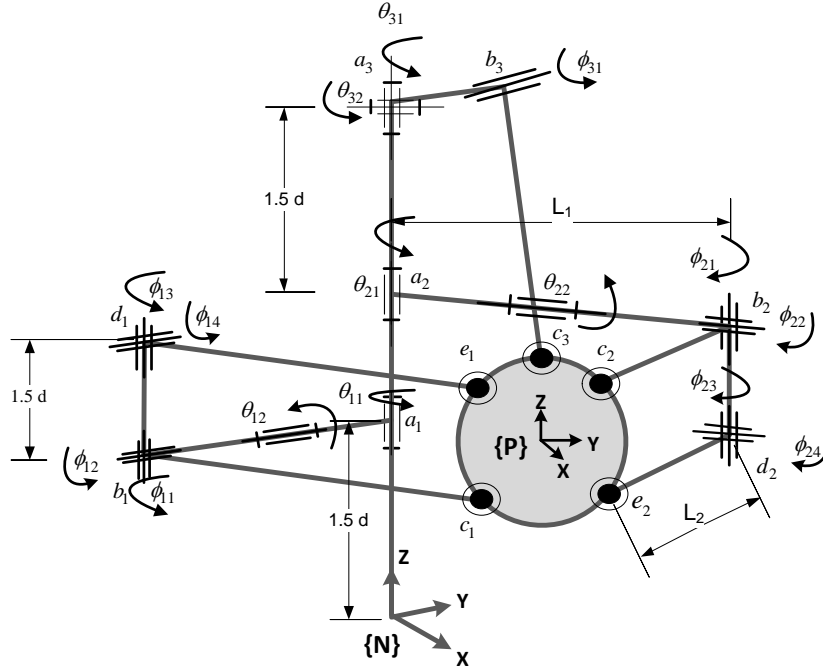


Fig. 3.2 – Schematic model of 6-DOF TAU

Inverse kinematics

The inverse kinematic problem for the proposed 6-DOF TAU configuration determines orientation of active joint angles $[\theta_{i1}, \theta_{i2}]$ and passive joint angles $[\phi_{i1}, \phi_{i2}, \phi_{i3}, \phi_{i4}]$, while the pose (position and orientation) $[p_x, p_y, p_z, \alpha, \beta, \gamma]$ of the platform are given. 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 path (a_i, b_i, c_i) and (a_i, b_i, d_i, e_i) , as given in equation (3.2) and (3.3). A detailed about formulation of these active and passive joint angles are given in (Paper A).

$$(c_{ix} - b_{ix})^2 + (c_{iy} - b_{iy})^2 + (c_{iz} - b_{iz})^2 = L_2^2 \quad (3.2)$$

$$(d_{ix} - e_{ix})^2 + (d_{iy} - e_{iy})^2 + (d_{iz} - e_{iz})^2 = L_2^2 \quad (3.3)$$

Forward kinematics

The forward kinematics problem for the proposed 6-DOF TAU configuration determines the pose $[p_x, p_y, p_z, \alpha, \beta, \gamma]$, of the platform, while the orientations (i.e., joint angles) $[\theta_{i1}, \theta_{i2}]$ with $i = 1, 2, 3$ of all actuators are given. No closed-form analytical solution is available for the forward kinematics of the 6-DOF TAU configuration, due to the complex nonlinear equations. Therefore, the Newton-Raphson numerical approximation method is used to solve the forward kinematics problem. The Newton-Raphson approximation of the solution is given by equation

$$X_{n+1} = X_n - [F'(X_n)]^{-1} F(X_n) \quad (3.4)$$

Where X_n is the initial guess value of the platform pose $[p_x, p_y, p_z, \alpha, \beta, \gamma]$, while X_{n+1} is the solution to be determined through function $F(X_n)$, and its derivative $F'(X_n)F(X_n)$ is defined separately for each kinematic chain. The functions are defined for each serial chain by differentiating the close equations (3.2) and (3.3). For each serial chain, this function is defined from joint position c_i, d_i of the platform, in case of $\theta_{i1} = f(c_{ix}, c_{iy}, c_{iz})$ and $\theta_{i2} = f(c_{ix}, c_{iy}, c_{iz}, e_{ix}, e_{iy}, e_{iz})$, so

$$\dot{\theta}_{i1} = J_{si1} \dot{c}_i, \quad J_{si1} \in 1 \times 3 \quad (3.5)$$

Where

$$J_{si1} = \begin{bmatrix} \frac{\partial F_{i1}}{\partial c_{ix}} & \frac{\partial F_{i1}}{\partial c_{iy}} & \frac{\partial F_{i1}}{\partial c_{iz}} \end{bmatrix}$$

And

$$\dot{c}_i = \begin{bmatrix} \frac{\partial c_{ix}}{\partial t} & \frac{\partial c_{iy}}{\partial t} & \frac{\partial c_{iz}}{\partial t} \end{bmatrix}^T$$

While

$$\dot{c}_i = J_{pi1} \dot{X}, \quad J_{pi1} \in 3 \times 6 \quad (3.6)$$

The element of jacobian for θ_{i1} can be find by putting equation (3.6) into (3.5) as given in equation (3.7).

$$\dot{\theta}_{i1} = J_{si1} J_{pi1} \dot{X} = J_{i1} \dot{X} \quad (3.7)$$

Here $X = [p_x, p_y, p_z, \alpha, \beta, \gamma]$ and $J_{i1} \in 1 \times 6$

The same procedure can be used for θ_{i2} as the one used for θ_{i1} , while in this case $J_{si} \in 1 \times 6$ and $J_{pi} \in 6 \times 6$, so

$$\dot{\theta}_{i2} = J_{si} J_{pi} \dot{X} = J_{i1} \dot{X} \quad (3.8)$$

$$J_{si} = \begin{bmatrix} \frac{\partial F_{i2}}{\partial c_{ix}} & \frac{\partial F_{i2}}{\partial c_{iy}} & \frac{\partial F_{i2}}{\partial c_{iz}} & \frac{\partial F_{i2}}{\partial d_{ix}} & \frac{\partial F_{i2}}{\partial d_{iy}} & \frac{\partial F_{i2}}{\partial d_{iz}} \end{bmatrix}$$

And

$$\dot{c}_i = \begin{bmatrix} \frac{\partial c_{ix}}{\partial t} & \frac{\partial c_{iy}}{\partial t} & \frac{\partial c_{iz}}{\partial t} & \frac{\partial d_{ix}}{\partial t} & \frac{\partial d_{iy}}{\partial t} & \frac{\partial d_{iz}}{\partial t} \end{bmatrix}^T$$

This is in the case when $i = 1, 2$.

In case of $i = 3$ both active joint angles are function of $\theta_{i1}, \theta_{i2} = f(c_{ix}, c_{iy}, c_{iz})$, so equation (3.7) is used to find the elements of the jacobian matrix for θ_{i1} and θ_{i2} . The jacobian of the complete system is given as

$$\dot{\theta}_i = J \dot{X}_i, \quad J \in 6 \times 6 \quad (3.9)$$

3.2.2 Workspace analysis

When we have developed the kinematic model of the selected concept that we are evaluating, we can perform a workspace analysis. A general numerical evaluation of the workspace can be deduced by formulating a suitable binary representation of a cross-section. A cross-section can be obtained with a suitable scan of the computed reachable positions and orientations, once the inverse kinematic problem has been solved as function of position and orientation of the TCP of the platform, A binary variable F_{ij} can be defined on the cross-section plane for a cross-section of the workspace as follows: if the (i,j) grid pixel includes a reachable point, then $F_{ij} = 1$; otherwise $F_{ij} = 0$, as shown in Fig.3.3.

Reachable workspace

The reachable workspace (constant orientation) describes the volume in space within which the manipulator's end effector centre point can reach. The reachable workspace is described in equation(3.10)

$$V = \int_{x_0}^x \int_{\theta_0}^{\theta} \int_{r_0}^r F_{ij} r dr d\theta dx \quad (3.10)$$

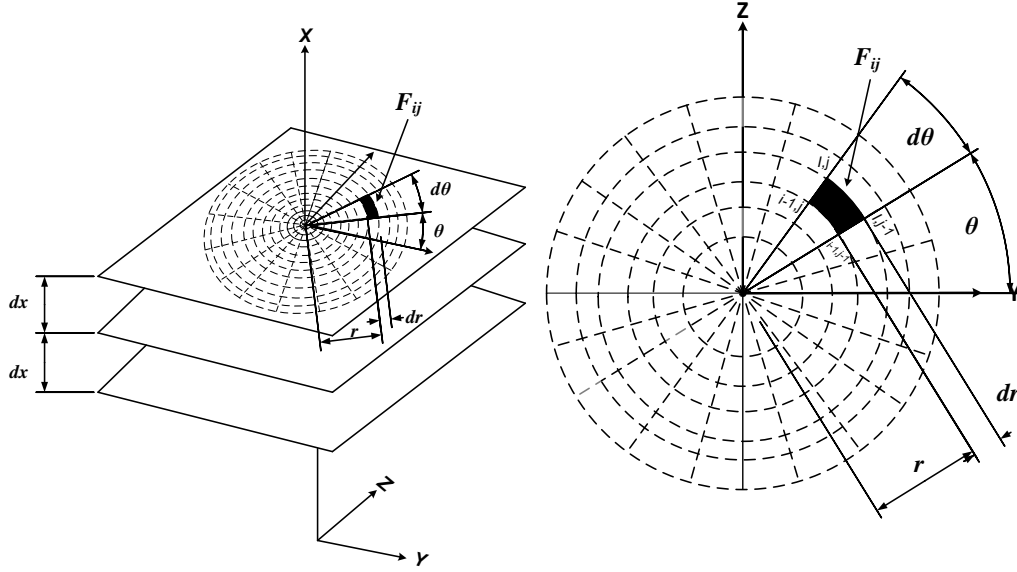


Fig. 3.3 – Workspace

where $dr = r_i - r_{i-1}$ and $d\theta = \theta_j - \theta_{j-1}$, and F_{ij} is a flag value depends the conditions given in equation(3.11)

$$F_{ij} = \begin{cases} 1 & \text{if } F_{ij} \in W(X, Y, Z) \\ 0 & \text{if } F_{ij} \notin W(X, Y, Z) \end{cases} \quad (3.11)$$

Here W is the grid points of workspace traversed by TCP with constant orientation of platform.

Dexterous workspace

The dexterous workspace is a subset of reachable workspace, which also consider orientational reachability of the workspace. It is defined as the workspace that is reachable by all the required maximum orientations at that point. To calculate dexterous workspace, the manipulator is traversed in workspace shown in Fig.3.3, and at each grid point in the workspace the prescribed rotations are applied. If any of the constraints on active or passive joints given in equation (3.12) and (3.13), or kinematic singularity given in equation (3.14) is not satisfied at any of the rotations. The grid point is not within workspace. The algorithm work by assigning binary numbers (0,1) to two flags *flag1* and *flag2*. If at each grid point both the flags are 0, the point is within the workspace, otherwise not. The dexterous workspace is calculated by the same

equation(3.10), but with the following conditions as given in equation(3.15)

$$\min(\theta_{ii}) \leq \theta_{ii} \leq \max(\theta_{ii}) \quad (3.12)$$

$$\min(\phi_{ii}) \leq \phi_{ii} \leq \max(\phi_{ii}) \quad (3.13)$$

$$\det(J) \neq 0 \quad (3.14)$$

$$F_{ij} = \begin{cases} 1 & \text{if } F_{ij} \in W(X, Y, Z, \alpha, \beta, \zeta) \\ 0 & \text{if } F_{ij} \notin W(X, Y, Z, \alpha, \beta, \zeta) \end{cases} \quad (3.15)$$

Here W is the grid points of workspace traversed by TCP with orientation of platform in X, Y, Z -directions with total of 3^n rotations at each grid point, when n is the no of rotation in one direction. An algorithm that calculates the dexterous workspace is given in Fig.3.4.

3.3 Multi-objective design optimization

As the performance of hybrid mechanisms is highly sensitive to their geometry and dimensions, design optimization is an important step in the design process. The main objective of the design optimization is to find the best compromise between kinematic performance indices like workspace, isotropy, force requirement based on the device requirements in the beginning of this chapter. Various performance requirements are mentioned, but the investigation reported in this thesis is focuses mainly on three basic performance indices, namely workspace volume; kinematic isotropy, and static torque requirements. The volume index of the device is defined using the inverse kinematic model, while the other two indices are defined on the basis of the Jacobian matrix discussed in section 3.2.1.

The workspace of a robot is a crucial criterion in comparing manipulator geometries. Reachable and dexterous workspace are used to characterize the workspace of a robot manipulator. The goals of an optimal design is to achieve the largest possible volume for both dexterous workspace and the reachable workspace, high isotropy and small static torque on the actuators. There is a close relationship between the kinematics performance and the manipulator structure. This is an iterative process, and an efficient design requires a lot of computational efforts and capabilities for mapping design parameters into design criteria, and hence turning out with a multi-objective design optimization problem. The solutions of such a problem are no dominated solutions, also called Pareto-optimal solutions. Accordingly, a multi-objective design optimization approach is proposed based on performance measures/criteria from kinematic.

```

for  $x \leftarrow x_{min}$  to  $x_{max}$ 
do {
  for  $\theta \leftarrow \theta_{min}$  to  $\theta_{max}$ 
do {
  for  $r \leftarrow r_{min}$  to  $r_{max}$ 
do {
     $y = r \cos \theta$ 
     $z = r \sin \theta$ 
     $flag1 = 0$ 
     $flag2 = 0$ 
    for  $R \leftarrow R_{min}$  to  $R_{max}$ ,  $R = [ R_x \ R_y \ R_z ]$ 
    do {
      if  $flag1 = 1$ 
      then {  $flag2 = flag1$ 
              $break$ 
            }
      else
      {
         $calculate, \theta_i$ 
        if  $\theta_i < \theta_{min} \cap \theta_i > \theta_{max}$ 
        then {  $flag1 = 1$ 
                $flag2 = flag1$ 
                $break$ 
            }
         $calculate Jacobian, J$ 
        if  $det(J = 0)$ 
        then {  $flag1 = 1$ 
                $flag2 = flag1$ 
                $break$ 
            }
        else
        {
          if  $flag1 \neq 1$ 
          then  $flag2 = 0$ 
        }
      }
    }
    if  $flag1 = 0 \cap flag2 = 0$ 
    then { The point is within the Workspace
    }
    return ( $r$ )
  }
  return ( $\theta$ )
}
return ( $x$ )

```

Fig. 3.4 – Workspace algorithm

3.3.1 Optimization objectives

The multi-objective optimization problem aims to determine the optimum geometric parameters of the TAU haptic device in order to maximize its dexterous workspace volume index VI , global isotropy index GII , and global torque requirement index $GTRI$. These indices are given in detail in (Paper B). Here, the workspace of the mechanism is discretized and the considered performance measures and constraints are evaluated and verified for each point.

For the studied TAU haptic device, we use the min-max fuzzy logic to define the objective function. The optimization problem can be formulated as to find the optimum design parameters x of TAU haptic device in order to maximize the volume VI , global isotropy index GII and minimize the torque requirement index $GTRI$ of the mechanism, subject to some design constraints on the active, passive joints and singularity, i.e when the determinant of kinematic Jacobian matrix becomes zero. Finally, a multi-criteria design objective function is defined in equation (3.16), as follows

$$GDI = \min \left[\frac{GII}{GII_m}, \frac{GTRI_m}{GTRI}, \frac{VI}{VI_m} \right] \quad (3.16)$$

where subscript m represents value of the design indices corresponding to the mid values of the input design parameters. The main idea underlying this approach is to make the indices dimensionless, to ensure that all design indices are equally active in the optimization process.

Mathematically, the problem can be written as in the form of equation (3.17):

$$\begin{aligned} & \underset{x}{\text{maximize}} && GDI(x) \\ & && \text{over } x = [L_1, L_2, R_p, d, \theta_{32}] \\ & \text{subject to} && \min(\theta_{ii}) \leq \theta_{ii} \leq \max(\theta_{ii}) \\ & && \min(\phi_{ii}) \leq \phi_{ii} \leq \max(\phi_{ii}) \\ & && x_{lb} \leq x_i \leq x_{up} \\ & && \det(J) > 0 \end{aligned} \quad (3.17)$$

where x_{lb} and x_{up} are the lower and upper bound of the design parameters x_i respectively.

Multi-objective Genetic Algorithm

Optimization of 6-DOF TAU haptic is complex, due to multi-objective, multi-constraints and an increase in the number of design parameters. A reasonable approach to such a 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. This is called a Pareto optimal solution. To find the Pareto

optimal solution, we used a multi-objective genetic algorithm (MOGA-II) [49] and non-dominated sorting based genetic algorithm (NSGA-II) [50].

Non-dominated Sorted Genetic Algorithm

The NSGA-II algorithm proposed by Deb et al. [50] is a new version of the NSGA algorithm. NSGA-II incorporates elitism and crowding distance. The population is initialized as usual. Once the population has been initialized, the population is sorted into fronts on the basis of non-domination. 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 rank (fitness) values based on the front to which they belong. Individuals in the first front are given a fitness value of 1, individuals in the second 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. The operation of NSGA-II in calculating the Pareto optimum is described in detail in [50, 51].

3.4 Dynamic model

The Lagrange method describes the dynamics of a mechanical system from the concepts of work and energy. The general equation for Lagrange dynamic formulation is

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = \tau \quad (3.18)$$

Where $L = K - P$, is the Lagrange function, K and P are the total kinetic and potential energy of the system, q_i is generalized coordinates $[p_x, p_y, p_z, \alpha, \beta, \gamma]$, and \dot{q}_i is corresponding velocity of generalized coordinates.

3.4.1 Lagrange equation in joint space

In order to derive the joint torques, we will use the transpose of the inverse of Jacobian matrix as given in equation.

$$\tau_j = J^{-T} \tau_C \quad (3.19)$$

The equation of motion that shows the torques on actuators in the joint coordinate system is expressed as

$$M(\theta)\ddot{\theta} + V(\theta, \dot{\theta}) + G(\theta) = \tau_J \quad (3.20)$$

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 and the last term $G(\theta)$ on the left side is the gravity force, while τ_J is the generalized Cartesian forces/torques at the end-effector. A detailed of formulation of dynamics equations are given in (Paper A). Furthermore

$$\dot{\theta}_i = J\dot{q}_i \text{ and}$$

$$\ddot{\theta}_i = J\ddot{q}_i + \dot{J}\dot{q}_i$$

3.5 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 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. These produced changes on geometry, due to the applied forces, are known as deformations or compliant displacements [52]. 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 to develop a generalized stiffness model of the manipulator and its evaluation with virtual (FEM analysis) and physical experiments. To develop this, a work procedure defined by the flowchart in Fig.3.5 is presented.

The procedure established by this flowchart is as follows:

The approach used in this methodology is to start with a simplified analytical model. This is compared (verified) by a simplified FEM model in an iterative way until these two models come into close agreement with results. 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, i.e. it doesn't validate the analytical model, a more detailed analytical model has to be developed.

For the detailed analytical model also the passive joints and actuation system are included. This is then verified with 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

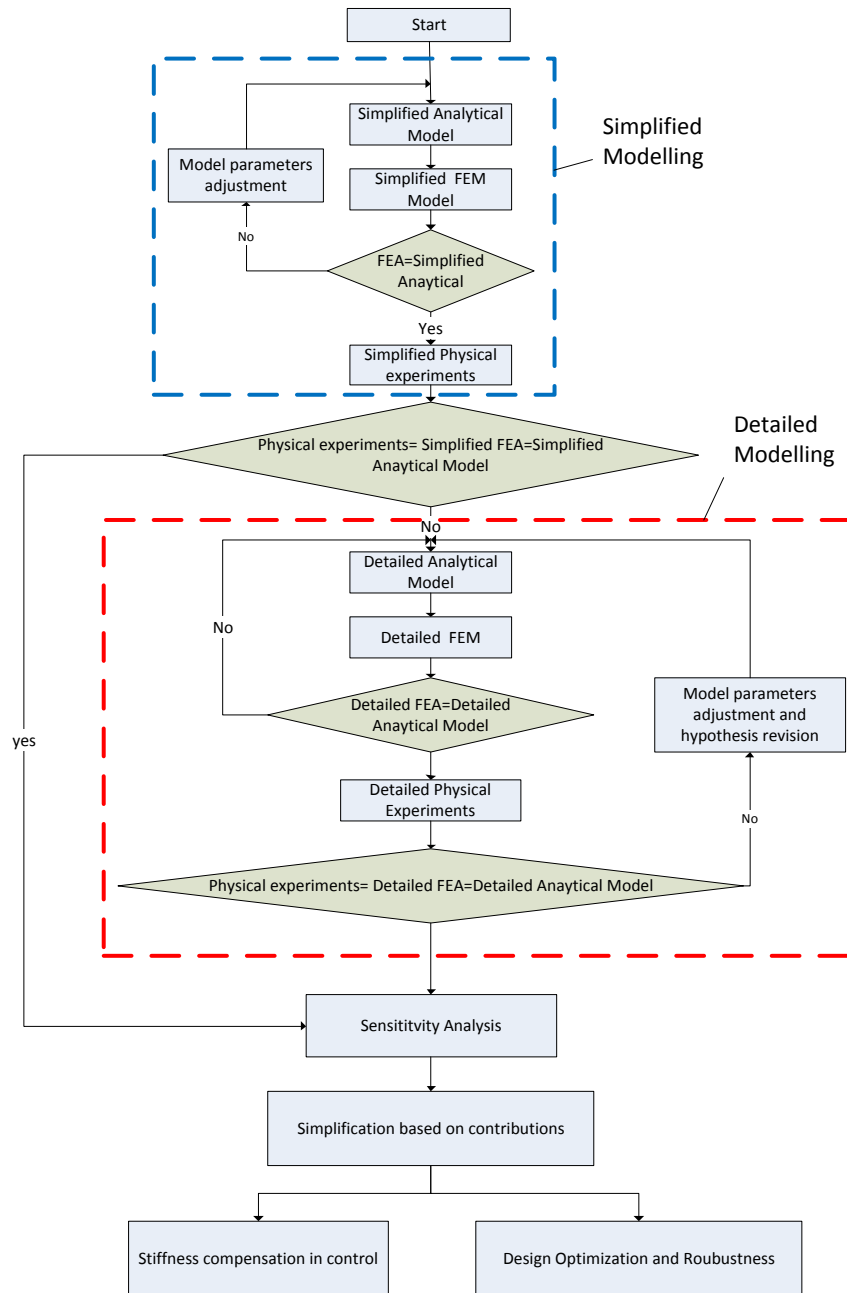


Fig. 3.5 – Stiffness modeling methodology

these maps, the engineering stiffness is visualized as a function of the generalized coordinates of the workspace. A detail description of this methodology is given in (Paper C).

A general stiffness model for N number of compliant elements serially con-

nected with each other is given in equation(3.21),

$$\begin{aligned}
 {}^0C_N &= {}^0J_{N-1}^{N-1}S_N^{N-1}J_0 + \\
 &+ {}^0_NJ_{N-1,disp}({}^0J_{N-2}^{N-2}S_{N-1}^{N-2}J_0){}_N^0J_{N-1,force} + \\
 &+ {}^0_NJ_{i,disp}({}^0J_{i-1}^{i-1}S_i^{i-1}J_0){}_0^iJ_{N,force} + \\
 &+ {}^0_NJ_{1,disp}({}^0J_1^0S_1^1J_0){}_1^0J_{1,disp}
 \end{aligned} \tag{3.21}$$

Where 0C_N is the compliance of the complete system, ${}^0J_{N-1}$ represents coordinate transformation Jacobian between local frame $N-1$ and 0, ${}_0^iJ_{N,force}$ is the force transformation Jacobian matrix which transforms the coordinate of application of the force vector from coordinate N to reference coordinate U , and ${}_N^0J_{i,disp}$ is the displacement transformation Jacobian which transforms the displacement from 0 to N . Where 0S_1 represents the compliance matrix in local frame.

3.6 Model verification

To verify the developed kinematic, dynamics and stiffness models, the first two models were verified in MapleSim [53], while the third model was verified by both FEM analysis (Ansys[54]) and physical experiments. The MapleSim model is shown in Fig.3.6.

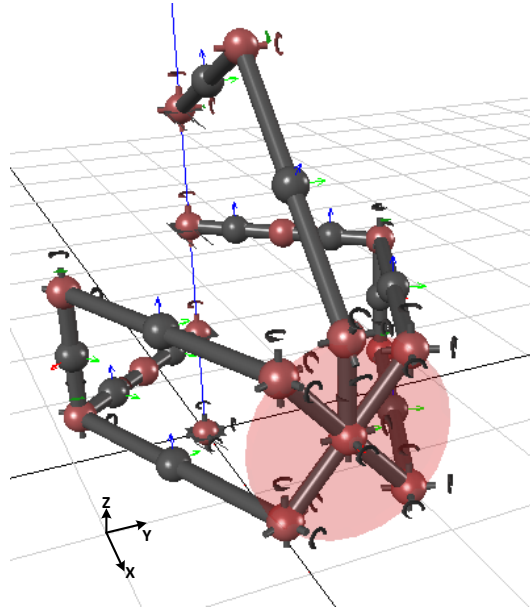


Fig. 3.6 – MapleSim model

3.6.1 Kinematic model

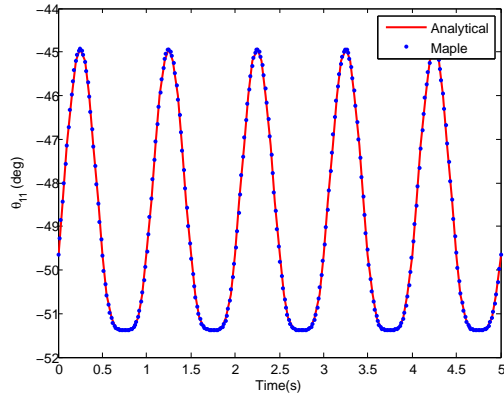
In order to validate the inverse kinematic model developed in section 3.2.1, an input trajectory of $\sin(\omega t)$ was applied in the rotational degree of freedom along the x-axis. The results from both analytical model and MapleSim model are shown in Fig.3.7. By comparing these results, we can validate the inverse kinematics calculation approach that has been presented in section 3.2.1. The results in Fig.3.7 shows that analytical model agrees with the MapleSim model, which verify the validity of the model.

3.6.2 Dynamic model

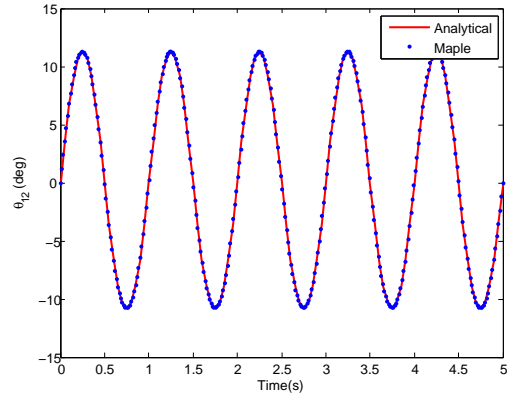
The dynamic model was verified using the same trajectory $\sin(\omega t)$ on the actuators, and the required torques on the actuators were calculated based on the analytical dynamic model of section of 3.4 and MapleSim model. The results from these analysis are shown in Fig.3.8, where we can conclude that the results from the analytical model agree the MapleSim model.

3.6.3 Stiffness model

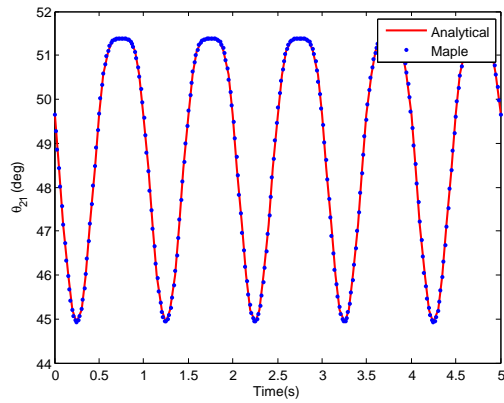
The stiffness model developed in section 3.5 is validated through simulation using Ansys and physical experiments. A detailed description about validation is given in (Paper C); some of the results are shown in Fig.3.9.



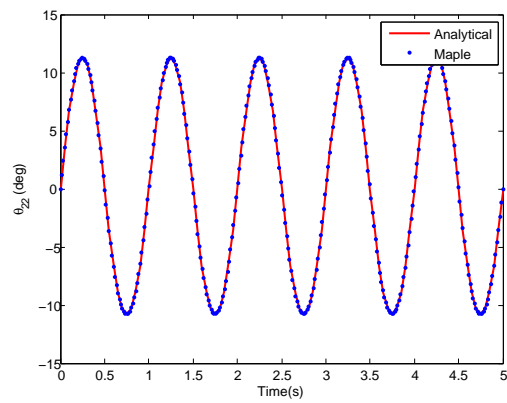
(a) Rotation of actuator 1



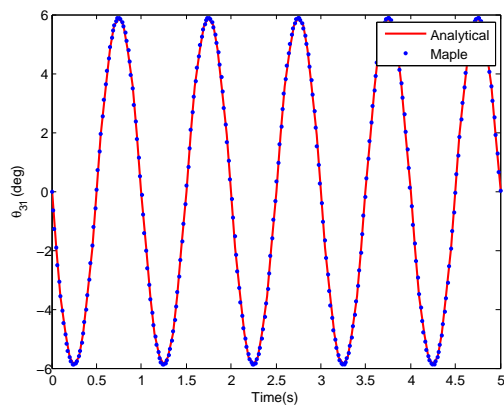
(b) Rotation of actuator 2



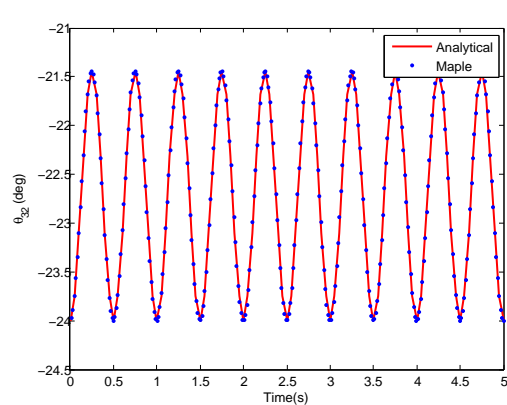
(c) Rotation of actuator 3



(d) Rotation of actuator 4



(e) Rotation of actuator 5



(f) Rotation of actuator 6

Fig. 3.7 – Comparison of Inverse kinematics by analytical and MapleSim

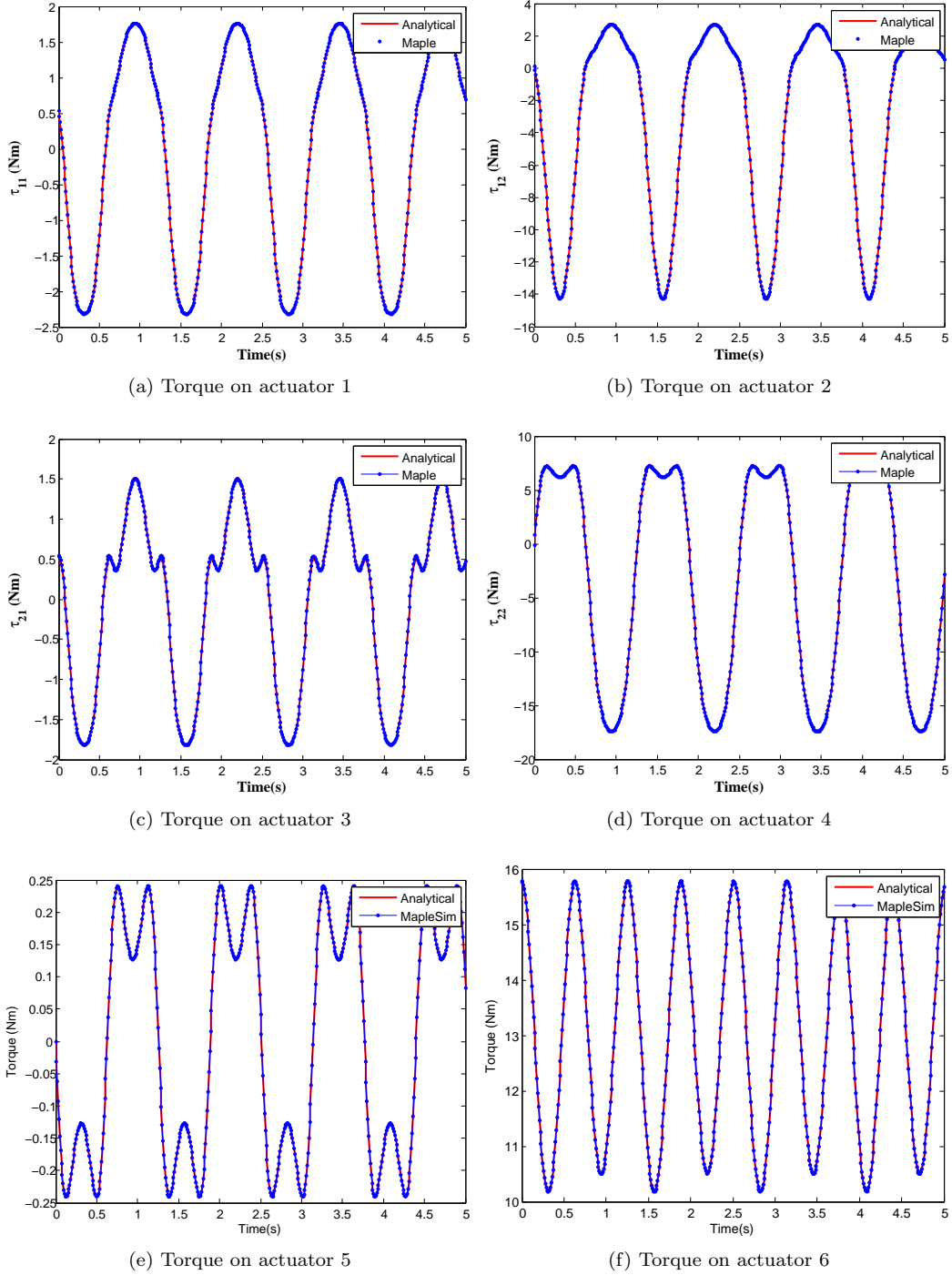
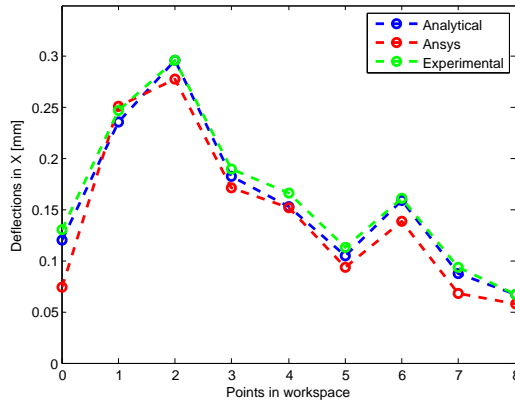
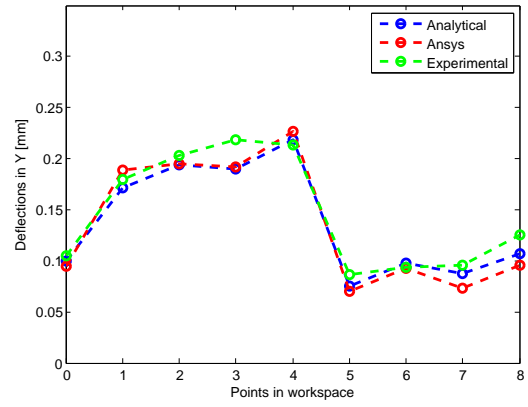


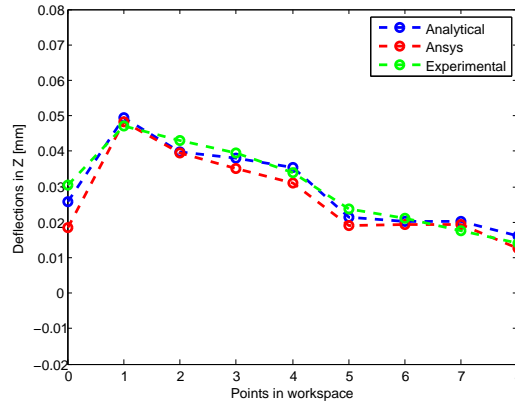
Fig. 3.8 – Comparison of Torque on actuators from Analytical and MapleSim



(a) Deflection of platform in x-direction.



(b) Deflection of platform in y-direction.



(c) Deflection of platform in z-direction.

Fig. 3.9 – Deflection of platform in x,y and z-direction.

Chapter 4

Summary of appended papers

This chapter gives a brief review of the appended papers.

4.1 Paper A: Kinematics and dynamics of a novel 6-DOF TAU haptic device

This paper presents the kinematics and dynamics model of the TAU haptic device. First, a kinematic model for inverse and forward kinematics was developed and analyzed. Then an algorithm to solve the close form inverse dynamics is presented using Lagrangian formulation. Numerical simulation was carried out to examine the validity of the approach and accuracy of the technique employed. A trigonometric helical trajectory of 5th order spline was used in Cartesian space for each degree of freedom of the moving platform in order to verify and simulate the inverse dynamics of the device.

4.2 Paper B: Design Optimization of the TAU haptic device

In this paper, a multi-objective optimization (MOO) approach has been used for optimum design of a haptic device by optimizing kinematic performance indices like workspace volume, isotropy and force/torque under constrain of active and passive joint angles, and singularity condition. For design optimization, performance indices such as workspace volume, kinematic isotropy and static torque requirements indices are defined. A new multi-criteria objective optimization (MOO) function is introduced to define the optimization problem. Multi-objective algorithms are used to solve this optimization problem using the defined objective function. Furthermore, sensitivity analysis of the performance indices against each design parameter is presented as a basis for selecting a final set of design parameters for the prototype. Finally, a CAD model and prototype of the device is developed based upon the simulation results.

4.3 Paper C: 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 for haptic device, which considers the stiffness of; 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 validation process is presented as a systematic guideline to evaluate the stiffness parameters both using parametric FEM modeling and physical experiments. Pre-loading has been used to consider the clearances and possible assembling errors during manufacturing. A modified JP-Merlet kinematic structure is used to exemplify the modeling and validation methodology. The approach used in this methodology is to start with a simplified analytical model. This 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 the experimental results is not acceptable, i.e. it doesn't validate the analytical model, a more detailed analytical model has to be developed. For the detailed analytical model also the passive joints and actuation system are included. This is then verified with 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.

Chapter 5

Discussion, conclusions and future work

The focus of the research presented in this thesis is to develop a model-based design approach based on multi-criteria requirements for the design of haptic devices, that can be used for simulation of surgical procedures of hard tissues. This chapter gives a discussion about the findings and presents conclusions about the investigated research questions.

5.1 Discussion

A kinematic model has been developed and verified using MapleSim. The workspace of the selected device has been analyzed both for reachable and dexterous workspace. An algorithm has been developed to analyze the dexterous workspace. This can then be used in the design optimization to examine if this will effect the performance like manipulability, isotropy, stiffness and force requirement index within the workspace.

The question is then; will we get better performance if we consider the dexterous workspace instead of constant orientation workspace during optimization?

To answer this question, we have investigated the use of dexterous workspace instead of reachable workspace during design optimization, and compared the results in terms of two kinematic performance indices, isotropy and force requirement. The same design parameters were used, and the same workspace were traversed. The results of kinematic isotropy and force requirement indices in the case of reachable workspace are *0.4374* and *1.7302* respectively, while in the case of dexterous workspace, these are *0.4619* and *1.6754* respectively. We also investigated the effect of workspace grid size on the kinematic performance indices, and observed that changing the step size of the orientation from 5° to 1° can further improve the isotropy and force requirement indices up to *0.4690* and *1.6430* respectively as shown in Table.5.1. From Table.5.1, it is clear that the use of dexterous workspace in optimization will

increase the performance in terms of isotropy and force requirement on the cost of workspace.

Table 5.1 – Effect of workspace grid size on kinematic performance

| | 5° | 2.5° | 1° | Reachable |
|------|----------|----------|----------|-----------|
| GII | 0.4619 | 0.4630 | 0.4690 | 0.4374 |
| GTRI | 1.6754 | 1.6767 | 1.6430 | 1.7302 |
| VI | 6.42E+05 | 6.42E+05 | 6.42E+05 | 7.80E+05 |

A methodology to create a generalized, highly compact and computationally efficient analytical stiffness model has been proposed. The proposed model is obtained in a step by step modeling manner starting with a simplified model considering the stiffness of all the compliant element within the system. The proposed model takes into account 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. The stiffness matrix is then calculated from the inverse of the compliance matrix. Another systems modeling approach covered by the proposed methodology is the introduction of the Hertzian contact model for both spherical and universal passive joints and a simply supported beam model for the universal joint.

A comparative analysis between the simplified modeling and detailed modeling were made, which shows that by considering the stiffness of passive joints, and actuation system reduces the relative error between analytical and experimental results from 83% to 16% and the average error from 79% to 8%. A comparison of contributions of compliant element was made, which shows the stiffness of passive joints have a considerable effect on accuracy of the model.

5.2 Conclusions

(Paper A), addresses the first question in section 1.3. In this paper the inverse and forward kinematic model are developed for the TAU haptic device. These models are then used to calculate the reachable and dexterous workspace and to verify that 6-DOF can be obtained. The second question is addressed in (Paper B), where the kinematic model of (Paper A) has used as a basis for defining performance indices, that were used in multi-objective design optimization. From this paper we can conclude that optimization based on kinematic properties is an important part in the development of haptic devices. The last question about how to model the stiffness of a haptic device is addressed by (Paper C), where a methodology is outlined. This methodol-

ogy gives a stepwise description of how to create and validate an analytical stiffness model of haptic device.

5.3 Future work

- Stiffness evaluation of the TAU haptic device using the developed model in (Paper C)
- Model based design optimization of the TAU haptic device by considering the requirements of inertia, dynamic properties(eigenfrequency) in (Paper A) and stiffness
- Development and verification of a friction model for haptic devices implemented on the Stewart-platform as well as the TAU structure
- Development of a model for precise singularity detection and avoidance of TAU device
- Development of a backlash model for haptic devices based on Stewart-platform
- Accuracy evaluation of the complete system with compensation for inertia, friction and position errors cause by deflection using the stiffness model developed in (Paper C)
- Evaluation of velocity and acceleration capabilities of the device

References

- [1] M. srinivasan. what is haptics? [Online]. Available: http://www.sensable.com/support/phantom_ghost/datafiles/what_is_haptics.pdf
- [2] C. M. Salisbury, “Haptic hardware: Evaluation, design and placement,” Ph.D. dissertation, Stanford University, 2010. [Online]. Available: <http://gradworks.umi.com/33/82/3382949.html>
- [3] M. G. Eriksson, “Haptic milling simulation in six degrees-of-freedom with application to surgery in stiff tissue,” Ph.D. dissertation, KTH, Stockholm, 2012.
- [4] Digital dentures: A complete game changer for local dental labs. [Online]. Available: <http://www.capedental.com/dental-blog/2011/11/digital-dentures-a-complete-game-changer-for-local-dental-labs/>
- [5] L.-F. Lee, “Analysis and design optimization of in-parallel haptic devices,” Ph.D. dissertation, University at Buffalo, Buffalo, 2010.
- [6] K. Suleman, K. Andersson, and J. Wikander, “A design approach for a new 6-dof haptic device based on parallel kinematics,” in *ICM 2009. IEEE International Conference on Mechatronics, 2009*, april 2009, pp. 1–6.
- [7] G. Gogu, “Fully-isotropic parallel mechanisms - an innovative concept for haptic devices,” in *Product Engineering*, D. Talaba and A. Amditis, Eds. Springer Netherlands, 2008, pp. 169–194, 10.1007/978-1-4020-8200-9. [Online]. Available: <http://dx.doi.org/10.1007/978-1-4020-8200-9>
- [8] S. Khan, “Design and optimization of parallel haptic devices design methodology and experimental evaluation,” Ph.D. dissertation, KTH, Stockholm, 2012.
- [9] S. Khan, K. Andersson, and J. Wikander, “Optimal design of a 6-dof haptic device,” in *Mechatronics (ICM), 2011 IEEE International Conference on*, april 2011, pp. 713–718.
- [10] Sensable technologies. [Online]. Available: <http://www.sensable.com>
- [11] Haption. [Online]. Available: <http://www.haption.com>

- [12] Force dimension. [Online]. Available: <http://www.forcedimension.com>
- [13] Y. Tsumaki, H. Naruse, D. Nenchev, and M. Uchiyama, "Design of a compact 6-dof haptic interface," in *Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on*, vol. 3, may 1998, pp. 2580 – 2585 vol.3.
- [14] J. Sabater, R. Saltarén, and R. Aracil, "Design, modelling and implementation of a 6 urs parallel haptic device," *Robotics and Autonomous Systems*, vol. 47, no. 1, pp. 1 – 10, 2004. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0921889004000259>
- [15] F. Gosselin, J.-P. Martins, C. Bidard, C. Andriot, and J. Brisset, "Design of a new parallel haptic device for desktop applications," in *Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint*, march 2005, pp. 189 – 194.
- [16] H. Cui, Z. Zhu, Z. Gan, and T. Brogardh, "Kinematic analysis and error modeling of tau parallel robot," *Robotics and Computer-Integrated Manufacturing*, vol. 21, no. 6, pp. 497 – 505, 2005. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0736584504000754>
- [17] Z. Zhu, J. Li, Z. Gan, and H. Zhang, "Kinematic and dynamic modelling for real-time control of tau parallel robot," *Mechanism and Machine Theory*, vol. 40, no. 9, pp. 1051 – 1067, 2005. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0094114X05000431>
- [18] R. Ur-Rehman, S. Caro, D. Chablat, and P. Wenger, "Multiobjective Design Optimization of 3-PRR Planar Parallel Manipulators," in *Global Product Development*, Nantes, France, Apr. 2010, pp. 1–10. [Online]. Available: <http://hal.archives-ouvertes.fr/hal-00464101>
- [19] F. Hao and J.-P. Merlet, "Multi-criteria optimal design of parallel manipulators based on interval analysis," *Mechanism and Machine Theory*, vol. 40, no. 2, pp. 157 – 171, 2005. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0094114X04001211>
- [20] X.-J. Liu, J. Wang, K.-K. Oh, and J. Kim, "A new approach to the design of a delta robot with a desired workspace," *Journal of Intelligent & Robotic Systems*, vol. 39, pp. 209–225, 2004, 10.1023/B:JINT.0000015403.67717.68. [Online]. Available: <http://dx.doi.org/10.1023/B:JINT.0000015403.67717.68>
- [21] Zbigniew Michalewicz, *Genetic algorithms + data structures = Evolution programs*. Springer, 1996.

- [22] S.-D. Stan, V. Maties, R. Balan, C. Rusu, and S. Besoiu, “Optimal link design of a six degree of freedom micro parallel robot based on workspace analysis,” in *Advanced Motion Control, 2008. AMC '08. 10th IEEE International Workshop on*, march 2008, pp. 637 –642.
- [23] J. Lee, K. Eom, and I. Suh, “Design of a new 6-dof parallel haptic device,” in *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*, vol. 1, 2001, pp. 886 – 891 vol.1.
- [24] S. S. Lee and J. M. Lee, “Design of a general purpose 6-dof haptic interface,” *Mechatronics*, vol. 13, no. 7, pp. 697 – 722, 2003. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0957415802000387>
- [25] Y.-K. Hwang, J.-W. Yoon, and J.-H. Ryu, “The optimum design of a 6-dof parallel manipulator with large orientation workspace,” in *SICE-ICASE, 2006. International Joint Conference*, oct. 2006, pp. 1255 –1259.
- [26] R. Ur-Rehman, S. Caro, D. Chablat, and P. Wenger, “Multi-objective path placement optimization of parallel kinematics machines based on energy consumption, shaking forces and maximum actuator torques: Application to the orthoglide,” *Mechanism and Machine Theory*, vol. 45, no. 8, pp. 1125 – 1141, 2010. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0094114X10000443>
- [27] J.-J. Park, B.-S. Kim, J.-B. Song, and H.-S. Kim, “Safe link mechanism based on nonlinear stiffness for collision safety,” *Mechanism and Machine Theory*, vol. 43, no. 10, pp. 1332 – 1348, 2008. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0094114X07001577>
- [28] J. Angeles and F. C. Park, “Performance evaluation and design criteria,” in *Springer Handbook of Robotics*, B. Siciliano and O. Khatib, Eds. Springer Berlin Heidelberg, pp. 229–244.
- [29] A. De Luca and W. Book, “Robots with flexible elements,” in *Springer Handbook of Robotics*, B. Siciliano and O. Khatib, Eds. Springer Berlin Heidelberg, pp. 287–319.
- [30] C. Gosselin, “Stiffness mapping for parallel manipulators,” *IEEE Transactions on Robotics and Automation*, vol. 6, pp. 321–342, jun 1990.
- [31] B. El-Khasawneh and P. Ferreira, “Computation of stiffness and stiffness bounds for parallel link manipulator,” *Int. J. Machine Tools & manufacture*, vol. 39, no. 3, pp. 377 –382, February 1999.
- [32] C. M. D. Zhang, F. Xi and S. Lang, “Analysis of parallel kinematic machine with kinetostatic modeling method,” *Robotics and Computer-Integrated Manufacturing*, vol. 20, pp. 151– 165, April 2004.

- [33] D. Zhang, “Haptic and visual simulation of a material cutting process,” Laval University, Quebec, Canada, Ph.D Thesis., April 2000.
- [34] C. Gosselin and D. Zhang, “Stiffness analysis of parallel mechanisms using a lumped model,” *Int. J. of Robotics and Automation*, vol. 17, pp. 17–27, April 2002.
- [35] Y. Wang, T. Huang, X. Zhao, J. Mei, D. Chetwynd, and S. Hu, “Finite element analysis and comparison of two hybrid robots-the tricept and the trivariant,” in *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*, oct. 2006, pp. 490–495.
- [36] Y. Yun and Y. Li, “Comparison of two kinds of large displacement precision parallel mechanisms for micro/nano positioning applications,” in *Robotics, Automation and Mechatronics, 2008 IEEE Conference on*, sept. 2008, pp. 284–289.
- [37] R. S. Gonçalves and J. C. M. Carvalho, “Stiffness analysis of parallel manipulator using matrix structural analysis,” in *Proceedings of EUCOMES 08*, M. Ceccarelli, Ed. Springer Netherlands, pp. 255–262.
- [38] D. Deblaise, X. Hernot, and P. Maurine, “A systematic analytical method for pkm stiffness matrix calculation,” in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, may 2006, pp. 4213–4219.
- [39] Przemieniecki, J.S, *Theory of Matrix Structural Analysis*. New York: Dover Publications, Inc, 1985.
- [40] W. Dong, Z. Du, and L. Sun, “Stiffness influence atlases of a novel flexure hinge-based parallel mechanism with large workspace,” in *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on*, aug. 2005, pp. 856–861.
- [41] M. Uchiyama, Y. Tsumaki, and W.-K. Yoon, “Design of a compact 6-dof haptic device to use parallel mechanisms,” in *Robotics Research*, ser. Springer Tracts in Advanced Robotics, vol. 28. Springer Berlin / Heidelberg, pp. 145–162.
- [42] T. Bonnemains, H. Chanal, B.-C. Bouzgarrou, and P. Ray, “Stiffness computation and identification of parallel kinematic machine tools,” *Journal of Manufacturing Science and Engineering*, vol. 131, no. 4, p. 041013, 2009. [Online]. Available: <http://link.aip.org/link/?MAE/131/041013/1>
- [43] C. Pinto, J. Corral, O. Altuzarra, and A. Hernández, “A methodology for static stiffness mapping in lower mobility parallel manipulators with

- decoupled motions,” *Robotica*, vol. 28, no. 05, pp. 719–735, 2010. [Online]. Available: <http://dx.doi.org/10.1017/S0263574709990403>
- [44] M. Ceccarelli and G. Carbone, “Numerical and experimental analysis of the stiffness performances of parallel manipulators,” in *2nd International Colloquium of the Collaborative Research Centre 562, Braunschweig*, 2005.
- [45] ANSI/RIA R15.05-1-1990 (R1999), *Evaluation of point-topoint and static performance characteristics of industrial robots and robot systems*, 1999.
- [46] ISO 9283:1998, *Manipulating industrial robots-performance criteria and related test methods*, 2003.
- [47] C. Carbone, “Stiffness analysis for an optimal design of multibody robotic systems,” in *Robot Manipulators New Achievements*, A. Lazinica and H. Kawai, Eds. In-Teh Olajnica 19/2, 32000 Vukovar, Croatia.
- [48] G. Castelli, E. Ottaviano, and M. Ceccarelli, “A fairly general algorithm to evaluate workspace characteristics of serial and parallel manipulators,” *Mechanics Based Design of Structures and Machines*, vol. 36, no. 1, pp. 14–33, 2008. [Online]. Available: <http://www.tandfonline.com/doi/abs/10.1080/15397730701729478>
- [49] T. Murata and H. Ishibuchi, “Moga: multi-objective genetic algorithms,” in *Evolutionary Computation, 1995., IEEE International Conference on*, vol. 1, nov-1 dec 1995, p. 289.
- [50] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, “A fast and elitist multiobjective genetic algorithm: Nsga-ii,” *Evolutionary Computation, IEEE Transactions on*, vol. 6, no. 2, pp. 182–197, apr 2002.
- [51] E. Zitzler, K. Deb, and L. Thiele, “Comparison of Multiobjective Evolutionary Algorithms: Empirical Results,” *Evolutionary Computation*, vol. 8, pp. 173–195, 2000. [Online]. Available: <http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.30.5848>
- [52] Rivin, E.I, *Stiffness and Damping in Mechanical Design*. New York: Marcel Dekker Inc, 1999.
- [53] Waterloo maple inc. (maplesoft). [Online]. Available: www.maplesoft.com
- [54] Ansys, inc. [Online]. Available: <http://www.ansys.com>