KTH Computer Science
and Communication

Reflective Spatial Haptic Interaction Design

Approaching a Designerly Understanding of Spatial Haptics

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Abstract

With a spatial haptic interface device and a suitable haptic rendering algorithm, users can explore and modify virtual geometries in three dimensions with the aid of their haptic (touch) sense. Designers of surgery simulators, anatomy exploration tools and applications that involve assembly of complex objects should consider employing this technology. However, in order to know how the technology behaves as a design material, the designer needs to become well acquainted with its material properties. This presents a significant challenge today, since the haptic devices are presented as black boxes, and implementation of advanced rendering algorithms represent highly specialized and time consuming development activities. In addition, it is difficult to imagine what an interface will feel like until it has been fully implemented, and important design trade-offs such as the virtual object's size and stability gets neglected.

Traditional user-centered design can be interpreted as that the purpose of the field study phase is to generate a set of specifications for an interface, and only solutions that cover these specifications will be considered in the design phase. The designer might miss opportunities to create solutions that uses e.g. lower cost devices since that might require reinterpretation of the overarching goal of the situation with starting point in the technical possibilities, which is unlikely without significant material knowledge. As an example, a surgery simulator designed in this thesis required a high cost haptic device to render adequate forces on the scale of human teeth, but if the design goal is reinterpreted as creating a tool for learning anatomical differences and surgical steps, an application more suitable for the lower cost haptic devices could be crafted. This solution is as much informed by the haptic material "speaking back to" the designer as by field studies.

This licentiate thesis will approach a perspective of spatial haptic interface design that is grounded in contemporary design theory. These theories emphasizes the role of the designer, who is not seen as an objective actor but as someone who has a desire to transform a situation into a preferred one as a service to a client or greater society. It also emphasizes the need for crafting skills in order to innovate, i.e. make designed objects real. Further, it considers aesthetic aspects of a design, which includes the subtle differences in friction as you move the device handle, and overall attractiveness of the device and system.

The thesis will cover a number of design cases which will be related to design theory and reflected upon. Particular focus will be placed on the most common class of haptic devices which can give force feedback in three dimensions and give input in six (position and orientation). Forces will be computed and objects deformed by an volume sampling algorithm which will be discussed. Important design properties such as stiffness, have been identified and exposed as a material for design. A tool for tuning these properties interactively has been developed to assist designers to become acquainted with the spatial haptic material and to craft the material for a particular user experience.

Looking forward, the thesis suggests the future work of making spatial haptic interfaces more design ready, both in software and hardware. This is proposed to be accomplished through development of toolkits for innovation which encapsulate complexities and exposes design parameters. A particular focus will be placed on enabling crafting with the haptic material whose natural limitations should be seen as suggestions rather than hinders for creating valuable solutions.

Acknowledgments

I would like to thank my advisor Eva-Lotta Sallnäs Pysander, who never stopped supporting me to find my own passion and path of research altough it took much effort before I finally landed in this design-centric thesis. Altough I have expressed a strong engineer ethos, perhaps she is right when she says it is now time for me to "come out of the closet as a designer". I am also greatful to my co-advisor Karl-Johan Lundin Palmerius for his advise on implementing the algorithm that lay the foundation for most of the applications I designed. And Jan Gulliksen for suggesting me to do this licentiate thesis which forced me to think through what I am actually doing. My deeper understanding of haptic hardware is all thanks to professor Ken Salisbury and Reuben Brewer at Stanford University, and for haptic algorithms there is no better colleague and friend than Sonny Chan.

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Chapter 1

Introduction

The purpose of this licentiate thesis is to initiate a reflective inquiry into design of systems that take advantage of a particular kind of human-computer interface and set of algorithms. The computer interface in question is the spatial (three dimensional) device which has a handle that a user can hold on to, move about and orient freely, while also receiving computer generated output in the form of three dimensional forces. The set of algorithms in question enables the user to utilize this device to explore and modify computer generated three dimensional shapes using the sense of touch.

The thesis will cover a number of applications designed by the author and critically reflect on the assumptions, process, purpose and outcome each application present. The applications, their technology and design process are introduced in the thesis and also presented in the attached publications. The reflections will form a basis for a discussion on whether a research program based in philosophy of design [Nelson and Stolterman, 2012] would be suitable to create knowledge regarding how to design and with and for the spatial haptic technology presented in this thesis.

A short overview of spatial haptic interface technology will be given in the remainder of this chapter, with focus on the specific devices and algorithms that will be studied in detail in succeeding chapters. This opens up for the over-arching research questions regarding spatial haptic interaction design that concludes this chapter.

This thesis will cover four applications designed and developed to a large extent by the author. Each application is designed to benefit from spatial haptics, but vary in form and purpose. Chapter two presents a background relevant for these applications; technology used by the author, the sense of touch this technology is supposed to support, and how applications are constructed using software libraries - previously existing and newly developed. Chapter three presents the details of the applications and how they utilize the technology presented in chapter two.

Chapter four summarizes the lessons learned from the design and development of the four applications, reports on novel tools and methods developed to support the design activities, proposes user experience theory relevant for the spatial haptic interface designer, and one evaluation of the impact of one important design consideration on a certain task's

performance. Each section in this chapter corresponds to a peer-reviewed paper presented at an international conference. Each paper will also be interpreted critically in the light of the research questions presented in chapter one, and to some extent from the perspective of philosophy of design.

Chapter five will take the discussion initiated in chapter four to a higher level of abstraction and bring in philosophy of design as a foundation to understand how the applications presented in the thesis have been brought into existence. Following an introduction to a *designerly* view of interaction design, answers to the research questions will be proposed under the headline *crafting haptic applications*. Finally, future research work will be proposed that intentionally supports crafting of applications and systems, including hardware, and why the production of systems with spatial haptic interfaces would benefit from such research.

1.1 Spatial Haptic Interface Technology

In this thesis Spatial Haptics, or 3D haptics, refer to the range of human interface devices that tracks the position of a manipulandum (handle) and renders forces back to the user, which enables the user to feel and manipulate virtual objects in space.

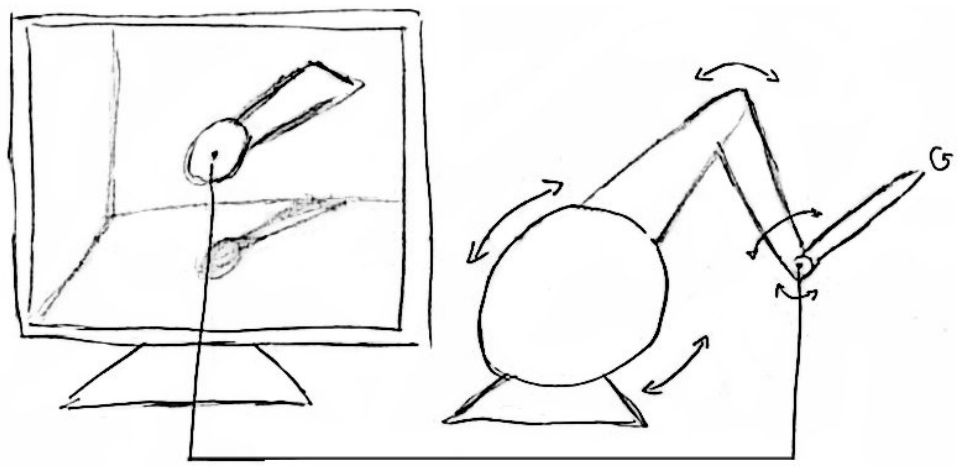

Figure 1.1: Virtual coupling between the manipulandum (the handle of the haptic device) and a three dimensional avatar. As the user moves and orients the manipulandum, the avatar moves and rotate on the screen.

Despite being around for almost 20 years, spatial haptics has not yet met its full potential for improving interaction in real world applications [Wright, 2011]. Spatial haptics have been quite inaccessible for interaction design practitioners. Bowman et al. writes in their 2008 survey paper that *"providing haptic (touch) feedback in 3D UIs has been a*

difficult topic", which motivated them to instead simulate haptic feedback through sensory substitution [Bowman et al., 2008].

For software designers, myself included, who are familiar with haptic feedback, there has for a long time been something "mystical" about the devices and rendering methods. For example, the cost of devices represent a large spectrum, where high fidelity devices costs tens of thousands of US dollars. This eliminates many solutions where the value created is relatively low. Another obstacle is that haptic rendering can only be perceived live and not communicated through pictures or video. When new algorithms are only communicated in paper form and require extensive implementation effort, few designers can perceive the interaction aesthetics they provide. Likewise, the fidelity of novel hardware devices and the possible alternations of their design (eg. workspace, maximum force, encoder resolution) are rarely accessible to application/system designers but left as black boxes.

1.2 Massie-Agus Haptic System

This thesis is primarily focused on the class of haptic hardware devices that I will refer to as the "Massie Class". Other devices will be mentioned and a designer should become familiar with the available range of devices. What signifies the Massie class from other sets of devices will become clear in the next chapter, but it is the most well known device class, often sold under the brand Phantom, that reads position and orientation while providing a directional force (and no torque) feedback. The reason for single out a particular class of devices is to enable deep exploration of the user experiences this class of devices affords. There are a range of devices within the Massie class. Their differences are subtle in that they all fundamentally have the same set of features. As a designer I have chosen to work with the Massie class, analogous to the designer who chose to work in wood and not steel or glass. There are several different kinds of wood and that impacts the quality of your crafted product. Some kind of wood is more suitable for certain products, but they are all wood.

The Massie class haptic device has six links with sensors that enables a manipulandum (handle) to be moved freely in space within its workspace as well as being rotated within limits (figure 1.1). In addition, the Massie class provides programmable directional force feedback at the rotation point of the manipulandum. The force is generated by actuating a combination of three motors that drives respective link in the mechanism (figure 1.2).

The Agus class of haptic rendering algorithms (explained further in next chapter) empowers the user to explore and modify geometrical objects with a virtual sphere "coupled" to the rotation point of the manipulandum. As the user moves the sphere over a surface, a repelling force is calculated and sent to the haptic device that produces a force on the manipulandum. The user can thereby feel the surface and follow its contours. The algorithm is also responsible for cutting or "drilling" into the colliding part of the surrounding environment. The variant of the Agus class I have chosen to implement and design with also provides the ability to define the different hardnesses of different regions of the virtual objects (figure 1.3 a and b).

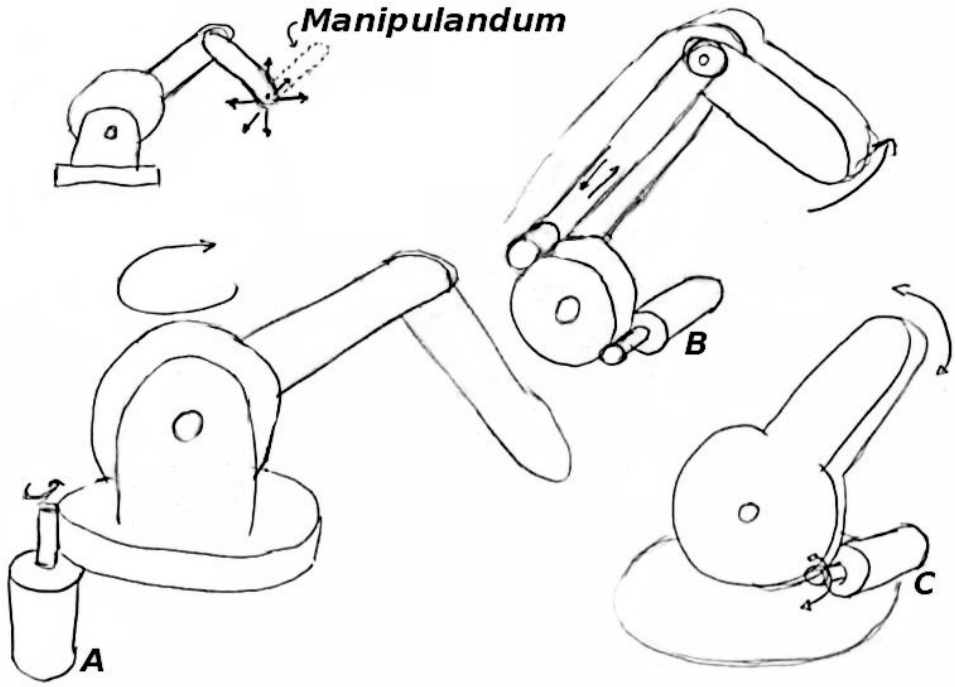

Figure 1.2: Engaging a combination of motor A, B and C translates into a force in any direction at the rotation point of the manipulandum.

The combination of a Massie-class haptic device and an Agus class algorithm yields a design space of potential applications. It has certain distinctive qualities and certain limitations. One important limitation is that for detecting collisions and calculating responses, only a sphere can be used to represent the virtual tool. It can have any shape visually, e.g. a surgical drill, but only the sphere located at the tip of the drill will respond to collisions. The user can without restriction move the shaft of the drill into the surrounding environment (figure 1.3 c).

1.3 Research Questions

With the applications that is presented in this thesis it is evident that the same fundamental technology can be shaped to different particular applications, suitable in different particular situations. It is however not self evident how this technology shaping is done, or should best be done in order to best make use of the potentials that spatial haptics have. To learn more about that, the following research questions will be asked and discussed throughout the thesis and answers will be proposed in the discussion.

1. Which are the most important characteristics of spatial haptic user interfaces? In

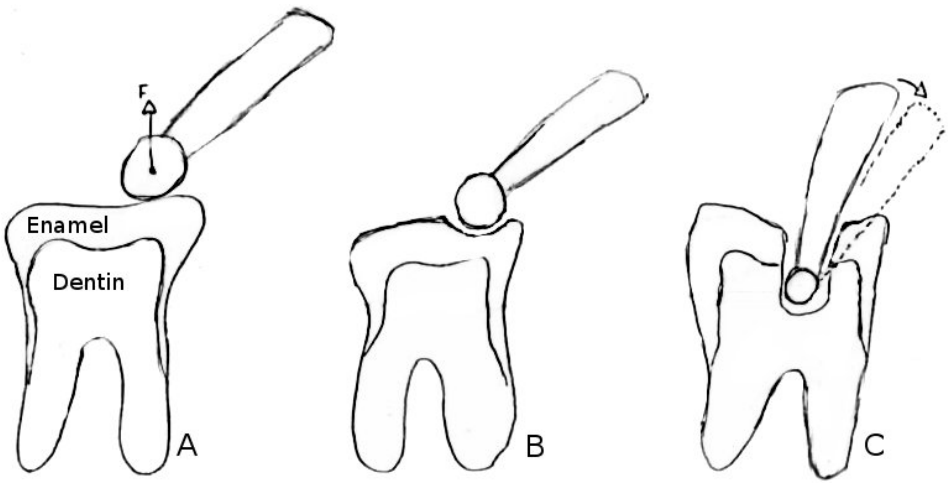

Figure 1.3: A. As the user moves a virtual drill and the drill bit comes in contact with a virtual tooth, a force F is calculated and rendered to the haptic device. B. The user can remove material from the virtual object, and the object can have different hardness, here enamel and dentin. C. No collisions are detected as the drill shaft collides with the surrounding tooth, it will simply overlap.

particular, what are the specific characteristics of the combination of a Massie class haptic device with an Agus class haptic rendering algorithm?

2. Which are the material properties (or parameters) that a designer should explore to understand what the haptic technology can do? In particular, what parameters can a designer tune for the Massie-Agus combination and what do they mean in terms of user experience?

3. What does an interaction designer need to know in order to successfully work with the spatial haptic material?

4. What should be the best future practice for creating innovations and applications based on (or with) spatial haptic interface technology?

5. How should haptic user interfaces be judged or evaluated?

Part I

Spatial Haptic Interaction Design

Chapter 2

Background

Spatial Computer Haptics as we know it today probably has its birth with the work of Massie and Salisbury in 1993. Haptics had been known and used earlier, but mostly in the form of the "master" side of a telemanipulation robotic system, or very complex exoskeleton systems. Massie constructed a comparatively less complex mechatronic device that read a three dimensional position of a mechanical *manipulandum* (handle) and fed that to a virtual environment. In addition, the device could engage motors to provide a directional force on the manipulandum. With the first haptic rendering algorithms, forces could be calculated based on position of the manipulandum, and users could experience collision and contour following of virtual walls, boxes and spheres [Massie, 1993].

Massies force-reflecting haptic interface provided a novel and fascinating material to applications designers. The device provided both programatically haptic feedback, and direct manipulation in 3D. Obviously it lead to questions of how the haptic sense can be used (psychophysics), how to provide physically based simulated forces (haptic rendering) and how to design effective interfaces with it (3D User Interfaces). Also the device itself and how to improve it have been studied (control theory, mechanics, robotics).

The perspective of the device differs between fields. As a software designer I have always wonder how the devices can be so expensive compared to other computer peripherals. For a robotics engineer that sees the device mainly as the master unit of a telerobotics system, the price can be compared to professional robotics equipment and in that perspective carry a just cost. The popular vibration technology in cell phones is also referred to as haptics, and conferences on the topic is today much more concerned with vibrotactile haptics than directional force haptics. The vibrotactile haptics has thus been over-shading the 3D counterpart as what most people in the field refer to with haptic interfaces. This thesis only address with 3D haptic interfaces and how we can design with and for them.

2.1 Haptic Interface Hardware

The application designer can usually only chose among a small set of haptic interface hardware, or *haptic devices*. The set is discrete in that there are no devices available "in

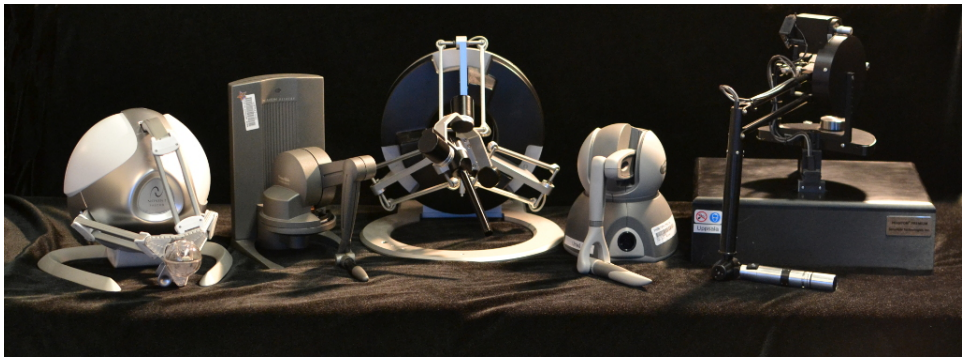

Figure 2.1: Commonly available haptic interfaces hardware. From left to right: Novint Falcon (3/3-DoF), Geomagic Phantom Desktop (3/6-DoF), Force Dimension Omega (3/6-DoF), Geomagic Phantom Omni (3/6-DoF) and Geomagic Phantom Premium (6/6-DoF)

between" the available devices from a software designer's point of view. The most common devices are depicted in figure 2.1. The cost of these devices range from a few hundred dollars to tens of thousands. For most application designers, the haptic device is treated as a black box. The choice of haptic device for a particular application has quite high impact on the applications user experience. In certain circumstances there would be meaningful to design and produce a custom device, to get certain resolution for example to meet specification derived from the nature of microsurgery [Salisbury CM, 2008].

Degrees of Freedom

This thesis is concerned with spatial haptic interfaces, which implies that the user can interact and get feedback using direct manipulation in at least three *degrees of freedom*. Today, many commercially-available haptic devices are asymmetric in that they have a different number of sensors than actuators (motors) [Barbagli and Salisbury, 2003]. The Massie class of haptic devices senses 3D position and orientation (6-DOF), but provides only directional force feedback (3-DOF).

2.2 Haptic Rendering Algorithms

The process of generating the forces to output, or render, to the haptic interface is called haptic rendering [Salisbury et al., 2004]. Haptic rendering of the sort we are concerned with in this thesis can be said to be drawn from control theory, collision detection and handling, interaction techniques and computer animation. The word *rendering* leads the reader to think of its analogue to computer graphics where rendering is the process of representing graphical objects on a visual display. Correspondingly, *haptic rendering* represent objects on a *haptic display*, a synonym to haptic device. However, since the haptic device is inherently bidirectional as the human haptic sense it is also the haptic

rendering algorithms responsibility to move the avatar that corresponds to the manipulandum's position and orientation. This is important since the main explorative procedure [Lederman and Klatzky, 2009] supported by the Massie class device is *contour following* that allows humans to form a mental image of an object by tracing its surface, for example with a pen. In addition a haptic rendering algorithm has to act as a *controller* in its control theory sense, keeping the physical manipulandum stable and safe.

One set of haptic rendering algorithms is concerned with direct rendering of abstract datasets while most are concerned with rendering of geometries [Palmerius et al., 2008].

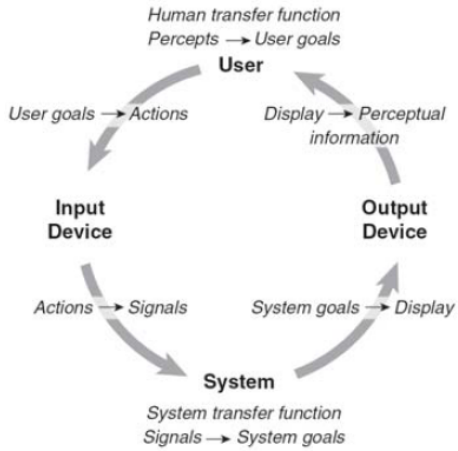

Figure 2.2: Interaction Workflow. notice that input device signals are decoupled from system goals. For our use, the user communicates a intent by moving the manipulandum, and the system interprets it before displaying a movement which allows for constrained movement. From [Bowman et al., 2004] used with permission.

An algorithm that support the interaction workflow (**??**interactionworkflow) of a system and give haptic feedback to the user, would require at least the following to be implemented:

- Read the position of the manipulandum of the haptic device.
- Interpret the manipulandum position as an intent of the user, usually "I would like to move the avatar over there".
- Given the intended movement either directly move the avatar to corresponding position in the virtual environment, or first detect inter-laying obstacles (collision detection) and constrain the movement of the avatar (collision response).
- Compute a directional force based on the position and orientation of the avatar and manipulandum and consecutively render it to the haptic device.

2.3 Forssim: A set of algorithms inspired by Agus

During the development of the Oral surgery simulator presented in chapter four a set of algorithms were implemented and collected in a software library named *Forssim*. These algorithms were inspired by [Agus et al., 2003]. The haptic algorithm in this collection has the benefit of being relatively easy to implement, since it does not distinguishes between avatar and manipulandum position, and thus no configuration solving is required. It only supports sphere - spatial sampled environment interaction, but as we will see this can still yield a variety of applications. The main drawback compared to more recent algorithms like [Chan, 2011] is the lack of full rigid body support (considering position and orientation, see figure 1.3 C) and utilization of an avatar-manipulandum distinction that guarantees that the avatar stays on top of a geometry and not penetrates it or pops through.

The Agus-like algorithm in the Forssim library is responsible for computing collision response forces and for deforming a geometric object (drilling). In the following sections the implementation used in my projects will be presented. Together they form the core of the *forssim* library that we developed and released as open source as an extension of H3D, another open source graphics and haptics library. Forssim has evolved since the initial development to include constraint and point-shell based rendering, which is now used in the latest version of the Oral surgery simulator. However, the early version of the simulator and the other Agus-like-based applications mentioned in this thesis all uses the Agus-like algorithm described below.

Some understanding of the workings of the algorithm may help the reader understand why certain parameters where chosen to be exposed for design. An exposed parameter is a parameter that can be accessed for tuning outside of the algorithm code itself, as application level code, as a parameter in a configuration file or as a slider or knob for interactive tuning. A method for attaching these parameters to a tangible midi controller is discussed in the attached Sketching paper.

Object representation

In this algorithm, the avatar is represented as a sphere - in other words a position and a radius. The object (eg. jaw bone) is represented by a set of volume bounding spheres, each sphere having the same volume as the equivalent voxel would have. This makes the bounding spheres overlap each other, but the total volume (including these intersections) remains intact. The bounding spheres are organized in a binary rectilinear grid. In other words, the bounding spheres are stored exactly like a voxel volume, where each voxel is treated as a sphere. This will simplify and speed up collision detection, since sphere-sphere collision detection can be determined by simply evaluating the distance.

Collision detection

As the user moves the haptic device's manipulandum, a corresponding virtual object is moved on the screen. This object is referred to as the avatar. The avatar is for haptic purposes modeled as a sphere of arbitrary size. The sphere does not need to be visually

represented as a sphere, for example in the oral surgery simulator it is used both for the surgical drill and the tip of a screw-like instrument called the elevator. A sphere has the benefit of being *rotational invariant*, in other words, only the position of the rotation point of the manipulandum need to be considered. This in contrast to more advanced algorithms for full rigid body interaction that also take into account the orientation of the manipulandum.

The algorithm first finds a bounding box of the avatar sphere, aligned with the frame of the object and includes all bounding volume spheres that are close enough for consideration. Then the volume intersection of the avatar sphere and the bounding volume spheres are calculated. Each bounding volume sphere in the bounding box is iterated and it's volume is either ignored (distance larger than radius of bounding volume sphere and avatar sphere), fully added (distance is less than bounding volume sphere radius subtracted from avatar sphere radius) or partly added (the sphere-sphere intersecting volume based on the radius of the bounding volume sphere and avatar sphere and their distance). The mean normal is calculated as the normalized sum of the vectors from the center of the avatar sphere to each bounding volume sphere's center point multiplied by respective intersecting volume. The result of the collision detection is thus an intersecting volume and a normal direction with respect to the center of the avatar.

Collision response - force computation

Collision response is as it's name reveals what should happen when collision is detected. In our algorithm we calculate a penetration force and display this force to the haptic device. This causes the physical manipulandum to repel from a deeper penetration state towards the surface. In other words, collision does not need to be explicitly avoided, or a surface located since the user will literally be forced out of a colliding state. The only thing required is to calculate the force. The magnitude of the force is defined to be a constant times the intersecting volume determined earlier. This constant is one of the most important design parameter to tune, since it is directly proportional to the amount of stiffness experienced by the user. The direction of the force is defined as the negative normal. Agus calculates a penetration depth and uses that as a basis for the magnitude, and also adds a friction component [Agus et al., 2003]. In Forssim we ignore friction for simplicity and use the whole intersecting volume as basis for force magnitude calculation.

In addition to calculate the force magnitude and direction, a damping factor is added which can reduce unwanted vibrations. The damping is calculated as a negative constant (tunable parameter) times the velocity of the manipulandum.

Deformation

Deformation is modeled to be based on the time in contact with the volume filling spheres, and the hardness specified for each sphere. The hardness is defined as the removal rate. For example, spheres belonging to the set "enamel" in the oral surgery simulator has a low removal rate value and thus requires more time before they are removed compared to "dentin".

The amount of "remaining material" is stored in a rectilinear grid of the same dimensions as the object representation used for collision detection above. An additional 8-bit rectilinear map is used to identify which of up to 255 segments each volume filling sphere belongs to. Each segment correspond to a pre-defined material such as "enamel" or "dentin" (figure 1.3).

For each graphic rendering loop the remaining material of each bounding volume sphere that intersects the avatar sphere is reduced by its hardness rate times the elapsed time since last entry of the loop. If the material remaining is less than zero, the material map is modified to classify the material as "air" which also applies to the structure used for collision detection.

2.4 The Haptic Sense

In this thesis we are concerned with the Massie-Agus-like system and what interaction it affords. The Massie-Agus-like haptic interaction system enables the user to explore the shape of a geometrical object by moving a virtual sphere "attached" to the center of rotation of the manipulandum and feel the repelling forces from collisions with the object. As the user moves the manipulandum s/he forms a mental image of the shape of the object. This strategy is one of several *explorative procedures* humans use to understand the properties of a physical object using touch [Lederman and Klatzky, 2009]. Other explorative procedures includes unsupported holding to estimate an objects weight which would be trivial to simulate with an Massie-like device. Temperature sensing is another procedure humans use to distinguish between e.g. copper and glass. This procedure is obviously not possible to support with a Massie-like haptic system, since it lacks temperature generation capabilities.

It has been proposed that integration of haptic interaction in applications requires understanding of human perceptions and that design guidelines can aid developers of such systems [Hale and Stanney, 2004]. While this kind of knowledge (what is *true*) is meaningful, I will in the discussion argue that it is not an absolute necessity. Inquiry into what is *real*, like a computer generated haptic sensation that already exists (the technology for producing these feelings have been around for years), can compensate for an incomplete understanding of the biological truth of how the haptic sense works.

2.5 Development Practice and Software Libraries

Design practitioners (producers) have to design with a reality that involves a range of hardware platforms, human recourses (e.g. programmers and artists) with limited skill sets, limited development tools and building blocks in form of software libraries and Application Programming Interfaces (APIs). Even if a designer choose to ignore these tools and technologies, a client would demand an explanation why costs were higher or results not comparable to that of competitors.

An API is as the name suggest an interface to a particular underlying technology, platform or service. The developers of an API and the application programmer agrees on

a common protocol that exposes underlying functionality to the application programmer without expecting the application programmer to have full understanding of what is going on "under the hood". Software libraries are similar to API's in that they encapsulate functionality for re-use by a set of applications, but they are often smaller and often targeting a well defined sub-task, e.g. encryption or network communication.

As new technological entities are introduced the "playing field" is changed. For example, a world with the iPad (and it's API) is not the same as a world without the iPad. Altough applications with touch based interfaces was technically possible before the iPad, large effort was needed to craft a high-quality user experience due to the lack of a ready-made high quality platform.

When software designers approach a new project, they have to consider the plethora of API's and libraries, as well as which hardware they support. The designers have to know or find out how much time it takes to implement a desired functionality using one or another API. In addition to leverage these building blocks, the designer has also the option of developing functionality on her own, or extending a library to provide functionality it does not readily provide. Depending on the complexity of the feature at hand, it might be required to consult relevant research literature in order to implement e.g. an advanced haptic rendering algorithm. If that is not sufficient, they might be required to engage in fundamental algorithmic development - in effect extending the state of the art. As one can imagine this technological "food-chain" represent an exponentially growing effort, and there is no clear line between what is design, development and fundamental technological innovation. What is important is to acknowledge that for a practitioner it is imperative that some algorithms exists in libraries, some exists only in academic paper form (and thus needs significantly more implementation effort) and some algorithms does not exist at all. In a pure academic context it is not a strong argument that a particular algorithm was chosen over another for the same fundamental problem just because it was easier to implement. Instead it is questions about complexity, memory consumption and data formats that are main considerations. A software producer however, needs to pay close attention to implementation effort to maximize return of invested time.

The Massie-Agus-like based applications mentioned in this thesis are built using the H3D API (SenseGraphics AB, Stockholm, Sweden). H3D provides means for organizing a virtual 3D scene of objects, some interaction techniques, easy access to haptic devices and some visual, auditory and haptic rendering routines. Altough some applications can be developed rapidly using the API, others require that the developer extends the API with fundamental functionality. The haptic rendering provided "out of the box" in H3D API is a one point interaction with polygon-based objects [Ruspini et al., 1997]. With this method, a user can explore geometric shapes with the tip of the manipulandum. There was by the time of my work no built-in functionality for deforming geometries. It is worth mentioning that H3D API is under continuous development, and as mentioned before, as more functionality is added, the barrier of leveraging the functionality in applications is lowered.

During my work with the oral surgery simulator I implemented *Forssim* as an extension to H3D API to handle haptic interaction with and modification of medical models derived from CT-scans. When this was implemented, it became "cheaper" to reuse this extended

API for other applications, than if I would have needed to re-implement it. It also made the choice of these methods over other equally legitimate algorithms more natural based on the reasoning earlier in this section.

Much research of today in haptic rendering is concerned with extending the previous work to full rigid body interaction in six degrees of freedom. This problem is much more complex since it involves considering the full geometry in collision detection between two objects and the dynamics or constrained movement including the orientation. An example of such an algorithm and what it takes to implement it, see [Ortega et al., 2007]. Obviously the implementation time is dependent on the experience of the developer, but for someone with a Masters degree in computer science it can fairly be estimated to be in the order of months rather than weeks for the algorithm I implemented. This is a big risk for the producer. However, eventually it can be expected that an algorithm like [Ortega et al., 2007] gets included into one of the popular libraries and the risk would momentarily drop.

For most projects in this thesis it has been *judged* by the designer that it is important to keep the risk low by trying to achieve as many objectives as possible with the general API and the Forssim extension. In one project it was judged inadequate and a much more fundamental development work was initiated, i.e. writing the application “from scratch” without use of a particular API (except for hardware communication) and investing in full implementation of more sophisticated algorithms like [Ortega et al., 2007].

Chapter 3

Applications

This thesis is focused on three different applications that have been crafted using fundamentally the same Massie-Agus-like haptic system. The applications are a) an oral surgery simulator, b) a liver surgery planning application, and c) a dental anatomy exploration tool. In addition, an art application has been created using the same system in collaboration with Konstfack, a university college for arts, crafts and design. This work will be left aside in this thesis, but illustrates the wide range of applications that can be crafted with the same technology base. The recent work includes an application for planning of maxillofacial fracture repair that takes advantage of two Massie-like haptic devices and an extension of the Agus-like algorithm to handle interaction between pairs of arbitrary shaped objects.

Each application has various features beyond haptic rendering, but for the sake of this thesis only the haptic aspect will be covered.

3.1 Oral Surgery Simulator

The Oral Surgery Simulator was designed to support learning of surgical extraction of wisdom teeth [Forsslund, 2008]. The primary users are the final year undergraduate students in dentistry and their teachers who mainly are Oral and Maxillofacial surgeons. The simulator has been continuously developed and produced by Forsslund Systems AB.

The system consists of a simulator unit called Kobra (paying tribute to the shape to the Ericofon), and a software called FS-Wisdom (figure 3.1). Kobra comes with a mannequin which helps the student to position herself correctly and also provides relevant hand support for the surgery. The 3D display is angled and mirrored in a way that provides colocation of the haptic and visual image of the virtual teeth and the physical mannequins mouth. This way the student can feel the teeth where she sees them. The physical mannequin provides hand support for the operator.

The visual rendering consist of a non-interactive mesh of a face, combined with a real-time surface extraction rendering of the interactive jawbone (figure 3.2). The jawbone is represented by a segment map that defines which volume bounding spheres should have which of the five different materials: “enamel”, “dentin”, “bone”, “pulp” and “air”. As

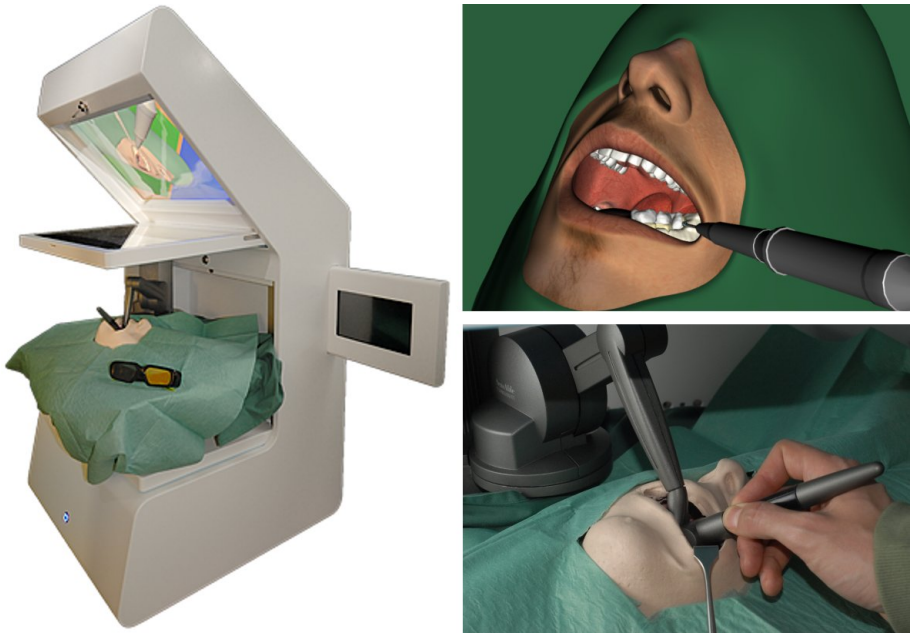

Figure 3.1: The current (April 2013) version of the oral surgery simulator Kobra running the application FS-Wisdom with a Phantom Desktop haptic device and a hand-made mannequin.

mentioned in the deformation section of the haptic algorithm described earlier, it is possible to assign a deformation rate to each material which will modulate the hardness feeling of respective material. Each material hardness is tuned by an experienced oral surgeon. Since the hardness parameter interplay with the overall stiffness and size of the probing sphere, all parameters have to be tuned at the same time.

The primary philosophy behind this application is to come as close as possible to reality while maintaining manipulandum stability and learning goals. The size of the virtual teeth are the same as real teeth, and so when the operator moves the manipulandum a few millimeter, the tip of the virtual dental drill moves the same distance over the virtual teeth's surface. Therefore the more expensive but higher fidelity haptic device Phantom Desktop was chosen over the more common Phantom Omni. In addition, as can be seen in figure 3.1, the manipulandum goes down into the physical mannequins mouth. The physical shape of the Omni makes this impossible to fit since it has a much larger joint and an extended tip.

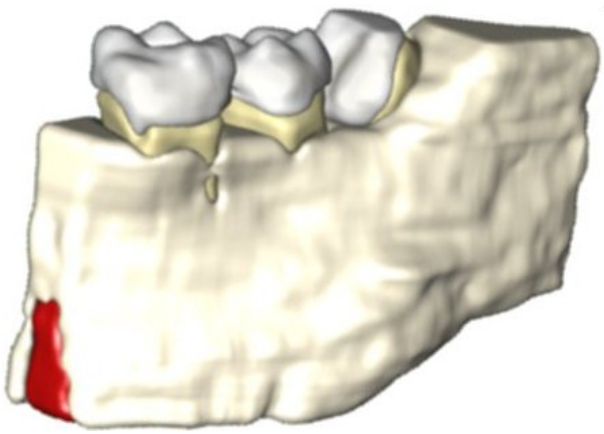

Figure 3.2: The interactive jawbone in the FS-Wisdom application

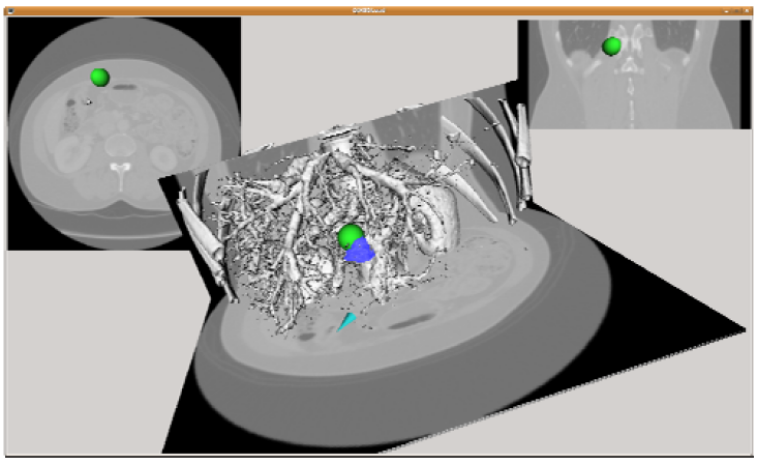

Figure 3.3: The liver surgery planning application. The green cursor is a sphere controlled by a Phantom Omni haptic device. The blue area is a tumor. The light blue cone is the mouse cursor moving in the plane also projected in the left corner.

3.2 Liver Surgery Planning

The liver surgery planning application was a prototype developed to support multi-disciplinary team meetings in highly specialized health care [Frykholm, 2013] [Sallnäs et al., 2011]. In these meetings surgeons come together with radiologists to decide if and how a cancer patient should receive surgery. Today the team is presented with slices of tomographic images that is controlled by the presenting radiologist. The conventional interface is very

Figure 3.4: Designer using a Phantom Omni device and MIDI controller interface to sketch the material properties of a dental anatomy exploration application

familiar to the radiologists, but the surgeons have sometimes difficulties in visualizing the spatial structure when the body is only represented by slices. The prototype we designed aimed at bridging the conventional interface of browsing a stack of slices by scrolling with a mouse wheel - and a more hands-on interface for the surgeons - using a Phantom Omni to move a 3D cursor of configurable size (figure 3.3).

A CT scan of a liver was down-sampled to reduce noise and render at interactive update rates. It was segmented into “air” and “tissue” by a binary threshold with an attenuation level that made the blood vessels stand out clear from the background. The patient had been injected with contrast-enhancing liquid which enabled this simple classification method. A third segment “tumor” was manually identified and “painted” layer by layer by a radiologist. The tissue and tumor was then rendered with the same method as the oral surgery simulator. The size of the liver was not necessarily life like, and the stiffness was set to be as high as possible while maintaining stability. The user could interactively change size of the interaction sphere which was useful in determining the amount of free space between the tumor and blood vessels. Several other functions were implemented, described in [Sallnäs et al., 2011].

3.3 Dental Anatomy Exploration

The Dental Anatomy Exploration application (figure 3.4) was an interactive sketch made with the design tool we developed for the purpose of sketching with the haptic material [Forsslund and Ioannou, 2012]. In contrast with the oral surgery simulator, this application did not utilize an isomorphic (1-to-1) mapping between manipulandum and virtual drill. The jaw bone was magnified and placed in the center of the screen without sur-

rounding tissue. Material differences was exaggerated so the user could clearly feel the difference between removing bone and the root of the teeth - an otherwise quite subtle difference. The rendering parameters where here tuned to maximize the user experience with the Phantom Omni without first hesitating and asking what pedagogical consequences a non-natural sized jaw and exaggerated material differences would imply. The conclusion is that applications could well be crafted using a subjective approach and create interesting applications as a result.

3.4 Maxillofacial Fracture Repair Planning

This application is designed to replace the widget-based spatial manipulation that is common in clinically used surgical planning tools, with bi-manual direct manipulation. A first application have been developed (figure 3.5).

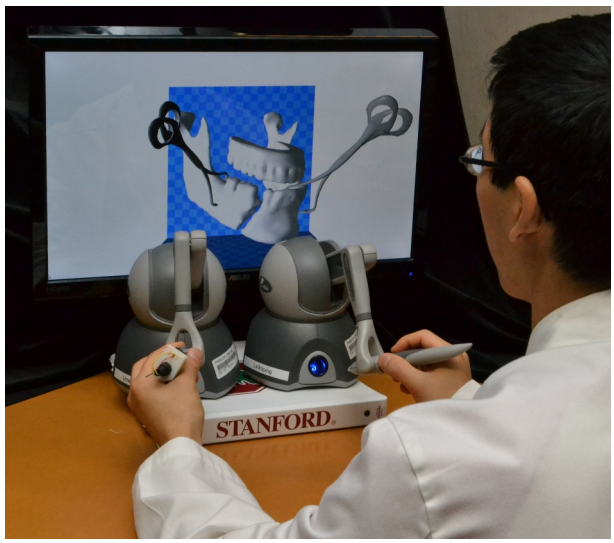

Figure 3.5: Bimanual haptic interaction in the Maxillofacial fracture repair tool

Most surgical planning tools in clinical use today are based on the Windows, Icons, Menus, Pointer (WIMP) interface paradigm. One example is Simplant OMS (Materialise Dental NV, Leuven, Belgium). By limiting the design to a WIMP or keyboard/mouse paradigm, the designer of a planning tool misses out on the last decades of progress in the field of 3D user interface technology. Emerging techniques such as direct manipulation and technologies such as free space trackers, bimanual interaction and haptic feedback have potential to improve the interaction in surgery planning applications. Although much of this technology is well known in the 3D User Interface research community, it is not yet widely adopted by the developers of interactive surgical planning tools for clinical use.

On the contrary, the research community for computer assisted surgery (CAS) has been very active in seeking out and incorporating much spatial input and advanced 3D visualization technology. Most applications reported in literature have only been designed with advanced interaction technology in the operating room, not for the pre-operative planning context. For example, Westendorff et al. uses 3D navigation in the operating room to assist the surgery, but plans the surgery on an ordinary WIMP workstation [Westendorff et al., 2006]. Another example is robotic assisted minimally invasive surgery, where the purpose of the robot is to overcome the constraints and low usability of traditional instruments [Guthart and Salisbury Jr, 2000].

Spatial input devices that support virtual object manipulation through direct mapping are easier and more natural to use for tasks that are fundamentally in 3D. The use of both hands to manipulate two input devices has further enhanced this effect, which improves spatial understanding of the manipulated objects [Hinckley et al., 1998]. Even tasks that are normally considered unimanual can be improved by using the non-dominant hand as a frame of reference [Ullrich et al., 2011].

Haptic feedback in virtual environments has been proven to significantly improve task performance and perceived virtual presence [Sallnäs et al., 2000]. Our recent studies also has showed that six degree of freedom haptic feedback significantly improve task performance over three degree of freedom haptic feedback in surgically relevant virtual environments involving direct manipulation of rigid objects [Forsslund et al., 2013]. The algorithm employed in that study only support unimanual interaction [Chan, 2011].

One of the very few studies that exists where both bimanual direct manipulation and haptic feedback are employed shows that task completion time is shorter in the bimanual case compared to unimanual setup [Ullrich et al., 2011]. Ullrich et al used a limited haptic algorithm, that would not be able to support interaction between two rigid bodies.

Recent work by our group [Chan, 2011] includes full six-degree-of-freedom constraint-based haptic rendering, but is limited to uni-modal manipulation. Chan's algorithm is designed for maintaining one volumetric dataset's isosurface (the patient) grounded and calculate interaction forces with a point-sampled surface geometry (the moveable tool). Compared to the volume, the tool has a small number of surface points that acts as feelers. Detecting and handling collision between two geometric rigid objects with many details requires another approach and symmetric data representations. State of the art algorithms in the haptic research field today includes [Barbic and James, 2008], [Ortega et al., 2007] and [Otaduy et al., 2004]. All of them are designed for unimodal interaction. The asymmetric data representation in [Barbic and James, 2008] makes extension to bimanual interaction non-trivial. [Ortega et al., 2007] present an update rate of 60hz for complex shapes which is insufficient for our purpose and [Otaduy et al., 2004] uses a dynamic simulation as collision response which bears instability risks in certain situations.

The aim of this work is to develop and study a fully bi-manual six degree-of-freedom haptic feedback system for direct manipulation of (groups of) high-resolution organic shaped rigid bodies. Thus, this work represent both purposeful design (improving the surgery planning software) and more fundamental technology development *enabling* the innovation of such application to use bimanual direct haptic manipulation.

Chapter 4

Conclusions from Papers

Here I summarize the conclusions from my studies and the contributions I have made to each attached paper.

4.1 Design of Perceptualization Applications in Medicine

This paper concludes the experience from designing three different haptic applications in the medical domain. Perceptualization is brought forward as an extension of visualization to support stimulation of other senses such as touch. In the paper it is described how a User-Centered Design approach is utilized to ground the application's design in field studies and co-operative evaluation sessions. Three different case studies are presented: Oral Surgery Simulator, Liver Surgery Planning and Heart Simulation. The paper brings forth the argument that User-Centered Design can support designers in finding real needs of professional users in the medical domain.

While the focus is placed on user-centered design in this paper, user-centered design activities are not the only form of influence on the applications' design. We can observe the authors bias in the form of a desire to explore how novel applications can benefit from haptic technology. This can be viewed as an instance of the designers desiderata [Nelson and Stolterman, 2012], rather than objectively grounding design in field data. We actively sought out situations where haptics had *potential* to make sense. Secondly, it is clear that the design is influenced by previous work in e.g. surgery simulation literature. The previous works cited also extends to social science [Johnson, 2007] and public policy [Giles, 2010].

Third, it is worth mentioning that the liver surgery planning prototype was developed using the same code base as the oral surgery simulator. This has the following implications. It could be implemented in a much shorter time than if one had to start from scratch. This obviously meant that feedback on the concept could be given much sooner than what otherwise would have been possible. In particular, the developed prototype utilized hard bone-like haptic rendering of the internal blood vessels of the liver. This despite the more logical solution to render them as the soft tissue it actually represent. However, imple-

menting soft tissue interaction with correct haptic rendering remains a challenging task, and could not have been implemented in a few weeks without previous experience of the topic. Actually correct soft tissue haptic rendering is still a topic for whole PhD theses themselves, and can today be done in reduced form [Barbic, 2007] if the implementor has enough skill and time to dedicate. Perhaps surprisingly, the quickly made prototype was warmly welcomed by representative users. It was discovered that navigating with a sphere through the nest of hard blood vessels gave an improved (subjectively reported) perception of the spatial structure they represents. In addition, by segmenting a tumor and selecting a known size of the movable sphere, the user could explore how much margin there was between the tumor and surrounding blood vessels. Also the very nature of the rendering algorithm employed - a penalty based rendering method ([Agus et al., 2003]) allows for small penetrations with colliding material. This means that the user was not completely stopped by collision with noise in the data (small chunks of material that was classified as hard by the binary classifier). Alas, the user experience was not too bad despite the rather simple application implemented. This section arguments for that a very strong influence of the applications design came from the capabilities of the technology and readily available tools and code, in addition to field studies.

4.2 Tangible Sketching of Interactive Haptic Materials

My experience of developing an oral surgery simulator for training and a number of other medical applications [Forsslund et al., 2011] have led me to question properties such as the necessity of isomorphic [Bowman et al., 2004] mapping for providing sufficient realism for a particular application. With the range of haptic interface devices available today the price is often very high ($10,000+) for devices with high resolution, stiffness and fidelity. Using a comparatively cheaper device makes isomorphic (1 to 1) mapping problematic, as the resolution and fidelity gets too low. However, if the model is enlarged they could be suitable. What more, we discovered that by tuning material properties manually instead of trying to derive properties from physical measurements, we could for example exaggerate small material differences (in our case between the slightly harder teeth bone compared to jaw bone).

This led us to create a design environment where we could tune haptic properties, including scaling, to provide a pleasing user experience even with a lower fidelity haptic device [Forsslund and Ioannou, 2012]. We used a tangible midi controller (figure 3.4) to adjust the parameters in real-time which enabled direct feedback on the invisible material property of haptic hardness and affords sketching [Dearden, 2006].

4.3 Three Themes of User Experience in Haptic Application Design

This paper was presented in a workshop about User Experience (UX) theory held at CHI 2012. It takes its ground in a Dagstuhl report on what user experience is and how it can be studied [Roto et al., 2011]. Dagstuhl seminars are highly renowned gatherings of international researchers who come together for about a week to focus on sorting out a particular

topic. One of their conclusions was that UX has a number of perspectives, of which one is UX as a *field of study*, with the purpose of developing design and assessment methods [Roto et al., 2011]. The purpose of my contribution was to understand and propose a framework for capturing, and ultimately design for, the user experience of haptic interfaces.

A literature study was conducted covering both user experience discourse and HCI's evolution as a field, e.g. what HCI should concern itself with, and how, especially in order to capture the "fuzzy" topic of human experiences. Different views are presented, such as the possibility and importance of quantifying user experience in order to improve it [Law, 2011], and the radically different approach based on professional judgment with roots in the humanities [Bardzell, 2011].

Grounded in my personal experience with spatial haptic application design, three themes was identified to be of particular importance to the topic of haptic interaction design: envisioned experience, quality of interaction and re-negotiation of experience. Envisioned experience is the kind of experience a designer envisions that a future product will or should have. This experience includes what features it has, what it enables the user to do, and how this empowers the user so s/he experience the product as e.g. cool [Holtzblatt, 2011]. Quality of interaction deals with the direct experience of interacting with the product. For a haptic interface, it is the way it feels in actual use. An example is given comparing two haptic devices running the same application: one can give a more stiff, crisp and less frictious interaction than the other. Buxton talk about *delightful perfection* of the feeling of a well designed mechanical juice press [Buxton, 2007]. Bardzell proposes *interaction criticism* to frame these qualities, in the same way a professional wine critic articulates the qualities of good wine [Bardzell, 2011]. Re-negotiation of experience is derived from Deardens concept of negotiation, for how designers as product development contractors negotiate with a client on what should be built [Dearden, 2006]. Dearden means that in real practice, development is as much about inquiry into what is possible to create as what is needed in a particular situation. Other authors, such as Sundström et al, talks about how their problem formulation changes as they learn more about the properties of materials (materials is here understood as a particular technology such as short range radio communication) [Sundström et al., 2011]. As the designers learn more about a material, such as haptic feedback, they come back to the negotiation table with the customer and propose potential solutions that better match technology and situation.

The conclusion of the paper is that design for good user experience is best approached with an understanding of technology as a design material that informs design solutions as much as the understanding of context of use.

4.4 The Effect of Haptic Degrees of Freedom on Task Performance in Virtual Surgical Environments

This paper explores a common misconception in haptic feedback research, that a sophisticated six degrees of freedom (DOF) haptic algorithm requires a fully actuated six degrees of freedom haptic device to be meaningful. While fully actuated 6-DOF haptic devices are highly interesting and valuable, they currently carries a significant cost premium over

devices with 3-DOF actuation. For details on 3-DOF, 6-DOF, fully actuated and under-actuated see the introduction chapter.

The paper reports on a quantitative and qualitative study on task performance of two surgically motivated interaction tasks, with different rendering algorithms and device capabilities as independent variables. The task was to move a virtual instrument, a surgical probe, in a constrained environment, and touch small virtual spheres without extensive collision with the surrounding environment. The rendering algorithms was either a classical 3-DOF haptic algorithm, that gives the user force feedback when a rotational invariant sphere (the tip of the instrument) collides with surrounding environment, or a full rigid body algorithm that takes the collision of the whole instrument into account. The capabilities of the haptic device was either outputting torque and directional force (6-DOF), or only directional force (Under-actuated 6-DOF and 3-DOF).

The results of the study shows no significant difference in completion time or errors for two particular tasks between full actuation and under-actuation. However, replacing the 3-DOF algorithm with a 6-DOF one significantly reduces number of errors and sometimes completion time, and this regardless of whether torque is displayed or not. This implies that designers should consider utilizing a 6-DOF algorithm even when a projects budget does not allow for a fully actuated device. It should be noted however, that some users could subjectively experience the difference, so the designer should be aware of the consequences of leaving out torque feedback. Not providing torque has also consequences for stability, as a virtual torsional spring that is loaded with energy without response (overly passive response) suddenly springs back with a high force (overly active response) as the user moves out of a collision state [Barbagli and Salisbury, 2003]. My conclusion is that it is up to the designer's judgment if this is acceptable or not for a particular situation. It is also possible that future research finds ways to accommodate or reduce the instability artifact.

4.5 Design and implementation of a maxillofacial surgery rehearsal environment with haptic interaction for bone fragment and plate alignment

The goal of this ongoing research project is to enable Maxillofacial surgeons to plan jaw fracture repair using an interactive planning tool with a novel 3D User Interface. Conventional software, such as Simplant OMS, presents the surgeon with a projection of bone segments that are manipulated using certain commands. Positioning and orienting a selected bone segment is accomplished with the mouse by alternating between two interaction states, one for translation and one for rotation. Simplant OMS has the ability to invoke bone segment collision detection on request by the surgeon, but it lacks any collision response mechanism such as haptic feedback, i.e., the software relies on the surgeon to move the bone segment out of collision. These semi-3D interaction techniques and lack of collision response makes the surgical planning process unnecessary lengthy and cumbersome.

We conducted field studies, interviews and collaborative evaluation session of functional and conceptual prototypes. Together with literature examplars [Bowman et al., 2004] it was clear that an effective 3DUI for this type of application would have benefit of sup-

porting:

- Direct manipulation in 6 DOF
- Bimanual interaction to provide a frame of reference and improve spatial understanding
- Enable grasping of multiple object in a hierarchy
- Real-time collision response
- High-fidelity haptic rendering

The paper reports on a low-fi prototype that was used to evolve a scenario describing how a system like ours could be used in a realistic setting. The idea of a bi-manual direct manipulation system was judged as technically feasible by implementing a proof-of-concept prototype of the most challenging part of the system; the haptic rendering, altough it used a very low-resolution version of the models at the time.

One reason we do not have more applications of this kind is that the most relevant haptic rendering literature such as [Barbic and James, 2008] and [Ortega et al., 2007] is only accessible to very few application developers. The fundaments that full 6-DOF haptic rendering builds upon puts quite high demand on the implementor in terms of knowledge in vector geometry, dynamics/statics, collision detection etc. In addition, what makes haptics more difficult is the symbiosis of a virtual simulation and a physical apparatus that requires stable control. An unsophisticated haptic algorithm can work in theory but makes a haptic interface of motors and cables go unstable.

Chapter 5

Discussion

5.1 Philosophy of Design

The overall purpose of my research is to improve the skill of an interaction designer (the reader) who wants to work with the spatial haptic material (or medium). This imply capturing the essence of haptic interfaces and how they can be appropriated in a particular situation. The way this thesis aims at improving the skill of the designer is by forming an intellectual, thoughtful [Löwgren and Stolterman, 2004] and reflective [Schön, 1984] approach to design of spatial haptic interfaces. It is based on an understanding of knowledge presented in philosophy of design below.

This research builds upon an understanding and purpose of haptic interaction design set forth in [Moussette, 2012], with philosophical roots in [Nelson and Stolterman, 2012]. Design in this view is about purposeful interventions in a *situation* to transform it into a preferred one. Situation is here a broad entity that can equally well be a product and its use in context, as an whole organization and how it can be changed. Even political action can be seen as design of a situation in this respect [Nelson and Stolterman, 2012]. A situation is more than just a context. For example, as we design a simulator for a dental education context, the situation involves the haptic devices available in the market at the time. As new devices appear on the market, the situation changes. Schön's *The Reflective Practioner* emphasizes that the inquirer (the designer) shapes the situation as s/he explores it: *He understands the situation by trying to change it, and considers the resulting changes not as a defect of experimental method but as the essence of its success.* [Schön, 1984] p. 151. This means that the situation is not something static that best can be studied with e.g. ethnographic methods alone, but something the designer has an active *dialogue* with, alters and experiments with during the inquiry and eventually transforms through deployment of a product or similar.

It is important to decide which philosophical framework to appropriate to a particular subject of study. The academic discipline of design research is fundamentally different from that of scientific inquiry. The main difference lies in that design research is as much concerned with what is *real* and *desired* as to what is *true* [Nelson and Stolterman, 2012].

It is not based on an understanding of knowledge that requires measurability of the subject of study. Nor is it about *problem solving*. Design is fundamentally about changing existing, real, situations into preferred ones. This requires one to form an understanding what a preferred situation constitutes, which is a topic in philosophy of ethics. For example, it cannot be taken for granted that a more efficient system is always better, see Sengers on Taylorism in Computer Science [Sengers, 2005]. The understanding of what is real includes human relationships already existing in the situation and how they will be changed by our design, and existing, real, artificial (human-made) objects including available technology such as software toolkits. Design knowledge also involves a large amount of *judgment*, and practical wisdom (phronesis in Aristotle's terms). This kind of knowledge is related to the pre-Socratic understanding of wisdom (Sophia) to mean the integration of reflection and action into the *knowing hand*. The archetypal designer was therefore the carpenter or blacksmith. The wisdom of the knowing hand was by Plato divided into thinking and doing, where that of doing was socially subordinated that of the thinking. In design philosophy, design wisdom requires the reconstitution of the knowing hand, Sophia, to mean the integration of reason with imagination and action (making and producing) [Nelson and Stolterman, 2012]. This is why an analytic-only approach to haptic interaction design would not suffice to capture the wisdom, or skill, that the purpose of this thesis is set to improve.

Potentially important works for shaping an understanding of spatial haptic design could include the following. For an introduction to *design thinking* as the main mind set of a designer, see [Brown et al., 2008]. For the philosophical foundation of design I refer to [Nelson and Stolterman, 2012]. For a text by same co-author with examples in Information Technology design see [Löwgren and Stolterman, 2004]. One example of the role of the humanities in design, as a way to judge and value products, see [Bardzell, 2011]. As examples of how a designed product such as surgery simulators can be critically analyzed from a social studies perspective [Prentice, 2005] and [Johnson, 2004] are recommended. Design has to be made real to have real impact, and this involves appropriate use of scarce resources, or economics. One example of works in the discipline of economics related to this thesis is [Von Hippel, 2003]. Aesthetics, visceral design and related subjects is practically approached in [Buxton, 2007] and [Norman, 2005]. The designers conversation with the situation is conceptualized in [Schön, 1984], and appropriated to digital design in e.g. [Dearden, 2006]. A good introduction to haptic interaction design, philosophy of design and interaction design research can also be found in [Moussette, 2012].

5.2 Interaction Design

My interpretation from reading numerous works on the topic of design and design research and its relation to human-computer interaction, is that interaction design should (for our purpose) be grounded in the thought tradition of "traditional" design practice, and it should be studied with a perspective that acknowledges the inherent subjectivity of the designer. In other words, it is not a thought tradition that strives at finding an objective truth to design practice. The engineering thought tradition is inclined to create

deterministic processes and methods where a given input yields a certain output, independent of the human actors involved in the process. User-Centered Design, as described by the ISO standard, is in my view intended as such an objective process. The design way [Nelson and Stolterman, 2012] presents an alternative, where the designer is a subject of flesh and blood, and where the outcome is primarily judged rather than evaluated. This view gives much freedom to the designer, but also much more responsibility. The designer is charged with the power to change the world, and has to act responsibly with that power - including concerns for environment and future generations. The designer must also educate herself in the tools and techniques for working with the material she chose in order to create something "good". In design traditions, as in art, what is "good" is inherently ill-defined in objective terms. Not even what most people desire can be consider "good" in the same way works in popular culture not necessary is considered the best culture works.

Classical video games such as Tetris and Sim City 2000 is currently on display in the Museum of Modern Art (MoMA), New York, as fine examples of interaction design. An exhibitions plaque reads:

> Tetris is one of the first video games to enter MoMA's collection, selected with thirteen others as a pillar of interaction design - one of the most important and oft-discussed expressions of contemporary design creativity. This acquisition allows the Museum to study, preserve, and exhibit video games as part of its Architecture and Design collection. The selection criteria emphasize not only the visual quality of each game, but also the overall experience and many other aspects - from the elegance of the code to the design of the player's behavior - that pertain to interaction design.
>
> Moreover, as with all other design objects in MoMA's collection, from posters to chairs to cars to fonts, curators seek a combination of historical and cultural relevance, aesthetic expression, functional and structural soundness, innovative approaches to technology and behavior, and successful synthesis of materials and techniques in achieving the goal set by the initial program. This is as true for a stool or a helicopter as it is for an interface or a video game, in which the programming language takes the place of wood or plastic and the quality of the interaction translates in the digital world what the synthesis of form and function represents in the physical one.

With this quote I would like to illustrate what we should expect from interaction design when it is at it's best. It is apparent that interaction design in MoMA's understanding is inseparable from programming - in fact the elegance of the code and the view of programming language as a material is very central to the judgment by the curator. The quote helps to motivate the research questions initially set forth in this thesis.

5.3 Crafting Haptic Applications

In this section I will address the research questions set forth in the introduction to this thesis. I will show how the work I have done in the projects I have been involved in can

illustrate or stand as evidence for certain statements I will make in this discussion.

Which are the most important characteristics of spatial haptic user interfaces?

A spatial haptic user interface is inherently a 3D User Interface. Therefore what applies to 3D User Interfaces in general is also applicable to Haptic 3DUI's. It became evident in the liver project that navigation (camera orbit around the virtual liver), a well known 3DUI topic, was central to the design of our application, although there was no haptics involved in that navigation. By the time of design I had very limited awareness of the canonical body of knowledge in the 3DUI field. In the more recent fracture repair planning project, I realized its relevance, discovered [Bowman et al., 2004] and read this book from cover to cover. The difference in my capability to verbalize the relevant aspects of the fracture repair planning application and the liver application is evident in the sections above about respective work. The importance of Bowman is not that it provides technical knowledge, but that it maps out the design space and discusses opportunities and limitations of different interaction techniques, technologies and systems. I conclude that the most important characteristic is that the Haptic (Massie class) 3DUI provides spatial interactions, direct manipulation in six degrees of freedom and a design space of interaction techniques that follow from these properties.

What makes Haptic 3DUI's unique compared to other tracker-based 3DUI's is then that it has the ability to give force feedback. In my work the force feedback has been computed using an Agus-like method (and extension of it in some cases). If we rephrase the question as: *Which are the most important characteristics of the combination of the Agus-like algorithm and a Massie class haptic device?* my conclusion would be:

- The combination enables direct manipulation of a rigid object in space
- The combination enables collision response in form of a force when the manipulated object partly penetrates the surrounding environment. This force is perceived by the user as a resistance. The more the user pushes against a surface, the higher the force - and this partly hinders the user from pushing through, indirectly affording a *constrained interaction*.
- The combination affords the *contour following* explorative procedure of voxel based virtual environments with a sphere [Lederman and Klatzky, 2009].
- The algorithm is based on collision detection with a sphere of arbitrary diameter. If more than half of the sphere penetrates the surface the rigid object will pop through.
- The algorithm's time complexity in its unoptimized form (without a bounding sphere tree) is $O(n^3)$ where n is the number of voxels in the environment that fit on the diameter of the avatar's sphere. Thus, it is fine to have a physically large sphere as long as the resolution of the environment is kept low (i.e. large voxels), but not a large sphere in combination with a high resolution environment. The designer must handle this trade-off.

- The device has a fixed and limited maximum force and stiffness. The Phantom Omni and the Phantom Desktop can provide different amount of maximum stiffness. Stiffness is the amount of force that can be provided per displacement unit - in other words how many Newtons can be displayed for each millimeter surface penetration. While this stiffness value can be set in software it will be displayed differently on different devices. A stiffness value of over 1N/mm will easily make the manipulandum unstable and vibrate unpleasantly on the Phantom Omni, while the Phantom Desktop handles it well.

- In addition to collision response, the algorithm can rigidly deform the voxel environment "drilling" with a different rate for each voxel. In other words, different "hardness" can be simulated in different regions of the virtual environment.

- The hardness is not completely arbitrary, but is a product of the stiffness selected and the stiffness the device can provide, the size (or scale) of the voxel environment, the fidelity (resolution etc) of the device which together determines the ability to distinguish between different virtual segments of the virtual environment.

Which are the material properties (or parameters) that a designer should explore to understand what the haptic technology can do?

The haptic technology is here understood as the haptic technology involved in the Agus-Massie system described above. In the Sketching paper (section 4.2) several parameters were identified as relevant for tuning. It is worth mentioning that me and my coworker share the same code base and the same kind of devices (her lab has a high-force variant of the Phantom in addition to our set of Omni and Desktop), for our different projects. Evidently can the same technology be tuned for my oral surgery simulator, for her ear surgery simulator and for our illustrative jaw anatomy exploration application described in the paper. To conclude, for a Agus-Massie system a designer should explore hands-on, tune and form an tacit understanding of the result of tuning at least the following haptic parameters:

- Interaction sphere diameter. E.g. burr size.

- Scale of virtual environment. E.g. scaling a virtual jaw to be twice as big as reality to increase stability with lower cost devices.

- Haptic stiffness. This factor which is multiplied with intersecting volume yields displayed force magnitude.

- Cutting rate that gives a perception of hardness of different segments (e.g. enamel is harder than bone)

- How different hardware devices behave when alternating any combination of the above parameters.

What does an interaction designer need to know in order to successfully work with the spatial haptic material?

As mentioned above, the main characteristic of a Massie-Agus system is that it is a 3DUI, and thus there is no excuse to not be familiar the most canonical works of the 3DUI field, i.e. [Bowman et al., 2004]. Practically the designer should know how to implement fundamental 3D interaction, which requires bachelor level computer science competence (programming and vector geometry in 3D). The interaction designer needs to acquire a sense for the haptic material by experimenting with different parameter values as mentioned above. Preferably s/he should know how to integrate those in a system for an holistic user experience.

Sometimes the parameters would not be sufficient, and the designer would have to decide if it is feasible to implement "new materials". For example, the Agus-like algorithm implemented in this thesis can be extended to handle friction. Friction will involve its own parameters that can be set to be derived from nature (measurement of friction of wood etc) or tuned interactively. This kind of material extension is not trivial to implement, even though solutions has already been published and are well known in the haptic research community. Now, friction might not be as hard as other haptic features to implement, but I argue that it is a *different activity* to implement a new material than designing with it. Personally it became evident when I got involved in implementing what is essentially six DOF rigid body interaction in the fracture repair project. To successfully implement a correct 6-DOF algorithm the programmer is required to know or learn a number of post graduate level "dependencies" in math-related subjects which makes the implementation work lengthy and with high risk of making mistakes along the way. I am not arguing that the interaction designer should necessarily have the competence to implement all published haptic algorithms. However, the more knowledgeable the designer is of not only how the material behaves, but also to what degree it can be extended, the more empowered the designer will be.

What should be the best practice for creating innovations and applications based on (or with) spatial haptic interface technology?

First of all, the innovator or designer has to know the existence of the opportunity of utilizing this technology. This applies to every interaction designer but requires not more than reading a high-level article. This kind of reading should be a regular practice (and not connected to any particular project) of a professional designer, to be aware of emerging materials in the field, just as conventional designers often keep themselves up to date with emergent physical materials. After knowing its existence, if it caught the curiosity of the designer for potential use in a particular setting, it is important to learn more of what the material actually can do, how it feels and behaves (it is an interactive material after all). This can be done with an application as described in the Sketching paper. It is also common for programmers to download and "play around with" one or several Software Development Kits, libraries and their examples. This is done by changing parameters to get a feel for both what can be done and how easy it is to work with, which gives the

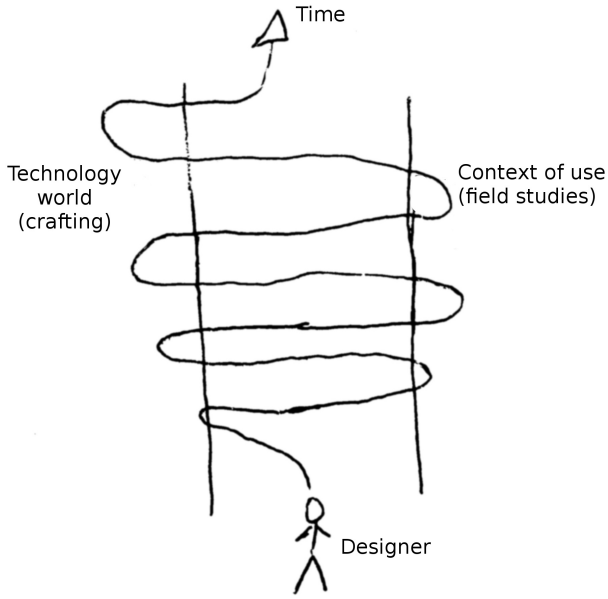

Figure 5.1: The technology designers path.

programmer a sense of what opportunities and risks are involved. A toolkit for innovation [Von Hippel, 2001] is very useful in this stage.

It is also imperative that the designer educates herself in similar solutions, what others have created as a collection of exemplars.

Of course it is still important that these activities are conducted in parallel with investigations of the particular design situation, mainly with field studies and interviews of potential future users. I would like to describe the designer as a kind of match maker between the technology world and the context of use, where deeper and deeper inquiry into each world is carried out over time. Both technology and context are allowed to change, i.e. a more promising problem formulation or application domain might be found over time. And perhaps controversially in HCI culture, this path necessarily starts with a walk in the technology world (as first paragraph argues). This back-and-forth walk is illustrated in figure 5.1.

In my first haptic project, the oral surgery simulator, I took such a path in parallel with the mandates of a User Centered Design process. I very early showed a haptic demo to the client (the surgery teachers) where they could poke a virtual box. This gave them and us a first understanding of the potential of the technology; that a haptics enabled simulator could actually be made. The question became more how and in what way, than if the idea was just fantasies. Nowhere is this kind of work to be find in the mandates by the User Centered Design process as described by ISO. This previously tacit knowledge of practice that I actually carried out, and always unconsciously carry out when I design, is important

to acknowledge.

How should haptic user interfaces be judged or evaluated?

This question is much more of a philosophical kind, but if the reader is interested in my opinion, it is that the only reasonable way of judging an interface is how well it achieves a goal, whether or not this goal is objective or subjective. To return to MoMA's decision process of which artifacts to include in their exhibition:

> curators seek a combination of historical and cultural relevance, aesthetic expression, functional and structural soundness, innovative approaches to technology and behavior, and successful synthesis of materials and techniques in achieving the goal set by the initial program.

It is the curator who judges these mentioned qualities. I believe a haptic application should be judged in the same way, which essentially is a form of interaction criticism [Bardzell, 2011]. The outcome I am looking for in an evaluation is most similar to that of a headphone review from a High Fidelity magazine (figure 5.2).

Of my creations I am most pleased, when it comes to haptics, with the jaw anatomy exploration application in the Sketching paper. I will here attempt to explain it's qualities as a haptic application review magazine would:

> This app is designed for use with the Phantom Omni, which keeps the system price one fifth of other apps in the genre. The interface is easy to understand and quick to get acquainted with. The anatomical landmarks are clearly visible and distinguishable from each other. The mandibular nerve can be viewed through the translucent bone, that makes it easy to understand where it is located relative to the teeth roots. The haptic feeling is crisp yet stable. We could not experience the "nervous" feeling of some similar system. Perhaps this has to do with the fact that the bone is three times magnified as natural size. As bone is removed and the teeth's roots appear, a distinct difference in resistance is perceived. The feeling is like carefully scooping soft ice-cream and coming in contact with parts of chocolate, the chocolate (roots) can be felt without being damaged - as long as not extensive force is applied. This is remarkable given the limited noticeable difference and dynamic range the Omni is so often blamed for.

The benefit of this kind of evaluation is that as much as possible of the full user experience can be captured using words, which is common in other judging professions such as wine critics [Bardzell, 2011].

5.4 Limitations of User Centered Design

In the attached paper *Design of Perceptualization Applications in Medicine* (section 4.1) a number of factors influencing the design is implicitly stated. These factors include tech-

Figure 5.2: A typical HiFi magazine review of a pair of headphones. Personal phrases with carefully chosen adjectives were used to describe the panelists judgment of the quality, e.g. *It has a virtually perfect balance, very clean and open-sounding*. Note also that the frequency response diagram and commentary: *The frequency response of the (headphone) confirms our listeners' impressions that its tonal balance is light on the bass and perhaps a tad treble.* [Sound+Vision, 2012]

nology capabilities (what a haptic system can provide), psychophysics (how the brain integrates information from multiple senses), ethnography findings (how surgeons carry out their tasks) but also larger societal questions including public policy (European Union limiting surgeons work hours) and social and cultural interpretation of practice (Johnson's observation that skills trainers imply that skill can be learned out of context and later rein-

tegrated in context).

This leads me to conclude that *design* is (or should be) concerned with integrating knowledge and influences from all of above. It is certainly impossible for any individual to cover such an avast range of disciplinary knowledge. Nonetheless can't we ignore that it is from this holistic perspective the product will eventually be judged by society.

5.5 Design Practice and Evaluation

Interaction criticism acknowledges the complex relationships between the interface including aesthetics and the user experience all the way to a societal level [Bardzell, 2011]. Future research would therefore benefit from further investigating the idea that works of purposeful design could more appropriately be valuated by something like interaction criticism than by reductionistic approaches (comparative studies of only a small part of a system).

However, interaction criticisms is based on the humanities, and *humanists are concerned with problems, not solutions*, a statement made clear at the Panel on The Humanities and/in HCI at the premier conference for Human-Computer Interaction, CHI 2012 [Bardzell et al., 2012].

Without proposing solutions a void remains for how the practice of interaction design should be carried out. An interesting concept that resonates well with my own thoughts is the designers *desiderata* proposed by Nelson and Stolterman [Nelson and Stolterman, 2012] and made relevant to haptic interaction design by Mousette [Moussette, 2012]. It gives the designer a much larger role to act towards intentional change. In addition it allows the computer scientist-as-designer to break away from the narrow efficiency goals of Taylorism [Sengers, 2005].

The understanding of design as driven by designers desideratas and evaluation of designers work by criticism is not in conflict with the HCI field's desire to improve interaction technology. Rather the opposite, it would free up capacity of the technologist to create materials for design. One way to do this is through creation of toolkits for innovation [Von Hippel, 2001]. Another is to create tools that enables design with complex materials, including tuning of perceptual qualities. This is what we accomplished with Tangible Sketching of Interactive Haptic Materials (section 4.2).

This thesis should propose how the research can be extended to form a PhD thesis. With the aforementioned argumentation I propose a research agenda focused on how to turn spatial haptic technology into a much more design-ready material that enables *crafting* high-quality applications. Practically that would involve researching which properties are the most important to expose to design, develop toolkits that exposes them, authoring applications for tuning perceptual properties and finally develop exemplars as *inspirational bits* [Sundström et al., 2011].

5.6 3DUI as a Body of Knowledge

In the first years of my work, I thought the most important topic to understand was haptics itself. How to use the device and how to construct rendering algorithms. As a close second

was the user-centered design process and contextual inquiry in order to form requirements as a basis for design work. In retrospect, I realize that the kind of interface I was constructing - 3D User Interfaces - was as much, if not more, dependent on the body of knowledge presented in literature by e.g. [Bowman et al., 2004], to be successful.

One example is the rotation interaction technique in the liver surgery planning application discussed in section 4.1 (figure 3.3). At first the application was developed without any concern for rotational abilities at all. However, the application was build on top of an API that per default provided a means of orbiting the camera around the focal point of the scene. The computer already had a mouse connected, and so this feature was provided to early test users. Now, while I was familiar with rotating virtual objects using the mouse, the surgeons were not. They really liked the ability to rotate though, although nothing from the contextual inquiry studies showed an indication of that. Reading [Bowman et al., 2004] retrospectively it is clear that we should have implemented other interaction techniques and perhaps other hardware like a 6-dof tracker to support navigation.

The book by Bowman et al is interesting in that it presents a well structured overview of solutions for 3D user interface technology and suitable interaction techniques for the major tasks: selection and manipulation, navigation, way finding and symbolic input. It's utility is not dependent on statistically proving that certain combinations of technology and techniques makes a more effective interface. Instead, the rich descriptions informs the designer of suitable solutions for a particular task. Haptics is mentioned in the book but does not play a large part. I believe future work on spatial haptic interaction design could generate knowledge that would find its way in to such a book.

5.7 Software Production

Design is an inclusive compound of inquiry into what is real, true and ideal. The real correspond to the world around us, including humans, human-made objects, and processes. The true correspond to facts, that we can find using the scientific method. The ideal correspond to what is desired to be. Designers work with turning the ideal into the real, and all three forms of inquiry are essential to designers [Nelson and Stolterman, 2012] (p. 37).

An inquiry into the real for software design ought to include inquiry into what building blocks and tools for production that exist in the current world. Just as industrial designers need to take limitations and possibilities with mass production processes into account when they design, so would the equivalent "industrial interaction designer". Perhaps we would also see an emerging "software producer" profession. Fictional movie producers such as Jon Landau (Known for Titanic and Avatar) and Stanley Kubrick (Known for 2001: A Space Odyssey and Barry Lyndon) is known to use cutting edge and custom made technology in their productions. Jon Landau has mentioned that during the production of Titanic, he and James Cameron asked the computer graphics group to create an underwater scene they know would pose a significant challenge. If the computer graphics group would fail, they knew they could cut the scene from the movie and maintain a coherent high-quality production - but if they succeeded they knew they had a new technology at their disposal for future movies [Landau, 2013]. A software producer that strive for excellence should

consciously adopt a strategy for balancing risk with emerging technology while guaranteeing highest quality of the final product.

5.8 Future Work

In this licentiate thesis I have presented my work on spatial haptic feedback rendering, interface construction and application design. The main idea of my future doctoral thesis is to provide designers of 3DUI applications with a subset of useful haptic technologies that can be considered in their future applications. My contribution will be a toolkit for innovation [Von Hippel, 2001] and set of inspirational bits [Sundström et al., 2011] that can inform designers of the properties and qualities of haptic hardware interfaces, as well as new rendering algorithms and authoring tools. By exposing some design properties for tuning, the designer will be able to form the digital and physical material properties of haptics for a particular application. The purpose is to lower the technological barriers and encourage wider use of haptics in the 3DUI community.

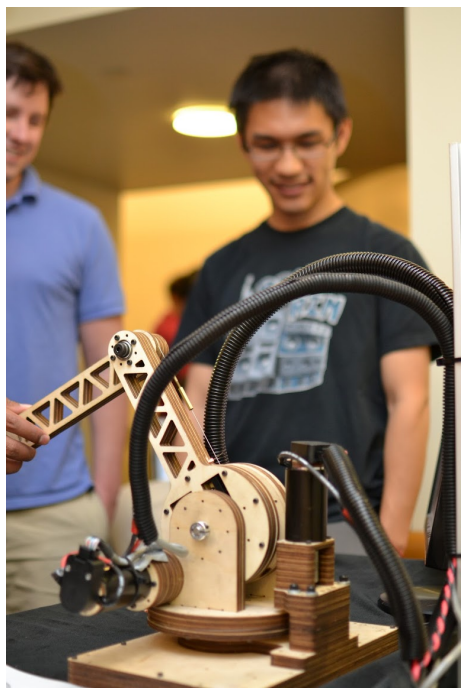

Figure 5.3: The 3-DOF wooden haptic device.

My wish is to, as far as it is feasible, encapsulate our work so that application developers with fundamental 3DUI knowledge and skills can incorporate accurate and stable haptic rendering through a software library. This library might impose some restrictions,

and might require tuning of some parameters, in which case they will be exposed to the designer in a convenient way.

Real-time collision response and high-fidelity haptic rendering seems not to have been extensively evaluated in literature. For example [Schultheis et al., 2012] compared bimanual tracker-based interaction to other methods, but their application lacked collision response. Research on the impact of these technologies could be an opportunity for a contribution as well.

In parallel with software development I have worked on a wooden haptic interface (to be published). The main purpose of this project has been for me as an application (or system) designer to get a deeper understanding of the workings, physicality and design parameters of haptic interface hardware. The first step of this process was to design and construct a haptic interface from scratch (figure 5.3). Despite being made of wood, this device actually has quite high fidelity, probably thanks to the high quality motors and precise encoders/electronics. It compares well to commercial devices.

The device itself represent nothing novel compared to it's 1993 conceptual foundation [Massie, 1993], but it provided me with both tacit knowledge (hands-on know-how) and the ability to articulate hardware qualities. Concept such as back-driveability, cable-driven, back-lash, gravity compensation and kinematics now have a real meaning for me.

Crafting

> Craft is the skill set a designer needs to use when working with the right materials, in the right proportion, with the right tool set in order to produce a final desired, designed outcome. [Nelson and Stolterman, 2012]

Crafting is a necessary part of bringing design concepts to life, and involves craftsmanship. Authentic attention must be paid to the maturation of a design, in all parts of a design process. Apple Corporation became famous for successfully turning concepts developed by others into products that set standards in the industry [Nelson and Stolterman, 2012].

Apple is also famous for producing a careful blend of hardware and software (for good and bad). This empowers its designers to craft a holistic user experience. Software engineers and hardware engineers are normally two different specializations, but crafting has the potential to bridging them into a coherent unity. Careful crafting requires dedicated time and effort. This requires that technical problems have to be solved first to an acceptable level of quality, so that focus can be shifted from adding features to tuning of user experience. I have acquired the skill to bring the fundamentals of a Massie-class haptic device and fundamental haptic rendering methods into life. However, several parameters are quite arbitrarily (e.g. workspace dimensions) chosen and it is likely that the device could be crafted to a higher level of perfection. From the same concept, several very different variants could be crafted, where each would be suited for a particular setting, e.g. a large workspace variant for standing interaction or a high force variant for heart rescue simulation.

Next step of this project is to explore how some of the hardware design parameters affect the final user experience in a very subjective way. For example, since the prototype is

made of wood it would be easy to replace an arm with a longer or shorter version to experience the change in workspace dimension. Eg. as workspace grows resolution shrinks, so how does this affect the experienced stiffness? Another component of big importance is the motors. What if the high-end Maxon motor ($100+) is replaced with a low cost alternative? Experimenting with these components could clarify why the Phantom Desktop feels better than the Phantom Omni. My goal would be to turn the prototype into a replicable form with a base design that designers can tinker with hands-on, like [Moussette and Banks, 2011] or [Sundström et al., 2011] in order to better discuss requirements with mechanical engineers for production. Crafting haptic hardware also enables me to work with visceral design [Norman, 2007].

I plan to package the wooden haptic device in a way where all but a few design parameters (e.g. workspace, motors) are fixed in a replicable and reusable base design. It will allow application designers to hands-on perceive how e.g. arm length will affect the perceived stiffness and inertia of the tool in an application. I will myself or together with external designers conduct some kind of open-ended experiment and document if and how this approach facilitate ideation and communication in an engineering team.

I will implement decent algorithms as part of a small library for bimanual direct manipulation of rigid objects with haptic feedback. The designer would be able to try different devices with the application or tune a few meaningful properties such as stiffness and scale. Some limitations will deliberately be left to the user to overcome. The user of my library might for example be required to render models with lower resolution haptically than visually, in order to maintain interactive update rates which is imperative to a high fidelity user experience. In this scenario having limitations will not be considered a problem, rather the opposite. By clearly stating the limitations and allow for exploration of which conditions the system works satisfactory, a design space is formed where meaningful applications can emerge.

I plan to continue our work on tuning virtual haptic material, and make it more robust to allow for easier access to external designers. Perhaps host a design workshop (like Mousette[Moussette, 2012]) to explore its usefulness to others.

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Part II

Attached Papers