Doctoral Thesis

Elastic computer input control in six degrees of freedom

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Elastic Computer Input Control
in Six Degrees of Freedom

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presented by
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Preface

Like many PhD theses, this thesis follows a basic research procedure including the identification of a research topic, literature analysis, experiment set up, data collection and a discussion on the results. Uncommon, however, is the awareness of the potential market value of the equipment developed to set up the experiments. Today time to market for new products is essential, so in order to avoid any time losses, emphasis was put on creating a product adapted to market needs in parallel to the research. Moreover, an additional goal has been to let a spin-off company launch the new product named SpaceCat.

In Switzerland as well as in the entire industrialised world, politicians emphasise the role of new high tech companies to inject new strength in the economy. Europe is often said to produce excellent research but to be poor in the commercialisation. In order to support researchers who are interested in the commercialisation of their research the Swiss initiative KTI-StartUp was founded. KTI-StartUp supports the technical development aiming at a product in line with the market as well as giving researchers the opportunity to develop a business plan together with an experienced consultant.

This thesis not only describes the research done with SpaceCat, but also the process leading to the product SpaceCat. It was supported by KTI-StartUp and demonstrates one way of how to integrate research and education in a product development process. In the project electrical engineers, software developers, mechanical engineers, ergonomists, industrial designers, and economists have contributed from four different universities and establishments of higher education. The SpaceCat project was supported during the initial networking phase by the Zentrum für integrierte Produktionssysteme (ZIP) at the ETH in Zürich, Switzerland. ZIP aimed at a more interdisciplinary approach to the optimisation of production and product development than the state of the art during the CIM-era of the 80's. This optimisation can be achieved only by an integral approach including human resources, technology, and the organisation. Consequently research institutes dealing with management sciences, work psychology and different production tech-
nologies participated in ZIP. This was a pioneer work in bringing researchers from different industry related disciplines together. Another goal set by ZIP was to achieve greater co-operation between universities and small or medium sized companies. There is a great potential in enabling such companies to actively make use of a knowledge base they cannot afford to build up on their own. The SpaceCat project took part in this process by including a network of small and medium sized companies for the product development and for the production of an initial batch of SpaceCat. From the experiences drawn out of the project I am convinced that a very important task for universities in the future will be to encourage the combination of research, education and entrepreneurship to become a starting point for innovation.

The success of the SpaceCat research and product realisation projects was dependent on the contributions of many persons. First I'd like to thank ZIP for financial support and visionary ideas. Here I'd also like to mention the other organisations and companies involved: Schule für Gestaltung und Kunst in Zürich, Ingenieurschule St Gallen, Hochschule St Gallen, Höhere Wirtschafts- und Verwaltungsschule Olten, Ingenieurschule Rapperswil, KTI Start-Up, Meyco Equipment AG, Maag Technik AG, Iftest AG, Ganzoni AG, Hubert Tricot, Proform AG, Federfabrik Kaltbrunn AG and all staff and students who have been involved at these institutions in their free time or in student works. Thank you to my professor, who made it possible for the SpaceCat project to have its basis at his institute although it was not completely in line with the other research activities at the institute. Also thanks to Professor Helmut Krueger and Joseph Weiss for ergonomics and physiology know-how, Philipp Bühler, Morten Fjeld and Mario Clerici for great discussions on the electronics design, usability tests and parallel kinematics, Joachim Wirth for good advice and a cool software demo, Gilles Caprari, Shausong Lu and Peter Willburger for parts of the micro controller program, software driver and 3D Studio MAX plug-in, Georg Kralidis for good advice on the statistics evaluation, Pierre Sachse for discussions on product development methodology, Michael Bucher for mechanical design and last but not least Michael Krohn, who gave SpaceCat its good looks!
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List of Symbols and Abbreviations

Abbreviations

MMI man machine interaction
HCI human computer interaction
DOF degrees of freedom
CAD computer aided design
CAM computer aided manufacturing
CAAD computer aided architectural design
CAID computer aided industrial design
OEM original equipment manufactures
ISV independent software vendor
NFR not for resale
QFD quality function deployment
SDK software development kit
API application programming interface
IP internet protocol
TCP transmission control protocol
UDP user datagram protocol

Device Properties and Transfer Function

$u$ position and orientation deflection vector of the device handle
$F_s$ forces and torques acting on the device handle
$M_s$ device handle mass and inertia matrix
$K_s$ compliance matrix
Bs viscosity matrix

\( \Gamma \) position and orientation of the controlled object

\( f(u, \dot{u}, \ddot{u}) \) transfer function

\( f_0, f_1, f_2 \) linear transfer function constants

**Spring Parameters**

\( L_s \) induction

\( R_s \) resistance

\( D_s \) coil diameter

\( d_s \) wire diameter

\( N_s \) number of coils

\( l_s \) length

\( k_s \) stiffness

**Oscillator**

\( C_s \) LC-circuit capacitor

\( Q_s \) LC-circuit quality

\( \omega_s \) LC-circuit resonance frequency

\( Z \) amplifier impedance

\( R_1, R_2, R_3, R_4, R_5, R_6 \) amplifier resistors

\( C_1, C_2 \) amplifier capacitors

\( C_a, C_b \) lead filter capacitors

**Sensor Geometry and Kinematics**

\( B_h \) base coordinates

\( A_h \) platform coordinates

\( \bar{A}_h \) equilibrium platform coordinates

\( l_h \) spring lengths

\( u_h \) platform position and orientation

\( f_h(u) \) inverse kinematics

\( J \) Jacobian matrix

\( \kappa(J) \) condition number of Jacobian matrix

\( S \) translation vector
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\( R \) rotation matrix
\( \theta \) Euler rotation angles
\( r \) platform radius
\( H \) equilibrium distance between platforms
\( \ell \) side length of octaeder

**Docking Task Geometry**
\( d \) cursor and target internal distance unit
\( s \) cursor and target size
\( Q \) normalised quaternion describing cursor orientation
\( \bar{e} \) normalised rotation vector
\( \theta \) rotation angle
\( S(t), Q(t) \) position of the cursor at time \( t \)
\( \hat{T}, \hat{\hat{T}} \) docking start time and end time
\( \hat{S}, \hat{Q} \) cursor start position and start orientation
\( \hat{\hat{S}}, \hat{\hat{Q}} \) cursor end position and end orientation
\( \Delta S(t), \Delta Q(t) \) cursor distance to end position at time \( t \)
\( \Delta \hat{S}, \Delta \hat{Q} \) difference between cursor start and end position

**Collected Data Description**
\( \Gamma_{nmlkjihg} \) cursor path
\( n \) subject id
\( m \) device id
\( l \) index for a set of docking trials
\( k \) index for a subset of docking trials
\( j \) distance index
\( i \) target size index
\( h \) degree of freedom index
\( g \) sample index
\( \xi \) measurement order index
\( \eta \) geometrical boundary index

**Fitts’ Law and Half Way Time**
$T$ completion time
$A$ movement distance
$W$ target size
$a, b, c$ Fitts’ Law parameters
$b_h$ half way time for each degree of freedom
$\tilde{T}$ idealised path following first order control law

Statistics
$r$ variance
$c$ covariance
$\rho$ normalised covariance
$\sigma$ Standard deviation
$\kappa$ improvement coefficient
$\lambda$ factor between SpaceCat and SpaceBall task completion time
$\beta$ half way time normalised with respect to task completion time
Chapter 1

Summary

1.1 Summary in English

Human computer interaction with six degrees of freedom (6DOF) is gaining importance because of the rapid development of 3D computer graphics. With more 3D power at lower cost new applications follow, which will be accessible for all computer users, e.g., 3D internet, 3D window managers, 3D visualisation and animation software, computer games, and interactive television. There are many input devices that have been developed to enable computer interaction in multiple degrees of freedom (e.g., data gloves, motion tracking sensors, or desktop input devices like the Space Mouse from Logitech). These developments do, however, only partly fulfil the requirements that have been pinpointed as ideal from researchers or use a technology, which is not applicable in mass production. Ideally the development of new technologies should be based on research results and profound ergonomics know-how. In reality, however, the development has been influenced more by current technical limitations.

In this PhD thesis requirements for 6DOF input are listed. Based on these requirements technologies are searched with an optimum for a target function including usability and production cost. The cost should be affordable for the wide mass of internet users. In the thesis a technical solution is presented and realised. The product is called "SpaceCat": an elastic desktop 6DOF computer input device (see figure 1.1). SpaceCat provides low production cost as well as great ergonomics properties such as:

- A workspace adapted to the hand’s movement
- An elastic suspension which provides a rich sensory feed-back allowing both fast and precise manipulation
• User’s choice between position or rate control

These properties makes SpaceCat appropriate both for manipulation of virtual objects (i.e., for actions like pan, zoom and rotate in a CAD-System) or navigation through virtual worlds (moving a eyepoint/viewpoint in walk through/fly through applications). The rate control works fine for navigation and coarse manipulation. However, for precise manipulation, the position control is advantageous. With a series of experiments SpaceCat’s properties were evaluated against the specified requirements and in comparison to previously existing technologies.

1.2 Zusammenfassung auf Deutsch

Computerinteraktion mit sechs Freiheitsgraden (6DOF) hat in letzter Zeit stark an Bedeutung zugenommen, weil die Preise für 3D-taugliche Computersysteme in den letzten Jahren stark gesunken sind. Damit kommen neue 3D-Anwendungen, die für jeden Computeranwender verfügbar werden, wie z.B. im Bereich 3D-Internet, 3D-Visualisierungssoftware, Computerspiele und interaktives Fernsehen. Es gibt viele Geräte, die für solche Anwendungen entwickelt wurden (z.B. Datenhandschuhe, Trackingsysteme oder Desktop-Geräte wie die Space Mouse von Logitech). Diese Entwicklungen erfüllen aber nicht oder nur teilweise die Eigenschaften, die in der Forschung als ideal hervorgehoben werden oder verwenden eine Technologie, welche sich für die Massenproduktion nicht eignet. Idealerweise sollte ihre Entwicklung von einem fundierten ergonomischen Know-how getrieben sein. In der Realität wurden sie oftmals eher von den technischen Möglichkeiten gesteuert.

In dieser Dissertation werden ergonomische Kriterien für 6DOF-Eingabe aufgestellt. Anhand der Kriterien wird nach Technologien gesucht, mit welchen diese ergonomischen Anforderungen optimal erfüllt werden können. Wesentlich ist auch, dass die Technologie sich zu tiefen Kosten realisieren lässt, damit ein Anwendungsfeld wie Internetinteraktion mit der Technologie für die grosse Menge der Internetanwender bezahlbar ist. Eine Lösung wird in der Arbeit detailliert ausgearbeitet und realisiert. Das Produkt mit dem Namen ”SpaceCat” ist ein elastisches Desktopeingabegerät mit sechs Freiheitsgraden (siehe Bild 1.1). SpaceCat weist sowohl tiefe Produktionskosten für eine Massenproduktion sowie gute ergonomische Eigenschaften auf, wie z.B.

• der Arbeitsraum ist der Hand angepasst
1.2. ZUSAMMENFASSUNG AUF DEUTSCH

- die elastische Aufhängung vermittelt dem Benutzer eine umfassende sensorische Rückkopplung, die schnelles und präzises Manipulieren ermöglicht
- der Benutzer hat die Wahl zwischen Positions- und Geschwindigkeitskontrolle

Durch diese Eigenschaften wird mit SpaceCat Navigation und Manipulation mit sechs Freiheitsgraden gut unterstützt, was das Produkt für oben erwähnte Anwendungen interessant macht. Mit einer Serie Experimente wird untersucht, inwiefern die Lösungen die aufgestellten Kriterien erfüllen und wie die neue Technologie funktioniert im Vergleich zu herkömmlichen Produkten.

Figure 1.1: SpaceCat, ein elastisches Eingabegerät für Computerinteraktion in sechs Freiheitsgraden. Der Arbeitsraum, welcher der Hand angepasst ist, ermöglicht eine direkte, präzise und schnelle Kontrolle des bewegten Objektes.
Chapter 2

Introduction

2.1 Motivation

3D Interaction on Personal Computers

Human computer interaction in three-dimensional space (3D HCI) is gaining interest because of the very rapid development of 3D graphics capabilities of standard Personal Computers. In this thesis 3D graphics and 3D applications means that the computer internally have a virtual representation of the 3D model, which is visualised on the screen using different computer graphics techniques like perspective projection, shading schemes, depth cueing, and hidden lines. This kind of visualisation is often referred to as 2.5D in the literature. Today professional 3D-computer applications for scientific visualisation, medicine, engineering (e.g., CAD), architecture or arts run on PCs. New non-professional applications emerge with 3D-internet, 3D window managers and interactive television. Furthermore an important driving force for the development has been the popularity of computer games. Over the past ten years the means of interaction with computers have changed little. The conventional computer mouse broke through when graphical user interfaces replaced the command prompt for the interaction with most computer applications. However, until now no standard has been established for multidimensional interaction. In this thesis multidimensional input means interaction with more than the two degrees of freedom the conventional mouse provides. It is an interesting research topic to predict which properties the successor of today’s computer mouse should have to cope with tomorrow’s 3D interaction demands.
Professional Visualisation Applications

The means of 3D interaction in professional use range from using the conventional PC base with a standard screen and a conventional mouse to virtual reality surroundings using a wide-field presentation of computer-generated, multi-sensory information and that tracks a user in real time. To get an idea of the applications where visualisation is needed we categorise the origins of 3D data:

- Data from measurement gauges like spectrometers, microscopes, computer tomographs (CT), laser-scanners or radar
- Data created by evaluating mathematical models like in molecular design, fluid mechanics or strength of materials
- Data created by engineers, designers or artists in different fields of applications like mechanical engineering, industrial design, architecture or computer graphics art

In all applications there is a need to let the user interact with the data. In some cases the user just needs to navigate, i.e., being able to define his viewpoint. Other applications demand manipulation, i.e., making changes in the data. Some examples of 3D interaction are:

- In visualisation and animation tools there is a need for both navigation and manipulation. This is needed when positioning virtual objects in a scene, assembling parts, positioning virtual cameras, defining camera paths, positioning light sources or deforming free form surfaces. Such tools are used in film production, for the creation of computer games, in industrial design, and for the visualisation of products created in conventional CAD systems. Visualisation tools are also called animation tools or graphic artist modelling tools or software in the literature.

- In a conventional graphical user interface the commands are executed by selecting buttons, sliders and items in menus with a 2D pointing device like the conventional mouse. 2D-selection is also used in 3D-applications, for instance to select a surface in a 3D CAD system. When dealing with volume data (e.g., CT-data) there is no two dimensional manifold on which a 2D cursor could point at. To select a point in this kind of data set a 3D-cursor with three degrees of freedom would be useful.
2.1. MOTIVATION

- In Molecular Design simulated molecules need to be visualised. One task in Molecular Design is to manually check how active substances fits into proteins electrically and geometrically. This is similar to an assembly task in mechanical engineering and requires precise positioning.

Despite the fact that these three examples stem from different applications with different data origins the 3D interaction functionality needed is similar. The question arises what the interaction primitives are and which input devices are best suited for the different tasks.

Other Professional Use

Before graphical workstations existed the research in man-machine multidimensional interaction concerned human vehicle control and telemanipulation. The task of steering a vehicle has similarities with a HCI navigation task and the positioning of a robot tool has similarities with a HCI manipulation task. One fundamental difference is caused by the dynamics these real systems have. Important fields of use include:

- robotics
- machine tools
- laparoscopy and other telemanipulation tasks in medicine
- aircraft, aviation and the control of vehicles in general

Common for all tasks discussed so far is an obvious mapping from the input device to the controlled system. A force or position input on the controller is typically transformed into a position, velocity or acceleration in the controlled system. In other applications no such direct metaphor exists. For example multidimensional input can be used to control sounds or colours. Further examples of possible use is the navigation in complex multidimensional data spaces or to interact with 3D operating systems [ea00] [AWP97].

Problem Statement

From the examples in the previous section it is apparent that there is a need for interaction with multiple degrees of freedom, i.e., interaction with three or more degrees of freedom. Especially interesting is the lack of 3D computer input although 3D applications are already widely spread for professional
use, and new applications for everyday use are emerging. New interaction schemes in this field will affect the daily life of hundred of millions in the near future. Some relevant questions in this context are:

- What kind of tasks should be solved with integrated multidimensional input techniques?
- What are the pros and contras of a universal input device compared to specialised solutions?
- What properties should an ideal universal input device have?
- What are the design principles that govern the usability of such a device in different applications?

A lot of information concerning the first three questions can be gained through literature analyses (see chapter 3). The last question is central to the main part of this PhD thesis.

### 2.2 State of the Art

Today 3D Interaction on Personal Computers is mainly used together with 3D CAD systems. Over the last few years 3D volume modelers have gradually replaced 2D CAD. This has opened up a new market for six degrees of freedom (6DOF) desktop input devices to be used with the non-dominant hand as discussed in section 3.1.5. The dominant products on the market are the Space Mouse (called Magellan in Americas) from LogiCad3D (Gilling, Germany) and the SpaceBall from Labtec (Vancouver, WA, USA). Both companies have sold in the order of 0.1 million devices.

The Space Mouse stems from the space industry [Hir96]. The predecessor Control Ball was implemented with resistive wire strain gauges and patented in 1983. The Control Ball did not allow any deflections, i.e., it was a pure isometric input device. In 1987 the optoelectrical sensor technology of Space Mouse was patented (European Patent No. 0 240 023). It allows reduced production costs and better ergonomics due to greater elasticity. The translation deflection is limited to 1.5 mm and the rotation is limited to 4°. Space Mouse has a total resolution of eight bits which corresponds to approximately 0.01 mm. The handle of the original version has the form of a cylinder with the diameter 66mm (A in figure 2.1). The main improvement in the newer Space Mouse Plus (B in figure 2.1) are two new buttons directly to the right and left of the handle, which make frequent input (like yes or no answers in
Figure 2.1: Products using the Space Mouse sensor: A SpaceMouse Classic, B SpaceMouse Plus, C Cyber Puck, and D CyberMan 2
CHAPTER 2. INTRODUCTION

the CAD system CATIA) faster. Other versions of Space Mouse have been developed for 3D internet and games (C and D in figure 2.1).

SpaceBall (see figure 2.2) is implemented with an optomechanical sensor patented in 1989 (US Patent No. 4,811,608). The first version of the SpaceBall was an almost ideally isometric device. In following generations more elasticity has been introduced. According to Labtec the resolution of SpaceBall is ten bit, but due to sensor noise the effective resolution is very far from this value. In Christou [CB98] and Honegger and Kurth [HK97] the SpaceBall was used to navigate in virtual environments. In both investigations considerable training was necessary to make the subjects familiar with the SpaceBall means of interaction. Honegger and Kurth write: "...with the SpaceBall the completion time was significantly longer than with the conventional mouse ... a training phase of 10 minutes was not sufficient to make the subjects acquainted with the SpaceBall." This investigation was made with the original isometric version of the SpaceBall, i.e., a predecessor of the more elastic "SpaceBall FLX" now available. The newer SpaceBall FLX has a workspace similar to Space Mouse but still too small to allow position control. In the latest SpaceBall 4000 the hand posture has been changed to allow the user to grip the handle from the side rather than from above (compare figure 2.3). Furthermore the diameter of the handle was reduced from 68 mm to 59 mm and a number of buttons have been added to allow for short cuts for commands in CAD programs for example. The changes in elasticity and shape are in the right direction concerning the concepts of elastic control and finger manipulation out of a relaxed hand posture (see chapter 3).

Other applications for 3D input are in use in the film and game industries, e.g., in motion tracking. Furthermore systems incorporating force feedback are used for planning surgeries and training for surgeons. The devices used for these purposes are typically at least a factor ten more expensive than the devices sold for use with CAD systems and will not play a central part in this thesis.

Both Space Mouse and SpaceBall are used mainly to control the velocity of the viewpoint in CAD systems. In this thesis the question is which changes are needed to find a wider range of use for multidimensional input devices.

2.3 Goal of this Thesis

The goal of this thesis is the conception, realisation and verification of an input device supporting different multi-dimensional man-machine interaction modes. The input device shall be suitable for novices as well as expert users.
2.3. GOAL OF THIS THESIS

Figure 2.2: Products using the SpaceBall sensor: A SpaceBall 2003, B SpaceBall 3003, C SpaceOrb 360, and D Ascii Sphere 360. A and B are intended for professional use whereas C and D are low price versions for computer gaming.

Figure 2.3: Labtec’s SpaceBall 4000 FLX
The input device shall be conceived in such a way as to support everyday needs in future 3D applications. This means that it must be possible to be produced at a cost comparable to the conventional computer mouse.
Chapter 3

Literature Analysis

3.1 Analysis of Multidimensional Input

Literature about input devices can be found from a range of research fields including experimental psychology, human motor control, aviation and aerospace, telemanipulation, man-machine interaction, etc. Early work concentrated on 1D or 2D typically for the design of input controllers for aircraft [Orl49] or on the human operator as a controller for dynamical systems in general. Through the development of automatic control systems the role of the human operator changed towards supervising such systems [She92], and the controlling aspect has become less important. Instead the field of human computer interaction has become central in the research on input devices. One fundamental task today in HCI is to search for efficient ways for information flows between user and computer [Jac96]. For the design of input devices this implies fundamental knowledge in perception, cognition and motor activity. Input device research is aiming at faster, more natural and more convenient ways for a user to transmit information to the increasingly complex software running on personal computers. Barber [Bar97] emphasises the importance of an integration of input devices in the computer system, where the task is focused. Barber uses the term interaction devices instead of input devices to stress this idea. In the future computer technology will become more and more portable and new tasks will emerge. This will lead to a rapid development of new interaction devices. Today one third of all sold PCs are portable and mobile phones are equipped with more and more functionality. Interactive television will in some years change information consumption behaviour dramatically. Because of these developments the computer interaction will take place less in front of a desktop and there will be a demand for new interaction technologies like speech recognition and multidimensional
interaction devices.

Skilled performance of a HCI-task is characterised by the combination of knowledge of the task and the ability to interact by means of given interaction devices. Results reported in Allard and Starkes [AS91] with computer game users show that the knowing and doing skills can be split into independent sources of information. For the expert, the knowing and doing elements that already exist can be combined as required. This means that when faced with a new input device the user only needs to learn a new set of actions to control the new device but does not need to relearn the required activity.

3.1.1 Interaction Primitives

Complex software products like CAD systems require a long learning period to enable the user to work efficiently. This means that the user for a long time has to concentrate on interaction details instead of using his cognition to solve the target problem. Buxton [Bux86] introduced concepts like chunking and phrasing to describe this process. An obvious goal is to search for interfaces where the process of learning is minimised. The interaction concept shall give novices a good starting point as well as providing a dextrous tool for the expert user. To gain a deeper understanding of what primitives the human computer interaction consists of Foley [FWC84] defined the following categories:

- Select an item in 1, 2 or 3D
- Position an item in 1, 2 or 3D
- Orient (rotate) an item in 1, 2 or 3D
- Path: specify a path, such as defining a camera path in a visualisation tool
- Quantify a numerical value
- Text: enter text, as in word processing

These primitives also apply to 3D applications. The first four primitives above are common to all applications mentioned in section 2.1. Note that Foley’s primitives are not all of the same abstraction level [Bux86]. For example, positioning in 3D could be done by selecting fields in a dialog box where the user has to quantify x, y and z coordinates. Positioning an item in 3D software could however also be solved directly with a 3D input device.
3.1.2 Multidimensional Interaction Requirements

Slater [SD91] defined the following requirements for 3D interaction with multidimensional input devices:

1. **Navigation**: The user should be able to navigate the scene by controlling the virtual camera.

2. **Global Selection**: The user should be able to select any object in the scene.

3. **Rigid Body Transformation**: This includes the usual requirements of translation and rotation, i.e., any transformation which changes the object’s position or orientation in space, but which leaves its local geometry unchanged.

4. **Local Selection**: The user should be able to select part of an object - for example a set of specific points, polygons or patches.

5. **Deformation**: Manipulating control points, polygons or patches.

Other authors use the categories `navigation` (requirement 1), `selection` (requirements 2 and 4) and `manipulation` (requirement 3 and 5). The requirements do not necessarily have to be solved with a multidimensional input device. When using a flat screen as output, for instance, selection can be done very efficiently with a standard 2D-pointing device like the conventional mouse. In virtual reality, or when working with volume data like point clouds, there is a need for 3D selection (see [HPGK94] for a review).

3.1.3 Strengths of Multidimensional Input

Because there are no standard devices for 3D interaction a lot of work has been invested to use the conventional 2D mouse for 3D interaction [Hou92]. Many 3D software products today use the mouse buttons or keyboard buttons to connect different degrees of freedom in the application with the two degrees of freedom of the mouse [CMS88]. There are reasons to expect a multidimensional input device to be more efficient than the mouse however:

- A multidimensional input device can provide a more direct map from the user’s intentions to the application. Therefore interaction with a multidimensional device should be easier to learn and provide a lower cognitive load.
• Multidimensional input opens more channels for transmitting information to the computer, thus offering a potential of time saving.

In the literature we find examples supporting this. Djajadiningrat et al. [DOS97] showed for a 3D rotational task how the performance differs depending on how many DOF are available. The best result was achieved for free rotation of all three rotational degrees of freedom. Hinkley [HTP97] compared the use of an arc ball controlled by a conventional mouse and a 3D input device. He found that the 3D input device was 36% faster without any loss in manipulation precision.

Jacob et al. [JS92] investigated for what kind of tasks an integrated multidimensional input device is of advantage. His conclusion is that when the multiple dimensions of a task are perceptually integrated a multidimensional input device is advantageous. For tasks where the multiple dimensions are separated, like when controlling the position of an object as well as the colour, it is easier to control the different degrees of freedom one at a time with an input device with a lower degree of freedom. Similar thoughts were also presented in Fracker et al. [FW89] and Sturmann [Stu91] and corresponds to the widely accepted concept of direct manipulation [Bar97]. We constrain this work to applications using direct manipulation although there exist examples of successful interaction not complying with this concept. One example is given in [BHJA98], where the possibility of intuitively interacting with sounds through a complex transfer function was demonstrated.

### 3.1.4 Interaction Metaphors

An interaction metaphor is the users internal model of how the interaction works. According to the previous section an interaction metaphor should be kept simple. Two basic metaphor categories are the egocentrical, i.e., the user navigates in a scene like he would have the camera through which he sees the scene in his hand, and exterocentrical, i.e., the user think he has the scene or object directly in his hand. The object in hand metaphor works better when the user interact with an object he think would fit into his hand whereas the camera metaphor works better when the user is embedded in a big object like a virtual word. Two versions of the object in hand metaphor and one version of the camera in hand metaphor were investigated by Ware [WO90] for the requirements 1 and 3 from section 3.1.1:

**Scene-In-Hand Metaphor (object in hand metaphor)** The scene is made to move in correspondence with the input device. If the handle of the input device is twisted clockwise the scene rotates clockwise. If it is translated left, the scene translates left etc.
3.1. ANALYSIS OF MULTIDIMENSIONAL INPUT

Eyeball-In-Hand Metaphor (camera in hand metaphor) The view the user sees is controlled by direct movement of a virtual camera. If the handle is twisted clockwise the scene rotates anti-clockwise. If it is translated left, the scene translates right etc.

Flying Vehicle Control (camera in hand metaphor) The same as Eyeball-In-Hand Metaphor, but the velocity instead of the position is proportional to the deflections of the handle. In this thesis the eyeball-in-hand and the flying vehicle control metaphors are both called camera in hand metaphor.

Ware performed an experiment in which it was shown that there is no best metaphor for all situations. For manipulation tasks the object in hand metaphor was superior whereas for navigation tasks the camera in hand metaphor was better. Other experiments have used further metaphors for interaction in virtual environments [PWBI99].

3.1.5 Multidimensional Input Embodiment and Usage

Many different kinds of input devices have been developed and attempts have been made to build taxonomies for input device classification. Foley [FWC84] classified input devices under the graphics subtasks they were capable of performing. Buxton [Bux87a] classified the input devices according to physical properties and the number of spatial dimensions they sense. Card [CMR91] ordered the input devices morphologically in order to detect spaces for new input device designs (see [Bar97] for a review on taxonomies).

Some multidimensional devices were developed in an evolutionary process from the mouse. Examples with up to 5DOF are found in [SD91], [BBKF97] and [ZM98a]. Balakrishnan et al. [BBKF97] presented a mouse with two translational and two rotational degrees of freedom. It was shown that in a 3D positioning task, this device was 30% faster in comparison to a conventional mouse operated by mode switching. Other designs cover all six degrees of freedom of a solid body (see section 2.2 and [Zha95]) or some of the 23 degrees of freedom of the human hand (see [Stu91] for a review).

One basic question is about the use of two-handed input techniques. Guiard [GF96] provides a framework for which classes of two-handed interfaces might improve performance without additional cognitive load. Multidimensional input can be achieved by using both hands with lower degree of freedom input devices. Zhai et al. [ZKSS99] use two 2D-joy sticks for a 3D navigation task. Hinkley [HCS98] uses a touch pad combined with a “touch mouse” for a 2D map navigation task and Kurtenbach [KFBB97] gives a similar example from the field of graphic artist modelling tools.
An example of a multidimensional input device in combination with the conventional mouse is the use of 6DOF input devices in CAD [HG98]. The 6DOF input device is used to orient the target object or change the viewpoint whereas the right hand operates the conventional mouse. It is a kind of space multiplexed [FB97] input where the 6DOF input device acts as a graspable user interface always connecting to the view port. Currently relatively stiff devices with small workspace are used with rate control (compare section 2.2). A number of buttons are used to freeze degrees of freedom, change sensitivity, or are connected with application specific functions like the function keys on a keyboard. Typically the 6DOF device is operated with the non-dominant hand. Hirzinger’s [HG98] motivation for this practise is the analogy to the work with physical tools and target objects. The left hand orients the target object and the right hand manipulates the tool. Hinkley et al. [HPP+97] investigated the roles of the left and the right hand when manipulating a physical target object with a tool, and found that the specialised roles of the hands only are significant when precision tasks are performed. This result is similar to the results in [KMB93]. Because the 6DOF-device is held with the non-dominant hand this implies that current 6DOF devices are not as applicable to precision tasks as the conventional mouse. This combination of 6DOF-input device and conventional mouse thus does not provide any means for precision 6DOF manipulation.

Gribnau [GH98] presents a study in which he compares the use of one 6DOF input device with one hand and two 6DOF input devices with both hands. He concludes that after a learning period the use of two-handed 6DOF input for an assembly task is advantageous. This is the only study I know using two 6DOF input devices for two-handed input.

Hinkley [HPGK94] makes a distinction between desktop input devices and spatial input devices. Spatial input devices or trackers are based on free-space 3D input technologies such as cameras or magnetic trackers. These systems are used to track 3D motion typically to digitise movements of the human body or as input devices in virtual reality environments [Eme99]. The systems are known to have noise and time lags, and are susceptible to magnetic disturbances like metal objects. Ultrasonic systems as used in Sibert [SG97] are an alternative, but they also have drawbacks in terms of high frequent sonic disturbances and restrictions in workspace and because of a demand for free sight between transmitter and receiver (see figure 3.1). Another possibility is acceleration measurement gauges, but by measuring acceleration it is difficult to achieve an accurate absolute position over time. Spatial input sensors have zero stiffness and have been used to test isotonic 6DOF manipulation (see [Zha95], [WJ88] and section 3.1.7). A frequently mentioned problem with isotonic 3D input is fatigue, since the user has to
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Figure 3.1: The 3D-Mouse from Logitech inc. (Romanel, Switzerland). 3D-Mouse was launched in 1992 and uses an ultrasonic measurement principle.

hold the input device freely in the air. For a review on spatial input see [HPGK94] and [JA96].

So far we have discussed input devices. It is possible to improve interaction by also using the input device as an output device [BOYBK90]. Providing 6DOF force feedback is certainly a future goal for a 6DOF input device, but the construction of such an input device is not in the scope of this dissertation. Furthermore force feedback cannot be produced at a low cost with any today known construction principle. There are simpler ways to provide haptic feedback with vibrotactile display [Stu91] but how to utilise this for a universal 6DOF input device will be left to future research.

3.1.6 Specialised Input Devices vs. Universal Input Devices

There are obvious advantages for the user with a single universal input device like the conventional mouse for many different applications:

- Most users are trained on the same input device. The input device is
available at most computer systems and can be used without considerable learning.

- Most software works with the input device independent of origin. The software is ready to use after download without any need to purchase a physical device.

- The limited desktop space is not occupied by a range of specialised input devices.

- A universal input device loaded with much functionality give professional users a potential to develop efficient interaction.

- Large produced volumes of a universal input device provide low cost.

For the software developer the arguments are similar. Software companies prefer one generic interface for a pointing device that is incorporated in the operating system. By using such an interface the software only depends on the operating system and the software companies don't have to bother about different input devices and versions or even build own retail organisations for an input device specialised to their application.

Computer applications have very different needs which are not satisfied by today's standard input devices mouse and keyboard [Bux87b]. In previous chapters we recognised that a 2D pointing device like the mouse is not optimal for 3D interaction. Special 3D input devices have been launched, for instance in CAD. However, none of these devices is used as a universal input device because they are not as good as a conventional mouse for pointing tasks. A new standard should allow 2D pointing as well as a 3D interaction according to the requirements formulated in section 3.1. According to Rossignac [Ros97] "...the solution should be suitable for inexpensive desk-top systems and for collaborative environments. Furthermore, the same paradigm should be used for controlling the relative position of the geometric features in an assembly as for controlling the view."

6DOF is a natural choice for a universal multidimensional input device since it corresponds to all degrees of freedom for a rigid object. Positioning and orientating a virtual object or the task of viewpoint navigation inherently have 6DOF. In cases where there is a need for less than 6DOF the most direct map from the input device to action can be chosen, e.g., when only 3D rotations are needed the three rotations of the input device are in use. Navigation is an example of a task which is not necessarily best solved with 6DOF. Zhai [ZKSS99] uses a two-hand solution with two standard pointing devices (i.e., 4DOF) in a special navigation task. A better solution in that
task is however to use a subset of the degrees of freedom in a 6DOF input device, since the map can be made more direct and solved with only one hand.

An open question is if there exists a technology suitable for all tasks. Selection, manipulation and navigation are inherently different and may need different metaphors for an efficient interaction. Fitzmaurice et al. [FB97] argue for many different input devices, each adapted for its special use and complying with personal preferences. Most probably a "one fits all" technology does not exist. On the other hand the conventional mouse is not the optimal standard input device. Our goal is to find a better standard, which handles the task the conventional mouse solves today, and also provides a basic 3D interface. We conclude that a 6DOF input device for one hand use is the best candidate.

3.1.7 Design Criteria for 6DOF Input Devices

Many different 6DOF input devices have been designed with different properties. The physical properties of the device can if we assume linear compliance $K_s$ and linear viscosity $B_s$ be described as:

$$M_s\ddot{u} + B_s\dot{u} + K_s u = F_u \tag{3.1}$$

where $F_u$ are the forces and torques acting on the device handle, $M_s$ is the device handle mass and inertia matrix and $u$ is the position and orientation deflection vector of the device handle.

Especially the compliance $K_s$ is an important factor in input device design. It is in the literature often called elasticity or device stiffness, which is also the terminology that will be used in this thesis. To categorise devices with different elasticity Zhai [Zha95] uses the categories:

**Elastic Input** The forces on the handle are proportional to the deflections, i.e., $M_s \approx B_s \approx 0$, and $K_s \not\approx 0$.

**Isometric Input** An elastic input device with infinite stiffness, i.e., the device handle does not allow any deflection and records force and momentum, i.e., $M_s \approx B_s \approx 0$, and $K_s = \infty$.

**Isotonic Input** An elastic input device with zero stiffness, i.e., there is no self centring effect and position or position change is measured, i.e., $M_s \approx B_s \approx 0$, and $K_s = 0$. 
The transfer function controls how the device handle actions are transmitted into the controlled system:

$$\Gamma = f(u)$$

(3.2)

where $\Gamma$ is the position and orientation of the controlled object.

In the literature the following transfer function categories are frequently found:

**Position Control (or zero order control)** The position and orientation of the controlled object is proportional to force (and torque) or position (and orientation) of the device handle, i.e., $\Gamma(t) = f_0 u(t)$ where $f_0$ is a diagonal constant gain matrix.

**Rate Control (or first order control)** The translation and rotation velocity of the controlled object is proportional to the deflection of the device handle, i.e., $\Gamma(t) = \int f_1 u(t) dt$ where $f_1$ is a diagonal constant gain matrix. Rate control has also been called velocity control in the literature.

**Acceleration Control (or second order control)** The translation and rotation acceleration of the controlled object is proportional to the deflection of the device handle, i.e., $\Gamma(t) = \int \int f_2 u(t) dt^2$ where $f_2$ is a diagonal constant gain matrix.

These control modes can be summarised in one expression:

$$\Gamma(s) = f_0 u(s) + f_1 \frac{1}{s} u(s) + f_2 \frac{1}{s^2} u(s)$$

(3.3)

where $s$ is the Laplace variable.

Zhai compared different combinations of stiffness and transfer function. Since acceleration control is known to be difficult to handle [KTES87] [Wic88] Zhai did not include it in his investigation. It is clear from his research that isometric position control as well as isotonic rate control are bad combinations.

Another important criterion for 6DOF input devices according to Zhai is whether the input device is designed for **finger manipulation**. In one experiment Zhai compared an isotonic device without clutch designed for finger manipulation (the "finger ball") with an isotonic data glove with integrated clutch. The position of the data glove was measured at the palm so for this device no finger manipulation was present. A clutch is necessary when no direct mapping exists between the controlled object and the workspace of
the input device or when the limits of the human limbs controlling the device do not allow the desired movements in a convenient way. If for instance the controlled object should be turned 180° but the workspace of the input device is limited to 90° it is necessary to "re-clutch" once. This is also called indexing and is similar to lifting the mouse in order to put it in the middle of the mouse pad. In Zhai's experiment 10% of the manipulation time was used for clutching. During clutching time the subjects were not necessarily idle but probably instead engaged in preparing next actions mentally. It is known that mental rotation takes up a certain amount of time [SM71]. Zhai showed that the manipulation with the "finger ball" was faster even if the clutching time was subtracted from the times achieved with the data glove. Zhai concluded from this that it is advantageous to design an input device for finger manipulation.

In a positioning task Zhai compared isotonic position control with isometric rate control. With isotonic position control the completion time of the task was shorter. Significant was also a shorter learning time for the isotonic position control. A benefit of the isometric device is less fatigue since the arm can rest on the desktop while using the device. This is in contrast to the isotonic device, which has to be manipulated freely in the air.

In another experiment Zhai compared elastic rate control with isometric rate control. It turned out that elastic rate control has shorter learning time. As a reason for this Zhai points out the richer proprioception in elastic devices. For an elastic input device we have to determine workspace and stiffness. According to Zhai the workspace should be adapted to finger manipulations according to the "finger ball" experiment. The optimal stiffness is a trade-off between better proprioception for a bigger workspace and a weaker self-centring effect with less elasticity. Since no elastic input devices adapted to finger manipulation are currently found on the market Zhai used a spatial input device suspended in rubber bands for his research.

Zhai has left the field of elastic position control to future research but regards it as potentially better than isotonic position control due to a greater proprioception. In the following chapters Zhai’s hypotheses on proprioception, finger manipulation, transfer functions, and device stiffness is validated against other research.
3.2 Human Perception and Motor Control

3.2.1 Proprioception

A major debate around input control focuses on proprioception, i.e., body internal feedback on muscle and joint positions [HN53] [Wei54] [BFS55] [BBF55] [Bah57] [Bur65] [BG65] [Pou74] [NT80] [NW81] (compare figure 3.2). Zhai [Zha95] made the following notes on elastic input devices and proprioception:

1. There are multiple neurophysiological sources of proprioception, some of which respond to force stimuli and others to movement stimuli. Elastic devices may elicit activation of more sources of proprioception. The different sources are joint receptors, muscle spindles, golgi tendon organs and cutaneous receptors [CH86] [GB92].

2. Proprioception may not only improve static control performance but may also improve dynamic aspects of control performance. Adams and Creamer [AC62] found that control loading such as elastic springs improve subjects' accuracy in estimating elapsed time.

3. Displacement JND (Just Noticeable Difference) is smaller than force JND, i.e., we have a greater capability to perceive relative changes in position than relative changes in force. Pang, Tan and Durlach [TPD92], found that force JND is proportional to the reference force. The average force JND was 7-8%, independent of reference force. In comparison, Durlach et al. [DA+89] show that length JND is not proportional to the finger span lengths $L$ used in the experiment. JND was 8.1% for $L$ =10mm, 4.6% for 40mm and 2.8% for 80mm. It appeared that human sensitivity to force is lower than sensitivity to length, particularly for large ranges of length (>10mm) or force (>2.5N). For smaller ranges of force or length, the JNDS are about the same.

Although proprioception has been central in the debate it is not clear what importance it actually has. In the psychomotor literature there has been an ongoing debate between centralists and peripheralists. Centralist support an open loop behaviour of the human motor system whereas peripheralists emphasise the role of proprioception in a closed loop control system, see Singer [Sin75] for an overview. New research shows that both systems synergetically cooperate in motor control. This research suggests that the proprioception has its greatest role during the learning of new motor programmes and in the control of slow and precise movements [Wei98].
3.2. HUMAN PERCEPTION AND MOTOR CONTROL

3.2.2 Finger Manipulation

Various parts of the human body are disproportionately represented in the brain relative to their physical size (see figure 3.3). Especially fingers and thumb have a large representation compared to wrists, elbows and shoulders. The fingertips are regions where cutaneous sensors have the highest density in the body [Sch98]. This provides an outstanding potential for complex manipulations, which might be of great importance for 6DOF interaction.\footnote{Note that figure 3.2 is simplified. When using an elastic input device the cutaneous sensors will also give exteroceptive feedback, i.e., body external feedback. An elastic 6DOF input device held in a finger grasp will activate the cutaneous sensors in the fingertips during manipulation.}

Fitts [Fit54] established Fitts' law, which is one of few simple relationships available in user interface research and development:

\[ T = a + b \log_2(cA/W) \]  

It models the time \( T \) needed to point to a target of width \( W \) at distance \( A \). The definition above is adapted from Barber ([Bar97] page 191). In Fitts' original formulation \( c = 2 \). \( \log_2(cA/W) \) is called the index of difficulty. The parameters \( a \) and \( b \) are determined empirically. The performance index 1/6 is measured in the unit bit/s and is used to determine the information.
Figure 3.3: Motor homunculus (adapted from [BM97]). The length of the underlying bars show the relative amount of cortical area devoted to each muscle group.
processing rate of the motor system. Research has shown that isotonic as well as isometric input devices follow Fitts' law ([DM97] page 107).

Langolf et al. [LCF76] tested the processing rate of different parts of the body. They concluded that the information processing rates $1/b$ for the fingers, wrist and arm were 38 bits/s, 23 bits/s and 10 bits/s respectively. This investigation has been cited by Card et. al. [CMR91] to predict promising improved alternatives to the conventional mouse, where the fingers are incorporated to a greater extent. There are products that have been designed according to Langolfs findings. A penformed device was presented in [Dah99], but to the authors knowledge no comparative studies including this product have been published yet. The track ball utilises finger movements to a greater extent than the conventional mouse. Zöller et al. [ZK99] compared a track ball with a conventional mouse. The conventional mouse was significantly faster, which is contrary to Langolfs prediction.

Zhai [Zha95] compared a 6DOF input device (data glove) controlled by the arm and wrist with a device (finger ball) controlled by the fingers. The test subjects completed a docking task. The data glove manipulation incorporated clutching operations which occupied a non-negligible interaction time. Zhai concluded the finger ball outperformed the data glove even if the re-clutching times with the glove were subtracted from the total completion time.

Balakrishnan et al. [BM97] criticised the method Langolf used to achieve his results and designed a new test to check the results for finger, wrist and forearm movements. They determined much lower rates for all tested limbs and actually achieved the lowest processing rate with finger movements. It is however questionable whether their experiment design is adequate. The measurement incorporated only the forefinger moving in the direction of thumb and middle finger, i.e., physiologically a different movement to the movements in the tapping experiments performed in Langolfs experiment. It is known that the fingers are weak for the movements Balakrishnan used.

A variety of handle concepts are reviewed in Jacobus [JRJW92] and Cutkosky [CH90]. Depending on the task, different handle concepts are recommended. For power tasks the hand should wrap around the whole handle to allow efficient force transmission from the strong muscles of the arm and shoulder. For dextrous tasks the finger grasp is appropriate.

In recent years there has been reports on increase in physical workload related pain due to the operating of conventional computer mice [FB95] [Bar97] page 243. Karlquist [Kar97] concludes that the mouse shall be operated near the body. The work with a track ball caused a lower shoulder posture and lower neck/shoulder strain. One possible reason for this is that manipulation with a track ball is performed with the fingers whereas mouse manipulation
employ larger muscle groups like arms and shoulder. Elastic 6DOF input devices designed for finger manipulation would be more similar to the track ball manipulation than the use of the conventional mouse and has therefore the potential to be beneficial in terms of physical workload.

It has been widely reported in the literature that isotonic 6DOF input devices cause fatigue. Weiss [Wei98] performed tremor measurements with an elastic input device. In order to avoid fatigue and tremor the hand and palm should be supported when manipulating these devices. This is possible to achieve with an 6DOF input device conceived for finger manipulation.

To conclude most research supports the idea that a 6DOF input device should be built for finger manipulation. This is due to human motor information processing speed as well as physical workload.

3.2.3 Analysis of the Movement Microstructure

A movement towards a target in a positioning task is compounded of an initial movement with open loop character followed by movements with closed loop character. This movement microstructure is not deterministic but consist of a series of irregular episodes of acceleration and deceleration which Jagacinski [Jag89] referred to as submovements. This is true for both position and rate control, where the mean number of submovements in one experiment was 2.1 for position control and 2.5 for rate control. In most cases only 2 submovements are needed to reach the target even if Fitts’ index of difficulty is large. In some cases, however, as many as five submovements were noted. To account for these observations the stochastic optimised submovement model (SOS-model) was developed by Meyer et al. (summarised in [DM97]). Current research favours that the first submovement has open loop behaviour whereas the following submovements are more characterised by a closed loop behaviour (compare section 3.2.1). The SOS-model accounts for the complex non-linear behaviour of the human motor system, and is probably the best model available although it doesn’t always provide a better fit to measured data than Fitts’ law.

Douglas and Mithal [DM97] used the movement microstructure to explain why the conventional isotonic mouse is superior to the isometric track point [BSRO95]. They found the track point to be 60% slower in pointing and 50% slower in dragging tasks ([DM97] page 170). This confirms other results ([MM72] and [CEB78]) which are summarised in section 3.3.1. Six participants performed a one dimensional Fitts’ task with both input devices. According to their work there are differences in the movement microstructure between isometric rate control and isotonic position control. Additionally the subjects showed great individual differences although the
overall macro results complied with Fitts’ law. Especially the isometric rate control task deviated from the SOS-model. Only two of the subjects in this experiment performed the characteristic long and fast first cursor move of the SOS-model. An important difference between the two input devices was the tremor present in isometric rate control. With the mouse the tremor is efficiently filtered mechanically because of sticking friction between the mouse pad and the mouse. In case of the track point there is no sticking friction present and the tremor of the limb is transmitted undamped to the sensor. Furthermore the track-points used by Douglas and Mithal had intrinsically very high noise levels which added to the tremor to account for a jittery signal. They conclude that jitter "makes it difficult for users to stop the cursor at a desired point on the screen and explains why some isometric joysticks are hard to control." From their investigation it is not clear, however, if the jitter is the factor providing the main difficulty or if the difference between isotonic position control and isometric rate control is actually of greater importance. The position control is more similar to our everyday experience of pointing in the real world and is more suited to positioning tasks. This is indicated by the fact that the SOS-model has to be adopted when dealing with rate control. Another reason to believe that tremor does not play an important role is that tremor is efficiently filtered in rate control due to the low pass properties coming from the integration of the signal. We expect tremor to be a much greater problem when dealing with elastic position control devices without sticking friction.

3.2.4 Exteroception

An important field of use for 6DOF input devices is to control 3D graphics visualised on a 2D screen. The visualisation provides many cues that help the user assess the 3D properties of the scene. In this section the different cues are shortlisted and the role of a 6DOF input device for visual exteroception is investigated.

The perception of depth in the visual representation can be divided into observer centred and object centred cues (see [Wic88] page 130). The observer centred cues are:

*Binocular Disparity* The images received by the two eyes, located at slightly different points in space, are disparate. The degree of disparity provides a basis for the judgement of distance.

*Convergence* The "cross-eyed" pattern of the eyes is necessary to bring the image onto the detail-sensitive retina of both eyes. The degree of convergence informs about the distance.
**Accommodation** The eye adjusts the shape of the lens to bring the image into focus on the retina. The nearer an object is the more the ciliar muscle contracts [Sch98].

Binocular disparity can be supported by different hardware means like 3D displays or shutter glasses. Note that only the binocular disparity is supported by such means. Some users find it bewildering that only the binocular disparity gives a cue about the depth whereas the other cues perceive the flat surface of the screen at a fixed distance.

The object centred cues can be subdivided into pictorial cues and kinetic cues. The pictorial cues are:

**Linear Perspective** When we see two converging lines we assume that they are parallel lines receding with increasing distance.

**Interposition** When the contours of one object obscures the contours of another, we assume that the obscured object is more distant.

**Height in the Plane** Because we normally view scenes from above rather than from below, we assume that objects higher in our virtual field are farther away.

**Light and Shadow** When objects are lighted from one direction they have shadows that offer cues about the object’s orientation relative to us as well as its three dimensional shape.

**Relative Size** If objects are known to be the same true size, those looking smaller are assumed to be farther away.

**Textural Gradients** The grain of the texture will grow finer at greater distance.

**Proximity-Luminance Covariance** Continuos reductions in illumination and intensity are assumed to signal receding distance.

**Aerial Perspective** More distant objects tend to be hazier and less clearly defined.

These cues are supported by different hard- and software means [ZBM96] [KP95] [AMR96]. The kinetic cues are:

**Viewpoint Parallax** (relative motion gradient) creating shifts by changing the viewpoint. When we move relative to a 3D scene, for instance, objects that are closer to us show greater relative motion than those that are more distant provided that we look at the distant objects.
Figure 3.4: Viewpoint and shadow parallax provide important cues to estimate the shape of objects. In the pictures the thumb support of the SpaceCat handle (compare figure 1.1) is visualised from three different angles. Note the shifts in shape and shading.

Shadow Parallax creating shifts by moving a light source around an object or moving an object when keeping a light source fixed (compare figure 3.4).

Ware et al. [WAB93] suggest that the kinetic cues are more important than stereo in yielding a strong impression of three dimensionality. This has been confirmed in a PhD thesis by Geisler [Gei94]. Christou [CB98] lets subjects use a SpaceBall to navigate in virtual environments. They compared the perception of the virtual world between the person in charge of the movements and passive observers. They suggest that active control of movements through a scene might result in the formation of a more flexible mental representation.

Voorhorst [Voo98] investigated how parallax shifts can be used to enhance exteroception in laparoscopic tasks. In one experiment a knot was unbounded with a laparoscopic instrument with and without the possibility to move the viewpoint (active and passive subjects). Active subjects solved 60% of the knots correctly whereas the passive subjects achieved a percentage of 40%. The active subjects needed more time during the first two rounds, but a strong learning curve could be noticed. In the third round the time used was the same. A second experiment compared shadow parallax, viewpoint parallax, no parallax and both kinds of parallax in combination. The use of no parallax resulted in significantly less correctly solved problems. There was no significant difference between using viewpoint parallax or shadow parallax.

Based on these results we conclude that viewpoint and shadow parallax are both very efficient ways to perceive 3D in computer graphics. These kinetic cues are used today in 3D CAD together with 6DOF input devices [HG98] which bring the user a better understanding for 3D shapes.
CHAPTER 3. LITERATURE ANALYSIS

3.3 Transfer Function

3.3.1 Device Stiffness and Transfer Function

A basic physical understanding for input devices was developed by Fitts and Bahrick [BFS55] [BBF55], and Bahrick [Bah57]. Their proposition is that the forces on the control handle should be proportional to the controlled variable. To control acceleration the mass of the control handle makes the user perceive a force proportional to the acceleration. Viscous forces accordingly support rate control. Finally an elastic force enhances the perception of a position, i.e., $M_s \approx B_s \approx 0$, and $K_s \neq 0$ in equation 3.1. In an experiment with different movements and different spring loads they found that subjects had smaller relative errors when the amplitude of movement was larger, the terminal torque was larger and relative torque change to displacement was largest.

Weiss [Wei54] made a similar experiment with an elastic control stick and found that relative positioning error decreased with the extent of movement but contrary to Bahrick [BFS55] that the elastic force had no effect on the accuracy. He therefore concluded that movement is more important for proprioception than force.

Lincoln [Lin53] showed that position control is superior to that of rate control. The experiment was done with a tracking system described in Lincoln and Smith [LS50] using an isotonic input device. Subjects tracked an irregularly moving target mounted on the circumference of a rotating wheel with a cursor mounted on a smaller concentric wheel driven by a hand crank.

Howland and Noble [HN53] comparatively studied isotonic, elastic, viscous and inertial controls and combinations of them in a position control tracking task. The target moved harmonically at 15 cycles per minute and the control handle was rotary. They concluded that the elastic input device had superior performance and attributed this to two factors: first, the elastic loading supports the forces which are needed in a harmonic movement, and second, the elastic device is beneficial in terms of proprioception.

Burke and Gibbs [BG65] made a study on position control with an isotonic and an isometric controller. The isometric input device was approximately 10% faster than the isotonic input device, which is contrary to the findings in Zhai [Zha95]. The interpretation of the data giving this conclusion have however been criticised from both Zhai [Zha95] and Poulton [Pou74]. Gibbs regards proprioception as a crucial factor and argues that the proprioceptive feed-back benefits from isometric control ([NT80] summarising Gibbs).

Mehr and Mehr [MM72] tested among other devices an isotonic joystick in position control mode and a finger operated isometric joystick in rate control.
mode. It was shown that the isometric device was superior both in terms of error and completion time in a positioning task. The isometric joystick and an isotonic trackball were however approximately equivalent in terms of completion time.

Poulton [Pou74] compiled a list of 17 investigations on isotonic and isometric input devices: 14 favoured isometric control whereas only 3 favoured isotonic or elastic control. Eight experiments used rate control, all of which supported isometric superiority. Two experiments used position control, one of which made no conclusion and one [BG65] favoured isometric superiority. Poulton himself argued in favour of elastic control. "The pressure cue augments the usual position cue and helps the man track more accurately."

Card, English and Burr [CEB78] compared an isometric joystick with an isotonic mouse for a 2DOF positioning task. They found the mouse to be significantly faster in a test program including different distances and target sizes. Furthermore the error rate was significantly lower with the mouse.

Notterman and Tufano [NT80] found that the isometric condition was better for randomly moving targets while isotonic control was better for predictably moving targets (0.5 Hz sine waves). They also conclude, contradictory to Zhai [Zha95], that elastic control takes longer to learn than isotonic control. They argue that the subjects had to learn the linear relation between position and force proprioceptive cues. At later stages when this relation is known they state that "subjects profit from whatever exteroceptive and proprioceptive cues are available."

Kim et al. [KTES87] investigate position and rate control for systems with different response time for a positioning task. They recommend position control for small workspace telemanipulation tasks, while rate control is recommended for slow wide workspace telemanipulation tasks. This is because position control only needs one hand movement whereas rate control needs two opposite movements in a positioning task. If a system is slow, the superiority of position control disappears.

Kantowitz and Elvers [KE88] argued in favour of isometric control: "Isometric tasks are simpler because limb displacement, and hence muscle length, remains constant...". In a Fitts' experiment, however, they found position control to be better for high index of difficulty. For low index of difficulty the position control and rate control were approximately the same. Significant was a smaller reaction time for rate control. The gains had only little effect in position as well as position control.

Jones and Hunter [JH90] conducted a study on elastic resistance ranging from isotonic to isometric in a step tracking experiment. They found that stiffer devices generate faster responses but as stiffness increases the accuracy tended to decrease. This means that the response may be fast but uncon-
trolled and the time for the system to reach the final target may be longer for the stiff device.

According to Sturmann [Stu91] the use of position or rate control depends on the task. Rate control is free from the indexing problem but comprises a trade off between accuracy and maximum velocity. With position control it is possible to combine high velocity with accuracy, but instead the control space is limited.

To summarise, there is a general trade-off between speed and accuracy for any input device [Jag89]. Most researchers support that isometric devices are better for fast responses whereas isotonic devices are better for accuracy. This means that isotonic control is advantageous for positioning tasks (which is a part in target acquisition or docking) whereas isometric control is advantageous in irregular tracking tasks. Other tracking tasks such as tracking predictable targets or tracking step changes are better with position control because they enable high accuracy combined with high speed and are narrowly related to positioning tasks. Proprioception is generally recognised to be a crucial factor in input technology but the literature has not been consistent on whether isotonic or isometric devices provide more proprioceptive cues.

3.3.2 Transfer Function Parameters

Sensitivity, Linear Gain

Kim et al. [KTES87] investigate the optimal gains for position and rate control in a simple linear transfer function (compare section 3.1.7). For both position and rate control there is an optimum depending on task, input device, and personal preferences. Zhai ([Zha95] page 28) measured a very flat optimum for an isometric rate control. The difference in mean completion time in a docking task varies within 10% if the gain varies by a factor four. This corresponds to other research, which states that the gain is of little importance for pointing devices for selection in graphical user interfaces (see [DM97] page 42 for a review).

Non-Linear and Acceleration Aided Rate Control

Dynamic filters and non-linear static filters make it possible to combine precision control and high velocity in rate control mode. Some early encouraging results were achieved by Bentley and Meyer [BM76]. Ware and Slipp [WS91] used a non-linear transfer function for isotonic and isometric rate control. The angular rate was proportional to the square of the applied torque
3.4 Conclusion And Hypotheses

\[ \dot{\theta} = T^2 \]. The transitional rate was described by \( \dot{x} = F^{2.5} \) where \( F \) is the applied force. SpaceBall uses \( \dot{\theta} = T^{2.2} \) and \( \dot{x} = F^{2.75} \) according to Zhai [Zha95], i.e., \( \Gamma = f_1 \int \begin{pmatrix} u_1^{2.2} & u_2^{2.2} & u_3^{2.2} & u_4^{2.75} & u_5^{2.75} & u_6^{2.75} \end{pmatrix}^T dt \) in equation 3.2.

Rutledge and Selker [RS90] tested other quadratic transfer functions for an isometric finger operated joystick called the track point in rate control mode. The track point is a widely spread pointing device for laptops. The transfer function actually in place [BSRO95] is described by \( \Gamma = f_1 \int u dt + f_0 u \) (compare with equation 3.3). With this PD-control of the velocity a negative inertia of the cursor is simulated.

Non-Linear and Velocity Aided Position Control

Filters are also used for position control to achieve both a big workspace and precision. In conventional mouse drivers the gain is typically dependent on the input device velocity, i.e., a rate aided position control described as \( \Gamma = f_0(\dot{u}) u \). This makes it possible to move longer distances without clutching. However, there is no research which confirms that rate aided position control gives a better performance [DM97]. One argument against rate aided position control is that it violates our experience of manipulating real objects. If we use linear position control a rotation of the input device handle to a certain extent will in the target system always cause the same rotation independent on how fast the movement is performed. Introducing complicated transfer functions not complying with our experience of real objects makes learning of motor programs harder, especially if the human control is of open loop character (compare section 3.2.3). If transfer functions without dynamics are implemented, the user when getting more dexterous in the handling, can use the same movement as previously learned at a faster pace achieving the same result. This is not the case for rate control or rate aided position control. An alternative giving a greater workspace and avoiding the problem are non-linear transfer functions having a gain dependent of the position according to \( \Gamma = f_0(\dot{u}) u \). Poupyrev [PBW196] used this in a Virtual Reality task, which he refers to as "The Go-Go Interaction Technique".

3.4 Conclusion and Hypotheses

According to the literature analysis position and rate control are useful in different tasks. In position control there is a trade off between workspace size and accuracy whereas rate control comprises a trade off between maximum velocity and accuracy. This means that rate control is advantageous when a large workspace is needed like in navigation tasks whereas position control
is better for precise manipulation. Because of the different characteristics of 6DOF interaction tasks that might occur within the same application, an optimal input device should allow position control as well as rate control. To achieve this a bigger workspace than today’s products on the market provide is necessary. According to research (see chapter 3.2.2) a well chosen workspace is adapted to finger manipulations.

From the literature analysis the following hypotheses can be derived:

**Hypothesis 1 (Control Mode and Control Task)**

*In a control task the control mode of the input device shall correspond to the controlled variable, i.e., position and rate control are optimal for different tasks. Accordingly a universal 6DOF universal input device must be capable of both position and rate control:*

- **Position Control Task:** When the precision and workspace of the input device comply with the target system. This is typically the case in positioning or manipulation tasks.

- **Rate Control Task:** When the workspace of the input device is much smaller than the workspace of the target system and there is a need to control velocity directly. This complies with navigation tasks.

**Hypothesis 2 (Device Stiffness and Control Task)**

*An elastic input device is suited for position as well as rate control. Different spring constants are appropriate for different tasks:*

- **Weak Elasticity is better for position control tasks and tasks demanding precision.**

- **Strong Elasticity is better for rate control tasks and tasks demanding fast reactions.**

**Hypothesis 3 (Physiological Implications on Handling and Learning)**

*The sensorial capabilities and motor skills of the human hand has consequences for input device design:*

- **Sensorial Capability:** Because of greater proprioceptive feedback the handling of elastic input devices is easier to learn than the handling of isometric input devices. Furthermore the greater proprioceptive feedback makes precise and slow movements easier to control.
Motor Control: An elastic input device designed for finger manipulation supports dexterous manipulation and fast learning because of extraordinary motor control of the human hand.
Chapter 4

Problem Analysis

4.1 Methodology

Man-machine interaction (MMI) is in general a very complex field. It is difficult to investigate only few parameters in an experiment. The results depend on physical device characteristics, transfer function, the limb used, fatigue, the type of task, the user's experience, and the way of collecting and evaluating the data. This is the reason why a lot of contradictory views can be found in the literature. An instrument to evaluate statistical tests in this field is given by Poulton [Pou94]. He has remarked that asymmetrical skill transfer function may distort results [Pou74]. Balanced tests use a within-subjects design, i.e., each subject performs all tests and the tests are ordered in a balanced way. Thus distortion from learning effects and fatigue is kept at a low rate but does not necessarily vanish because of asymmetrical skill transfer functions, i.e., part A of a test prepares the user better for the coming part B than vice versa. If we reject the within-subjects test design bigger test groups are necessary to avoid individual differences. In our test we will therefore use the within-subjects procedure although there is a risk of having the results distorted by asymmetrical skill transfer.

Taking the 2D pointing devices as an example we get a hint of the complexity of input device development. There are a lot of pointing devices around like conventional mice, track points, touch pads, track balls, tablets and touch screens (see [Bar97] for a review). Some work with position control, others with rate control. Partly the diversity is motivated by a variety of applications, but a major reason is also different user preferences. Not only the way of interaction varies, but also the technology on which the measurements are based. The mouse can be equipped with potentiometers, a rubber ball combined with optical sensors, or even a camera combined with
Because of the complexity of input devices, managing the product development process of such devices is very important. Know how from different disciplines like industrial design, ergonomics, mechanical engineering, electrical engineering and software design on different levels have to be coordinated. The goal to develop a universal input device to be used with many different applications contributes to the complexity. The development has to be iterative including a fast prototyping in software as well as hardware combined with usability tests. "Managing input is so complex that it is unlikely that we will ever understand it. No matter how good our theories are, we will probably always have to test designs thorough actual implementations and prototyping. The consequence of this for the designer is that prototyping tools (software and hardware) must be devolved and considered as part of the basic environment" [Bux87b].

Sturmann [Stu91] has developed a methodology for the design of input devices to be used by the whole hand. It provides a framework especially for the product specification and the testing and refinement. Task characteristics are analysed and compared with the corresponding hand action capabilities. This leads to a specification of the device capabilities (compare section 4.3).

The product development process was guided by Ehrlenspiel's methodology [Ehr95]. It comprises five phases: Goal and product specification, conception, design, elaboration and realisation. The documentation of the design, elaboration and realisation phase was collected and analysed in order to compare this product development with other development projects and with methodological theory. This analysis has been published in [SLSH99].

In this chapter the problem is analysed and the product specification is presented. To set up this specification we first need to define a target application and a user group (section 4.2.1). Our goal is to create an efficiently working system consisting of the input device together with its software embedding in the chosen application. In chapter 5 the product development process including the conception, design, elaboration and realisation is briefly described. The problem is divided into sub problems and technical solutions are presented. This finally leads to a working system ready for usability tests in chapter 6 and 7. This evaluation gives hints for product improvements that should be incorporated in a redesign for a second generation of SpaceCats.
4.2 Usability Analysis

4.2.1 User Segments

The desktop products for multi-dimensional input can be divided into two non-overlapping sets (compare the figures 2.1 and 2.2):

*high end products* intended for professional use

*low end products* intended for computer games

These segments correspond to two different user groups of professional users and "gamers", which both in turn can be divided in a range of sub groups.

The gamers consist mainly of PC users and game console users. The market is potentially huge: Sony, one of the three big producers of game consoles, shipped 53 Million of their "PlayStation" by the end of 1999. The price of the input device has to be kept low at around USD 30. To be able to reach a low retail price large-scale production is necessary.

The currently biggest potential market for professional use is CAD with a total value of some USD 4.4 Billion in 1998. In this segment 6DOF desktop input devices are sold for approximately USD 700 and are generating a turnover of approximately USD 25 Million shared by two competitors (compare chapter 2.2). Most CAD users still work with 2D CAD but there is a strong growth in 3D CAD [SR99] [Ber99]. The CAD system with most users worldwide is Autocad from the company Autodesk with approximately 3 million software licenses sold.

Closely related to CAD are software products intended for visualisation and animation. The purpose of such software is to generate pictures good enough for the human eye in art, architecture, geographical data processing, advertising, computer games, industrial design, or film. This is in contrast to CAD, which is used as input to CAM systems to generate control data for NC machines. In a visualisation tool, features can be positioned approximately with a 6DOF input device while a CAD model needs precise positioning of its features within a certain tolerance which is often easier to specify by alphanumerical data. Likewise assembly can often be done approximately with a 6DOF input device in a visualisation tool whereas CAD systems typically use assembly with mathematical constraints. A free form surface in CAD should at least be $G^2$-continuous to have a continuous acceleration in a three axis milling process or to obtain satisfactory aerodynamic properties. Furthermore $G^2$-continuity is necessary to avoid discontinuities in light reflexes on the surface. In a visualisation tool the modelled surfaces will never come
in contact stringently with the laws of physics and the problems with light
reflexes can be fixed sufficiently with a number of rendering techniques. This
makes it easier to write tools to interact with free form surfaces conceived for
visualisation rather than CAD and to have such a modelling tool supported
with a 6DOF input device. Other frequent 3D actions in visualisation tools
like defining animation paths or setting light sources, could also be supported
by a 6DOF input device.

Visualisation tools are interesting for research purposes because they are
far ahead of the mainstream CAD market concerning 3D modelling. All
users work with 3D models and much functionality has been implemented like
positioning virtual objects in a scene, assembling parts, positioning virtual
cameras, defining camera paths or positioning light sources. Since these users
are strongly exposed to 3D functionality a new optimally designed 3D input
device would represent a great advantage. All this make us believe that
a visualisation tool is a much more promising application for 6DOF input
devices than 3D CAD and should be chosen for its embedding and used for
the usability test in chapter 7.

The market research institute Frost and Sullivan expects an increase of
sales from USD 185.6 Million 1997 to 410 Million USD by 2004 in this seg¬
ment. Autodesk is a leading company also in this segment with some 80 000
licenses of their software 3D Studio MAX sold at a license cost of approxi¬
mately USD 4000 each. This opens up the possibility to use the system in
a first stage as test platform and then sell the input device to a number of
users for a continuing hard test. At a retail price of USD 700 and some one
hundred devices sold this experiment would be self financing. We choose 3D
Studio MAX as our test system for a number of reasons: first, it is one of
the most widely spread systems, second, there is a well developed application
programming interface (API), and third, we had no problems to get software
test licences by adhering to the not for resale (NFR) condition.

4.2.2 Analysis of Professional Users

An initial usability analysis was performed with CAD users, since 6DOF
input devices are currently widely only used in that segment. The goal was
to find out how 6DOF desktop input devices are used in a computer graphics
application and to use the analysis as a basis for the product specification.
Currently there is a change in the CAD community from 2D to 3D CAD. 3D
CAD systems have been around for many years, but the majority of CAD
users are still working with 2D CAD. According to an investigation from
CAD/CAM-Report [SR99] 20% of the CAD users work with 3D CAD. An
investigation in Ny Teknik [Ber99] gives a similar result. To change from
4.2. Usability Analysis

2D CAD to 3D CAD implies a big change for the user, perhaps even bigger than the change from the drawing board to 2D CAD. When computers were introduced for construction and design this meant a change of the tool but not in the work methodology. New 3D CAD systems require a thorough change of work methodology to make use of the new features like parameterisation and a visual interface capable of producing realistic object representations with almost photographic quality.

In the work place analysis designers working at the Sulzer Meditech company with the CAD system Unigraphics were visited. At Sulzer Meditech implants are designed. This task is predestined for 3D CAD because of frequent use of free form surfaces and other complex forms. The designers used SpaceBall 3003 or the keyboard with their non-dominant hand and controlled the conventional 2D-Mouse with their dominant hand as described in [HG98]. Note that the SpaceBall 3003 is not equipped with any function buttons which means that only the keyboard provides shortcuts. It turned out that the SpaceBall was used to a very small extent compared with the conventional mouse. During less than 10% of the time of interacting with the CAD application the SpaceBall was in operation. To utilise the 6DOF functionality of the input device in Unigraphics the device has to be embedded more closely. For a wide range of tasks research has shown that the use of the dominant hand is more appropriate. This includes, for instance, command selection, modelling tools, and assembly.

In these studies it was noticed that designers had their designs rotating on the screen without knowing why when being asked. Our explanation is that the designer by the rotation collects information about the 3D shape from parallax shifts (compare with section 3.2.4). \(^1\)

An investigation on user need was also performed with a QFD-Analysis [Bop98]. One direct result was that the customers ask for function buttons on the input devices. We also see this in the development of SpaceBall and Space Mouse. Labtec presented their SpaceBall 4000 in spring 1999 with 12 buttons compared to the 2 buttons of the previous version. The CAD users want to program these buttons with shortcuts to some CAD functionality. LogiCad3D have equipped their new model Space Mouse Plus with two extra buttons, i.e., 11 buttons instead of 9 in the previous version. These two extra buttons are conceived to allow the designer to quickly answer the frequent yes and no answers in the CAD-System Catia. We would expect it to be more

\(^1\)An anecdotal notice: One designer sometimes used the conventional mouse for 2D rotation and sometimes the SpaceBall. A possible explanation is that this designer used the conventional mouse when the precision of the isotonic position control of the conventional mouse was of greater help than the concurrent use of all 6DOF with the isometric SpaceBall.
transparent for the designer to use the keyboard for shortcuts and the 6DOF input device purely for 6DOF interaction. This would associate the input devices with distinct tasks in order to make the system easier to learn and provide a lower cognitive load. The reason why CAD-designers want many buttons on their 6DOF controllers is to avoid homing times for moving their non-dominant hand between the 6DOF controller and the keyboard. If the most frequently used functions are programmed on the 6DOF controller mini-keyboard the users will adopt a two handed operation with mainly mouse and 6DOF controller instead of a two handed operation with mainly mouse and keyboard.

CAD designers are seldom as flexible in the scheduling of their workday as ergonomics guidelines recommend. Many spend most of the day in front of the computer, which makes fundamental ergonomic knowledge very important when designing input devices. As we are striving to conceive a universal input device which shall be used as extensively as the conventional mouse the ergonomic standards must be set very high. Weiss [Wei98] performed tests to find the ergonomic boundaries of an elastic desktop input device. His findings have been included in the product specification in this chapter.

4.2.3 State models for a 6DOF elastic input device

Buxton [Bux90] introduced a three state model for computer interaction with a graphical user interface (compare figure 4.1). The conventional mouse is switched between State1 and State2 by pressing and releasing a button. State0 would correspond to lifting the mouse from the mouse pad.

One possible state diagram for a universal elastic input device for position and rate control for 2D selection and 3D manipulation and navigation tasks is given in figure 4.2. Some fundamental questions are how to change between the states and by which transfer function 2D tracking and dragging are best supported. Furthermore the four extra degrees of freedom for a 6DOF input device compared with the mouse can be incorporated in a new interaction concept, e.g., by using the z direction to enlarge or reduce the view of the document or the rotational degrees of freedom for scrolling operations. The state model in figure 4.2 is also not complete for all 3D applications. In volume data, e.g., there is a need for 3D selection as mentioned in section 2.1. Today’s 6DOF isometric input devices for use in CAD systems [HG98] only support a small part of the state diagram in figure 4.2 and typically contain one single state as shown in figure 4.3.

The 6DOF input device is always connected to the viewpoint and the change of the viewpoint position is proportional to force and torque on the handle. Correspondingly a state model where the position of the controlled
4.2. USABILITY ANALYSIS

Figure 4.1: State model for a conventional mouse according to Buxton [Bux90].

- **State 0**: The movements of the device are not being monitored.
- **State 1**: Moving the device causes the tracking symbol to move.
- **State 2**: Allows one to move objects in the interface.

Figure 4.2: State model for a universal input device. The state model of the conventional mouse in figure 4.1 have been extended with two state for 6DOF control.
Figure 4.3: State model for conventional rate control 6DOF input devices as used in CAD systems. The 6DOF input devices SpaceBall and SpaceMouse are connected directly to the view port and thus only supports one single state.

Figure 4.4: State model for position control without clutch. A position control device supporting only one state will have a very limited workspace and generally not applicable to computer graphics applications.

object is always connected to the position of the tracker is given in figure 4.4. This state model is usually not practicable for an elastic input device. We need to introduce a clutch when there is no one to one mapping between the workspace of the device handle and the workspace of the controlled object (compare section 3.1.7).

The state model in figure 4.3 is likewise problematic for an elastic input device. Zhai [Zha95] claims that a stiffer input device makes rate control easier because the user can perceive where the zero position is. A loose input device on the other hand allows bigger workspace, which makes position control easier [TPD92]. Small forces are also of advantage due to fatigue [Wei98]. To mitigate this contradiction the use of the clutch can be introduced also for rate control. The velocity of the controlled object is in this case not proportional to the deflection of the handle but from the point where the clutch was last pressed. Using the clutch in this way also bring a technical advantage because the reference point is set every time the clutch is pressed and we avoid long term stability problems. A promising state diagram for an elastic input device for 6DOF-manipulation and -navigation is accordingly given in
4.2. USABILITY ANALYSIS

Figure 4.5: State model for 6DOF manipulation and navigation. By introducing the clutch and a switch between position and rate control a generally applicable 6DOF input device can be achieved.

How to realise all state transitions in figure 4.2 is an open question. An elastic input device equipped with a clutch provides many possibilities. A short tap or a "double-tap" on the clutch can be used to trigger functions. This is similar to how track pads are used today. Furthermore a short tap combined with a long tap on the clutch may be used for drag and drop. The triggered function may also be dependent on where in the workspace the tap was performed. At least twelve such "virtual buttons" are easily distinguished corresponding to the maximum positive and negative deflections in each degree of freedom. Alternatively the free hand (the hand not controlling the 6DOF handle) can be used to switch between states, for instance by using the modifier buttons on the keyboard. The work of finding an optimal solution to figure 4.2 or even finding an optimal state diagram for a universal input device will be left however to future research.
4.3 Product Specification

In the product specification the long term and short term goals are being kept apart. The short term goals shall be achieved within the scope of this work, whereas the long term goals mirror the potential of 6DOF input and should be accounted for as far as the product development resources allow at this early stage.

4.3.1 Range of Application

Long Term The goal is to create an input device with the potential of replacing the conventional mouse as standard interface. It will comprise the functionality of the mouse and add new functionalities for 3D interaction.

Short Term The SpaceCat realised in the scope of this work shall be conceived for high-end computer graphics users. For usability test the computer visualisation and animation system 3D Studio MAX will be used, but it shall also be possible to embed SpaceCat in other high-end application with little effort.

4.3.2 Cost Targets

Long Term The cost target must be adapted to a few US dollars, which is the OEM retail price for today’s conventional computer mouse.

Short Term The production cost of each device in the initial batch of approximately 20 SpaceCats should be less than USD 700 which makes it possible to sell these prototypes for test purposes.

4.3.3 Name and Message

Long Term "SpaceCat" – expelling the computer mice

Short Term "SpaceCat" – a new professional input device with free choice between position and rate control in six degrees of freedom

4.3.4 Task Characteristics

Creation of a concept which is adaptable to different kinds of future needs. SpaceCat allows the user to perceive 3D on a conventional computer screen through parallax effects, without the need for shutter glasses or special 3D
displays. The trend away from the desktop computer should be taken into consideration, including laptops, game consoles or interactive television. To make combinations with different kinds of input devices possible, SpaceCat shall be adopted to one handed operation for both right and left hand use. The feasible combinations include:

- SpaceCat and keyboard (or a SpaceCat integrated in a keyboard)
- SpaceCat and conventional mouse
- SpaceCat and speech recognition
- two SpaceCats

To make an efficient gradual enlargement of the embedded applications possible the following software driver functionality is needed:

- possibility to freeze every degree of freedom separately
- free choice of position and rate control for every degree of freedom
- sensitivity and gains separately adjustable for every degree of freedom
- freely programmable buttons
- support of some common formats for the transition of the data, including transformation matrix and quaternions for the orientation information
- possibility to extend the interface to more than one SpaceCat
- tremor filter

In the test environment the visualisation tool 3D Studio MAX will be supported including the following functionalities:

- positioning of selected object groups
- navigation by change of the camera viewpoint
4.3.5 Device Specification

SpaceCat shall be designed as a multidimensional desktop input device for both position and rate control with a clutch.

*Degrees of Freedom:* six, which corresponds to the degrees of freedom of a rigid object in 3D space

*Device Constraints:* conceived for office applications satisfying standards regarding electrical and fire regulations

*Range of Motion:* ±15mm translations and ±30° rotations

*Cross-Coupling:* no noticeable mechanical cross-coupling between the degrees of freedom to achieve a haptically correct interface, i.e., $M_s$, $B_s$, and $K_s$ in equation 3.1 should all be diagonal matrices.

*Absolute Accuracy:* No noticeable errors to the users. Furthermore measurement cross-coupling errors shall not be noticeable to the user.

*Spatial Resolution:* $300\text{dpi} \approx 0.1\text{mm}$

*Temporal Resolution:* $\geq 50\text{Hz}$

*Short Term Steadiness:* one bit noise level over one hour

*Long Term Steadiness:* no noticeable errors to the user, designed for at least a three year warranty

*Reliability:* $>99\%$ probability that an incorrect measurement value due to transmission errors is automatically detected and removed

*Mass:* $<0.5\text{kg}$

*Maximum Size:* $160 \times 110 \times 80 \text{ mm}$ for the whole part

*Elastic forces and torques:* $<2\text{ N}$ and $<0.03\text{ Nm}$ at maximum deflections

*Sticking Friction, Viscosity:* not noticeable to the user

*Mass and Inertia of Handle:* negligible compared to the human hand

*Convenience of Handling:* equivalent to current track balls
4.3. PRODUCT SPECIFICATION


Serial Interface RS232: single ended cabling, one transmit and one receive device, full duplex communication mode, unbalanced signaling, 50 feet maximum distance at 19200 baud, data 1 between -5V and -15V, data 0 between 5V and 15V, minimum input level at ± 3V, maximum output current 500mA (driver ICs normally used in PCs are limited to 10mA)

RS232 Interface Parameters: 9600 baud, 8 data bits, 1 stop bit, no parity check, checksum

Power Supply: via RS232 data line levels, i.e., limited to 9mA
CHAPTER 4. PROBLEM ANALYSIS
Chapter 5

Realisation

5.1 Functional Analyses

The SpaceCat development can be divided into a range of subtasks (see [B97]) concerning:

- sensors and analogue electronics
- elastic suspension
- workspace limitation
- clutch
- assembly
- input device micro controller software
- host computer software driver
- application plug-in

The first four items comprise physical components and are narrowly coupled. A great effort was put in an attempt to combine these functionalities in the same components, which was successful for sensors and suspension (see sections 5.2 and 5.3) by implementing a metal spring suspension. Metal springs are cheap (less than 1.5 US cent each in a series of one million), allow a large range of motion, and provide long life span if correctly dimensioned. These are the reasons to believe that a metal spring suspension is a preferable solution when conceiving an elastic input device. A great potential for cost savings would be to consider how the position of the handle could be
determined using the spring suspension as measurement gauge. The measurement of induction in metal coil springs is a promising solution because no other parts than the spring itself are needed for both suspension and measurement. Theoretically it would be sufficient to measure six spring lengths to determine the six degrees of freedom of the device handle. Alternatives to the inductance measurement have been listed in the patent [Sun96]. They included resistive, capacitive, inductive, and mechanical ways of measuring within a metal spring suspension. Because the inductance measurement is obviously the most promising method only this alternative will be analysed in this chapter.

Ensuring the spring length measurements is only one of many crucial functionalities when developing an elastic input device. Further hardware topics are to provide workspace limitations and an efficient clenching mechanism (see section 5.4). The development of the last three subtasks is dominated by software creation. As soon as the interfaces between these software subtasks are well defined the development can be performed quite independently. In section 5.5 these interfaces and the software subtasks are described. Finally, in section 5.6, an overview over the product with its hardware components is given.

5.2 Sensors and Analogue Electronics

5.2.1 Metal Spring as Sensor

An approximate relationship between coil spring length and inductance for long springs is given by [N89]

\[ L_s(l_s) = \frac{\mu \pi D_s^2 N_s^2}{4l_s} \]  \hspace{1cm} (5.1)

where \( \mu \approx 4 \pi \cdot 10^{-7} \text{Vs/Am} \) is the permeability for air, \( D_s \) is the diameter of the spring, \( N_s \) is the number of spring windings, and \( l_s \) is the spring length. For more precise results the formula given in [N89] on page 797 can be used.

It is essential for the usefulness of a spring as sensor if there is an acceptable way of connecting the spring electrically to an inductance evaluation circuit. By soldering the spring directly on a print an economical and reliable connection could be achieved. The soldering is easily done when, e.g., using copper alloy springs. A copper alloy has also the advantage of high electrical conductance which improves signal quality (compare sec. 5.2.2 eqn. 5.5). In order to avoid fatigue the spring should be stiff near the soldering point and have a continuous change of stiffness. The spring constant for an
extension spring is given by \([\text{DIN91}]\)

\[
k_s = \frac{G_s d_s^4}{8 D_s^3 N_s}
\]  

(5.2)

where \(G_s\) is the shear modulus and \(d_s\) is the wire diameter.

The stiffness depends cubically on the spring diameter \(D_s\). By reducing the spring diameter to, say, \(1/4\) at the end points the stiffness increases by a factor 64. By inserting such conical spring ends the spring wire fatigue problem is efficiently solved. Note that \(d_s\) occurs with power four in equation 5.2 but does not occur in equation 5.1 which provides a strong tool to change the spring constant without changing the inductance.

### 5.2.2 Oscillator

When inserting realistic values in equation 5.1 we get an inductance of some few \(\mu\text{H}\). This makes an LC-oscillator feasible for the inductance measurement. A solution has been chosen in which the sensor springs are connected to one common ground in order to minimise the number of connections between the handle and the fixed reference part. A common spring sensor ground is not possible in standard oscillator types like the Colpitts- or Hartley-oscillators \([\text{SRC87}]\), so in order to achieve one common ground for all measurement springs a special design of the oscillator had to be developed.

**LC-circuit with negative impedance**

In figure 5.1 the LC-circuit is shown with a parallel capacitor \(C_s\) and a spring modelled as an ideal inductor \(L_s\) with a serial resistance \(R_s\). \(Z\) is an impedance with \(\Re\{Z\} < 0\), which is needed to compensate for the losses caused by \(R_s\).

The system shown in figure 5.1 is in Laplace transform notion where \(s = j\omega\) is the Laplace variable described by

\[
\frac{1}{Z(s)} + sC_s + \frac{1}{R_s + sL_s(l_s)} = 0
\]  

(5.3)

Solving equation 5.3 for \(\omega\) gives the resonance frequency as a function the spring length \(\omega(l_s)\). When assuming \(\text{Im}\{Z\} = 0\), i.e., an ideal amplifier without any phase shift, the resonance frequency becomes

\[
\omega_s(l_s) = \sqrt{\frac{L_s(l_s) - C_s R_s^2}{L_s(l_s)^2 C_s}}
\]  

(5.4)
The resonance circuit bandwidth quality value is defined as

\[ Q_s = \frac{\omega_s L_s}{R_s} \quad (5.5) \]

The higher the frequency the better is the quality value of the resonance circuit, but on the other hand the realisation of a high frequency amplifier with small phase lag is difficult to achieve. As long as equation 5.1 is valid it is of advantage to use springs with many windings since \( L_s \sim N_s^2 \) but \( R_s \sim N_s \).

**Amplifier Properties**

The negative impedance \( Z \) is realised by means of an amplifier. In figure 5.2 the amplifier has a gain \( k \) and an output impedance \( Z_0 \), i.e., \( Z = \frac{Z_0}{1+k} \). Since a spring does not constitute an ideal inductor an amplifier have to be conceived with a sufficient \( k \gg 1 \). First attempts with high frequency operational amplifiers were not successful. To get a solution working for a wide range of measurement springs a two stage transistor amplifier was conceived to achieve high gain and big bandwidth (figure 5.3). In order to enhance the amplification for high frequencies two lead filters are introduced with the capacitors \( C_a \) and \( C_b \). Assuming infinite transistor gains and big capacitors \( C_1 \) and \( C_2 \) we arrive at the following expression for \( Z \):

\[ Z(s) = -\frac{R_2 R_0}{R_3(1 + sR_2C_a)(1 + sR_6C_b)} \quad (5.6) \]
5.2. SENSORS AND ANALOGUE ELECTRONICS

Figure 5.2: Representation of the negative impedance $Z$ with an ideal amplifier with amplification $k$ and output impedance $Z_0$.

Figure 5.3: Oscillator circuit with the LC-circuit from figure 5.1 and a detailed representation of the amplifier from figure 5.2.
The circuit in figure 5.3 may not be an optimal solution but it gives opportunities for fine tuning by means of $C_a$ and $C_b$ and has proved to work satisfactorily in our application so far.

Cross-Talk

So far a single inductive length measurement gauge has been discussed. To measure six degrees of freedom six measurement gauges are necessary. In order to avoid electromagnetic cross talk between the gauges the measurement can be organised sequentially, as outlined in figure 5.4. Furthermore it was necessary to connect non active LC-circuits to ground in order to prevent them from absorbing any signals by electromagnetic or electrical coupling.

Measurement Accuracy

The measurement of the spring length is performed indirectly by measuring the frequency of the LC-oscillator. The function $l_s(\omega)$ can be achieved from the equations 5.3, 5.1, and 5.6. Since we know that higher order effects have a great influence in each of the equations no attempt was made to theoretically calculate the resonance frequencies. The frequency is measured by counting
oscillations during a fixed time (see figure 5.4). Since the temporal resolution according to the product specification is 50Hz there is 20ms time for the measurements. The measurement period $T_s$ is thus limited to approximately 3ms, which gives a total measurement time for all six springs of approximately 18ms. The remaining 2ms are used mainly to start up the oscillators before each measurement. The number of counted oscillations is $n_c(\omega) = \frac{2\pi T_s}{N_c}$, where $N_c$ is a counter prescale factor to prevent the counter to overflow.

The static measurement accuracy was in the specification in section 4.3.5 described by absolute accuracy and spatial resolution. Since there is no need for a precise absolute measurement in an input device controlled by the human hand the achievement of the specified spatial resolution is the difficult engineering task. The condition for the absolute accuracy is fulfilled if the spatial resolution is approximately constant over the whole measurement spring working length, i.e., the oscillator frequency is approximately a linear function of the spring length.

The spatial resolution of the spring length $\Delta l$ is dependent on the change of resonance frequency per spring length change $\Delta l = \frac{d\omega}{d\omega} \Delta n_c = \frac{d\omega}{d\omega} \frac{N_c}{2T_s}$. In order to achieve the spatial resolution specified in section 4.3.5 the spring sensors were improved in several development cycles. Although the equations 5.3, 5.1, and 5.6 are not good enough to accurately predict the resolution $\Delta l$ these equations give us qualitative information how the resolution can be improved for each part of the sensor. During the spring sensor development the spring geometry, measurement frequency, measurement time, and amplifier were adjusted to achieve a resolution of the spring length near $\Delta l_{\text{max}} = 0.05\text{mm}$ in the whole measurement range for the spring in use by the time this is written. The desired noise level of one bit (compare with the specification in section 4.3.5) has been achieved successfully.

### 5.3 Suspension

The coil springs have to be organised in a way that allows the measurement of six degrees of freedom. To achieve this six springs are necessary. How to arrange the springs to achieve this is a well established problem in robotics and the conceiving of parallel manipulators [Heb00]. One well known solution to the problem is given in figure 5.5 and comprises one platform connected by six springs spanned in an octaeder structure to a base. This structure is called *Stewart Platform* and will be used throughout this thesis.

Basically there are two different kinds of coil springs: *extension springs* and *compression springs*. Since, first, the suspension must allow a big workspace, second, compression springs cannot be used for long working lengths
Figure 5.5: Sensor springs connected between base positions $B_h$ and platform positions $A_h$

without guide pins, and third, guide pins would obviously make the design more complex, extension springs have been chosen.

### 5.3.1 Parallel Kinematics

Characterising for parallel structures is that there is an explicit formulation of the inverse kinematics (compare figure 5.5 and figure 5.6):

$$ l_h = f_h(u) = \|A_h - B_h\| = \|R\bar{A}_h + S - B_h\| \quad h \in [1, 6] \quad (5.7) $$

where $l = (l_1 l_2 l_3 l_4 l_5 l_6)^T$ are the spring lengths and $u = (S_x S_y S_z \theta_x \theta_y \theta_z)^T$ is the translation and orientation of the platform.

The base coordinates are given by $B_1 = B_6 = (0 0 r)^T$, $B_2 = B_3 = (r\sqrt{3}/2 0 -r/2)^T$, and $B_4 = B_5 = (-r\sqrt{3}/2 0 -r/2)^T$.

The platform coordinates in the zero position (the position where the suspension brings the handle to an equilibrium) are given by $\bar{A}_1 = \bar{A}_2 = (r\sqrt{3}/2 H r/2)^T$, $\bar{A}_3 = \bar{A}_4 = (0 H r/2)^T$, and $\bar{A}_5 = \bar{A}_6 =$
Figure 5.6: Stewart platform seen from above with base coordinates $B_i$ and platform coordinates $A_i$. $r$ is the distance from the platform centre to $A_i$. $l$ is the length of one side of the platform.

\[
\begin{pmatrix}
-r\sqrt{3}/2 & H & r/2 
\end{pmatrix}^T.\]

Setting the distance between the platforms along the y-axis to $H = \sqrt{2}r$ creates an ideal octaeder structure.

$S = \begin{pmatrix} S_x & S_y & S_z \end{pmatrix}^T$ is the translation vector and $R = R_xR_yR_z$ is the orientation where the rotation matrices $R_x$, $R_y$ and $R_z$ are defined as:

\[
R_x = \begin{pmatrix}
0 & -\sin(\theta_x) & \cos(\theta_x) \\
\sin(\theta_x) & 0 & \cos(\theta_x) \\
-\sin(\theta_x) & 0 & \cos(\theta_x)
\end{pmatrix}
\]

(5.8)

\[
R_y = \begin{pmatrix}
\cos(\theta_y) & 0 & \sin(\theta_y) \\
0 & 1 & 0 \\
-\sin(\theta_y) & 0 & \cos(\theta_y)
\end{pmatrix}
\]

(5.9)

\[
R_z = \begin{pmatrix}
\cos(\theta_z) & -\sin(\theta_z) & 0 \\
\sin(\theta_z) & \cos(\theta_z) & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

(5.10)

By differentiating equation 5.7 we get

\[
dl = J^{-1}(u) \, du
\]

(5.11)

where $J(u) = (\partial f_i(u)/\partial u_j)^{-1}$ is a $6 \times 6$ matrix called the Jacobian.
The platform velocities are accordingly
\[ \dot{u} = J \dot{\ell} \]  
(5.12)

The forward kinematics must be solved numerically. Polynomial formulations of this problem range from a single equation of order 20 [dZS92] to a system of nine second order equations
\[
\| A_i - B_i \|^2 - \ell_i^2 = 0 \\
\| A_2 - A_3 \|^2 - \ell^2 = 0 \\
\| A_4 - A_5 \|^2 - \ell^2 = 0 \\
\| A_6 - A_1 \|^2 - \ell^2 = 0 
\]  
(5.13)

where \( i \in [1, 6] \) and \( \ell = \sqrt{3} r \) is a side length of the octahedron.

The actually implemented equation use quaternions (compare section 7.1.1) which give seven third order equations to be solved in the iterations of Newtons method for non-linear equation systems [DB74]. The factor \( \ell \) determines how translations and rotations are scaled and should be chosen at a value that results in a good condition number for \( J \). Choosing \( \ell = 1 \) and expressing the rotations in radians gives almost an optimal solution (compare equation 5.15).

### 5.3.2 Spatial Resolution

The Jacobian can be used to calculate how errors in the spring lengths \( l \) affect the calculated platform position.
\[ \Delta u \approx J(u) \Delta l \]  
(5.14)

We need to determine a workspace \( W \) in which the resolution \( \Delta u \), is as small as possible for every \( u \in W \) and with the equilibrium position of the handle in the centre of \( W \). The resolution is directly related to the condition number of \( J \) [SS96]. Because of symmetry there is only one geometrical parameter \( H \) to adjust for an optimal workspace. Minimising the condition number of \( J \):
\[
\min_{\ell, H} \kappa(J) = \min_{\ell, H} \| J \| \| J^{-1} \| 
\]  
(5.15)

subject to the height \( H \) and the scaling between translations and rotations \( \ell \) as described in section 5.3.1 results in an optimal \( H = \ell/2 \). However we cannot chose this point as the equilibrium position if we want to achieve a
Figure 5.7: The norm $\kappa$ of the Jacobian $J$ as a function of the distance $H$ between the platforms normalised in $r$.

workspace with $\Delta u$ as small as possible for every $u \subset W$ since the condition of $J$ quickly worsens near singularities of $J^{-1}$, i.e., in this case as $\mathcal{S}_y$ get near $-H$ (compare figure 5.7). Currently the value $H = r$ is used.

An estimation of the maximum absolute error in each degree of freedom is given by [Mer00]

$$\Delta_{\text{abs}}u_h = \sum_{i=1}^{6} |J_{hi}| \Delta_{\text{abs}}l_i$$

(5.16)

where $\Delta_{\text{abs}}l_i$ is the absolute measurement error of each spring length, which is a combination of the quantisation error $\Delta l_{\text{max}}$ as defined in section 5.2.2 and errors due to the non-linearities mentioned in section 5.2.

According to the specification we are less interested in a low absolute error than in a high resolution. The resolution in the degree of freedom with worst resolution is described as

$$\Delta u_{\text{max}} = \hat{j} \Delta l_{\text{max}}$$

(5.17)

where

$$\hat{j} = \left\{ \min_{1 \leq i \leq 6} \left( \max_{1 \leq j \leq 6} |J_{ij}| \right) \right\}^{-1}$$

(5.18)
Setting $H = r$ and allowing translations of $\pm r/2$ in all directions from the equilibrium position the resolution worsens by a factor $\tilde{J} \approx 2$ or less in the whole workspace for allowed translations. Adding rotations of $\pm 30^\circ$ worsens the resolution by less than a factor $\tilde{J} \approx 3$. However, the currently used workspace limitations will not allow this (compare section 5.4.1). As the exact form of the workspace is yet to be defined a more thorough analysis of accuracy and resolution will be left to future work.

### 5.3.3 Forces and Torques

The relationship between spring forces and the platform forces (i.e., forces and torques) is

$$F_u = J^{-T} F_l$$

where $J^{-T}$ is the inverse and transposed Jacobian. This relationship is obtained from the power balance $F_l^T \dot{u} = F_u^T \dot{u}$ and by substituting $\dot{u}$ using equation 5.12.

So far we have neglected that there must be at least one spring element dispersing the two platforms when using an octaeder structure of extension springs for the measurement, i.e., $J^{-T}$ must be extended to at least a $7 \times 7$ matrix in order to perform analysis on forces and torques. One solution with a total of nine springs is given in figure 5.12 $D$ containing three dispersion springs spanned in a plane. By using dispersion springs that are much stronger than the measurement springs the haptics is only dependent on the dispersion springs and the elasticity can easily be adjusted by exchanging only these springs. A drawback of using three dispersion springs in a plane is that the suspension will not be haptically optimal. The torques will be weak since the dispersion springs are fastened on a small inner radius. Especially stabilising torques for rotations that are performed around any axis in the plane will be weak.

When investigating the haptics of SpaceCat it is also necessary to take the influence of the cuff into account. The cuff obturates the sensor from dust and damps the spring-mass system. The cuff was made of cloth in the first generation SpaceCat and will be made of silicone in the second generation SpaceCat. Especially the effects of the cloth cuff are difficult to simulate and have to be tested experimentally.
5.4 Other Hardware

5.4.1 Workspace Limitations

Since it has to be assured that $J^{-1}$ never becomes singular and metal springs do not provide any means for avoiding over-extension it is necessary to provide workspace limitations. Consider two concentric rings in a plane with radius $r_1$ and $r_2$ as in figure 5.8. Between the rings strings of length $l_w$ are radially spanned. If a large number of strings would be spanned the inner ring can move by $x_{\text{max}} = r_1 + l_w - r_2$ from its concentric position in the plane. In the direction orthogonal to the plane the movement $y_{\text{max}} = \sqrt{l_w^2 - (r_2 - r_1)^2}$ is possible. Maximum rotation in any direction is $\cos \gamma_{\text{max}} = (r_1^2 + r_2^2 - l_w^2)/2r_1r_2$. Using these equations reasonable values can be achieved for the workspace, e.g., $r_1 = 38\text{mm}$, $r_2 = 60\text{mm}$ and $l = 42\text{mm}$ creates a workspace with $x_{\text{max}} = 20\text{mm}$, $y_{\text{max}} \approx 36\text{mm}$ and $\gamma_{\text{max}} = 45^\circ$. In order to avoid the singularity of $J^{-1}$ in the $-y$ direction the housing had to be used as an additional limit.

In a second generation of SpaceCat this solution has been changed to a version with all limitations contained in the housing of the handle. This simplifies the assembly and provides a better shelter of the springs compared with the solution in the figures 5.8 and 5.12.

5.4.2 Mechanical Tremor Filter

Weiss [Wei98] showed that hand tremor is a problem for an elastic 6DOF input device in position control mode. In rate control mode the high frequent tremor is not a problem since the integrator in the transfer function for rate
control is a very good low pass filter. The tremor can be damped either by mechanical or software means. The advantage of a mechanical filter with friction is that the physical tremor is actually damped, which the user can perceive directly. The drawback in this case is that a mechanical filter makes the construction more complex. To test how a mechanical filter works we built two models shown in figure 5.9. In these models strings are attached to the springs. The strings are connected to the handle via deflection points which are causing the friction. In versions without friction the springs are attached directly to the handle. Due to the following reasons we decided not to include a mechanical tremor filter:

- For most subjects the tremor was not a major problem. The tremor is, however, very individual and therefore a damping function should be individually adaptable. This is easier to achieve with a software filter.

- When introducing sticking friction no distinct self-centred position is possible. The handle will come to rest at random in an area around the elastic equilibrium depending on how the handle was let loose. That the user cannot feel the equilibrium point is a drawback for the elastic control and makes a transfer function based on the state model in figure 4.3 haptically incorrect.
5.4. OTHER HARDWARE

5.4.3 Realising the Clutch

One crucial question for an elastic input device for position control is how to realise the switching between the \textit{State0} and \textit{State1} (compare figures 4.1, 4.2 and 4.5), which is also called indexing or clutching. Different possibilities were tested including:

- foot pedal
- clutch controlled by the hand not controlling the 6DOF handle
- tactile button on the 6DOF handle for thumb or index finger
- touch sensitive button on the handle for thumb or index finger

In a number of experiments it was found that a touch sensitive clutch for the index finger works best. The thumb cannot be used for clutching since it holds the handle against the other fingers and cannot be released without letting the handle lose. The tactile button induces a movement on the handle. To control the clutching with the hand not controlling the 6DOF handle is more difficult to synchronise than providing the clutch and 6DOF handling for the same hand. Moreover it is an advantage to have one hand free for other tasks. Even more difficult to synchronise is a foot pedal. Furthermore opinions are divided among computer users whether they want to use their feet for computer interaction at all.

In order to find out which shape the touch sensitive area on the handle should have a number of persons were asked to perform manipulations with a prototype handle (figure 5.10). The thumb and the index finger are the only fingers with an own area not touched by any other finger during manipulation [Wei98]. Since the use of the thumb as the clutching finger is not feasible the index finger is the only possible finger to perform the clutch actions.

Some recent work concerns the use of touch controls. Hinkley [HCS98] extended the state diagram in figure 4.1 with two different zero states. The state \textit{T0} correspond to an out of range state triggered by touching the device with the hand whereas the state \textit{P0} corresponds to an out of range state triggered by device proximity to a sensor. According to this notation the state diagram for elastic input devices would support only state \textit{T0} but not state \textit{P0}. In Hinckley and Sinclair [HS99] a realisation of a capacitive clutch with a D-Flip-Flop is described. In SpaceCat the capacitive sensor was realised with a RC-Oscillator to allow software calibration of the trigger capacity.
5.5 Software

In this chapter we analyse how to handle the interfaces between the SpaceCat and the application. We divide between the hardware interface, which is used for communication between the SpaceCat micro controller and the software driver, and the software interface, which is used for the communication between the software driver and the application (see figure 5.11).

5.5.1 Application and Software Interface

Although an initial test phase with the visualisation tool 3D Studio MAX is targeted, it would be unwise to design SpaceCat’s interface only considering this application. It must be possible to embed SpaceCat in a wide range of 3D graphics application with minimal effort. When there is an interest from a software producer to test SpaceCat it should be possible to embed SpaceCat according to current conventions. This will speed up the embedding and will most probably be demanded from the software producer if he is going to contribute to the embedding. Thus a well thought through Software Development Kit (SDK) is an important part of the product.

It would also be unwise to restrict the use of SpaceCat to only one operating system. There has been a shift in computer graphics applications like CAD from the traditional UNIX platforms to Windows (trademark of Microsoft, WA, USA). For one of the bigger CAD-Systems “Pro Engineer” from PTC Inc (Massachusetts, USA) the most rapid change took place be-
Figure 5.11: The different parts of the technical system and its interfaces

between 1996 and 1998 with a share of Windows growing from 0% to 60%. Still, however, in medical and scientific applications UNIX is dominating. The increasing interest for open source software and especially for the open source UNIX system LINUX also supports the UNIX alternative.

The hegemony of operating systems is further stressed by the need in robotics for real time operating systems. This means that the software must be structured in a way that makes the portability between different operating systems feasible. The best way to guarantee this is the parallel development on different operating systems and hardware platforms. Because of the dominating position of Windows and because 3D Studio MAX is only running on Windows computers the emphasis will, however, be put initially on a working driver for the Windows operating system.

There are standards for input devices for the different operating systems. The X consortium have introduced the X11 Input Extension Protocol Specification for UNIX. Microsoft and Apple have introduced DirectX and Sprockets respectively in order to support game controllers. For professional applications like CAD there is currently no accepted standard. The two competitors Labtec and LogiCad3D have their own proprietary solutions. For the first test phase with SpaceCat for high-end applications a new proprietary interface will be created using the standard means of communication provided by the operating system, i.e., messages in Windows and events in UNIX. By supporting these two operating systems the vast majority of all 3D graphics
One extra feature that has been implemented is communication over an internet protocol (IP). IP-sockets are available today on all major operating systems and would provide a way to make a test-implementation for SpaceCat relatively independent of the operating system, especially for platform independent software, e.g., JAVA. Furthermore, by choosing the TCP/IP-protocol, it will be possible to check the data from the SpaceCat using a standard internet application like telnet. Therefore we use TCP/IP and not UDP/IP, although the simpler UDP/IP-protocol would suffice in this case. By using the local host to transmit data internally in one computer system the transmission is fast enough. Additionally supporting an internet protocol also makes it possible to connect the SpaceCat to one system and transfer the data via internet to another computer, e.g., to connect SpaceCat to a computer system for which no SpaceCat driver is available.

As seen in the previous chapters there are many possible applications for SpaceCat with very different needs and this has to be considered in the design of the SDK. The SDK should be conceived in a way that gives the programmer maximum freedom for customised embeddings. This challenges his or her creativity and makes new solutions possible. We defined the following list together with a CAAD-company for embedding SpaceCat:

- possibility to freeze every degree of freedom separately
- free choice of position and rate control for every degree of freedom
- sensitivities separately adjustable for every degree of freedom
- freely programmable buttons
- support of some common formats for the transition of the data, including transformation matrix and quaternions for the orientation information
- possibility to extend the interface to more than one SpaceCat

This functionality can either be included in the software driver or in a library attached to the application. We have chosen to provide a dynamic link library (DLL) for Windows. For UNIX the source code is kept open to anybody wanting to embed SpaceCat, because in an initial phase the effort to provide shared libraries for all UNIX platforms would be too big. The reason to put this functionality in the application is to minimise the communication between driver and application. If these functions would be provided by the driver, the driver would have to keep a list with application specific data of
all applications currently using SpaceCat and adapt the information sent to
the current application, which is a more complex solution.

5.5.2 Micro Controller, Driver and Hardware Interface

The minimal requirement on the hardware interface is to transmit informa-
tion on the position and orientation of the handle and clutch information
from input device to host computer. The interface shall be robust to changes,
i.e., follow a modular design. Furthermore the probability for transmission
errors shall be kept low.

To transmit data from the SpaceCat to the host computer a serial in-
terface is appropriate. With the standard transmission rate of 9600 baud it
would be possible to send information about the six degrees of freedom with
16 bits resolution at 80Hz, which is at about the same rate as the image on
the computer screen is repainted and much faster than the graphics subsys-
tem generates images. This means that the standard serial interface RS232
can be used for the data communication. As an alternative the Universal
Serial Bus (USB) can be taken into consideration. It is getting through as
a new standard for Windows workstations. UNIX workstations will follow,
but it will take a long time till the installed base of workstations all have
this standard. The serial port RS232 has been supported for many years by
most systems. It is also common in the industry in robotics tasks. Further-
more there are currently only few micro-controllers supporting the new USB
standard. Therefore we chose RS232 for the first version of SpaceCat.

The data sent over the serial port should be as invariant as possible
against constructive or sensor technology internal changes in the SpaceCat.
New versions of SpaceCat shouldn’t cause any changes to the rest of the sys-
tem. This is satisfied if the position and orientation of the SpaceCat handle
is transmitted. An alternative would be to send position and orientation
changes. The following items make the sending of absolute data the more
favourable of the two solutions:

• Lost data packages cause less problems since no integration in the host
  system is needed.

• No accuracy is lost because of the differentiation in the SpaceCat.

• Absolute position is necessary when we want to use a homeomorphic
  mapping from the workspace of the SpaceCat to the workspace of the
  controlled device according to the state model in figure 4.4.
To send the orientation data quaternions are used [HL92]. There are other possibilities including Euler angles, the whole or two colons of the rotation matrix or using the Roudriges transformation. The quaternions were chosen because they are an appropriate choice in computer graphics applications. The choice is supported by the fact that because only a restricted workspace is needed only the minimum of three parameters have to be transmitted for the rotation description. Furthermore an algorithm was found which can be implemented easily in the micro controller.

Sending the position and orientation of the SpaceCat handle sets minimal conditions for a proper interface definition. It would be possible, though, to incorporate more functionality in the SpaceCat. The argumentation against this is similar to the argumentation to provide more functionality in the SDK and less in the SpaceCat software driver. Putting much functionality in the SpaceCat makes more communication over the serial interface necessary, which is even more problematic than the communication between the software driver and the application via the operating system. The tremor filter is one candidate to be brought into SpaceCats micro-controller, but there are strong arguments against this:

- The tremor filter is likely to improve over time. New driver versions can easily be downloaded over internet. To change a micro-controller program is more complex.
- The tremor filter is application dependent, e.g., for position control a different filter is needed than for rate control.
- The implementation in the micro-controller requires a higher initial cost.

For these reasons it seems sensible to keep the micro-controller software at a minimum.  

To detect transmission errors parity checks or check sums can be used. Because a checksum brings a higher probability to find an error but is not more difficult to calculate, SpaceCat will use a checksum. To generate smooth movements a picture rate of approximately 30Hz is necessary. This corresponds to the best case of what computer graphics subsystems can provide. If we chose 50 Hz as our transmission rate we are sufficiently better than

---

1One argument raised in favour of implementing the tremor filter in the SpaceCat micro-controller is that it provides a real-time system with a constant sampling rate, which makes the implementation of digital dynamic filters easier. This is not a strong argument however. Since the transmission rate is constant we can take advantage of the constant sampling rate also when implementing the filter in the host computer.
5.6. ASSEMBLY

the graphics subsystem. The maximum time lag because of the transmission would be 20 ms. This is well below 100 ms, which corresponds to the minimal time lag the user would be aware of but assumes that the specification for the time lag is relaxed. At 9600 baud a data package of 16 bytes is possible at 50 Hz, which is sufficient to transmit the six degrees of freedom data with 16 bits resolution, the checksum and button information.

One may ask if it would be possible to use an already existing RS232 protocol for the communication over the hardware interface. The answer is no: we cannot connect to the interfaces in use by current desktop rate control devices because of SpaceCat’s bigger workspace and the need for a higher resolution. Furthermore the existing protocols use rotations around x, y, and z to describe orientation, whereas other methods are better suited for a bigger workspace. Finally existing drivers supporting the currently used hardware protocols do not support the requirements stated in the previous chapter.

5.6 Assembly

In the last section of the realisation chapter we take a look at the physical parts and how they fit together. The long term cost target stated in the product specification has been achieved when it comes to the bill of material. For SpaceCat the assembly will be a critical cost component to minimise when it comes to mass production. In figure 5.12 the steps of the current version of SpaceCat assembly are shown. Picture A shows the plastic basis part of SpaceCat. In picture B two prints have been added, the upper one for the connection of the springs in the handle and the lower one for the base spring connections and the electronics. In picture C the measurement springs have been spanned between the prints in an octaeder structure as described in section 5.3. Picture D shows the dispersion spring positions in the plane of the upper print as described in section 5.3.3. In picture E the prints and springs have been brought to their positions in the basis, the cuff and workspace limitation have been added and the handle and palm support are shown. On the handle the left clutch field of conductive silicon (the small black field) and a silicon support for the thumb (the big black field to the right on the handle) are visible. On the palm support two extra capacitive buttons of conductive silicon have been added, which are freely programmable for the application plug-in programmer. Finally, in picture F, the other side of the symmetric device is seen, with right clutch, thumb support and functional buttons visible and with the handle in its equilibrium position.
Figure 5.12: SpaceCat assembly. In picture A to E the following parts are successively added: A basis plastic part, B prints, C measurement springs, D dispersion springs, and E handle and palm support with capacitive buttons. Finally, in picture F the complete assembly is shown.
Chapter 6

Qualitative Usability Tests

In this chapter three qualitative usability tests are presented. The first test was performed in an early stage of the development cycle to find out about SpaceCat’s qualities and verify that the right strategy for the software development had been chosen. The second test confirms the results in the first test and the third test states a first reaction from a test performed by one of the producers of six degrees of freedom input devices currently on the market.

6.1 Video Recorded Usability Test

In recent years, there has been an increased use of six degrees of freedom (6DOF) input devices in computer aided design (CAD) following the trend from 2D- to 3D-CAD systems. The 6DOF device is typically used by the non-dominant hand for non precision tasks as a complement to keyboard and mouse. It allows the user to translate and rotate the virtual model. This enhances the 3D understanding and helps controlling the optimal viewpoint according to the literature analysis in chapter 3.

The video recorded usability test was performed to find out whether the use of SpaceCat would significantly improve the task solving time in a CAD assembly task supported by mathematical constraints for experienced users compared to the currently used SpaceBall. Furthermore, in a second part of the experiment, inexperienced users made spoken comments on the two input devices. The stiff elastic SpaceBall was used with rate control whereas the weak elastic SpaceCat was used with position control. The experienced CAD users were also experienced SpaceBall users but had no experience of SpaceCat whereas the inexperienced users had never tested any kind of 6DOF input device before.
CHAPTER 6. QUALITATIVE USABILITY TESTS

6.1.1 Hypothesis

Since the assembly is supported by mathematical constraints and no precise manipulation is performed we do not expect the transfer function to show a major difference for the experienced users. These users have learned to perform the needed 6DOF functionality with their non-dominant hand sufficiently for the task we study. That is: No significant performance difference for experienced users.

We expect a preference for SpaceCat in inexperienced users, due to faster learning according to hypothesis 3 in section 3.4. That is: Significant preference for SpaceCat for inexperienced users.

6.1.2 Apparatus

The qualitative experiments [Wei98] were performed with SpaceCat (figure 1.1) and SpaceBall 3003 (figure 2.2). The experiment was performed on a Digital Alpha Station 400 MHz under Unix 4.0A with the Unigraphics CAD system Version 13 (figure 6.1). The SpaceBall was connected to the CAD-system through the preinstalled plug-in using rate control whereas the SpaceCat used a new position control plug-in especially developed for the usability tests. The experiments were recorded on video with two cameras according to figures 6.2 and 6.3.

6.1.3 Procedure

In the first experiment [SWS00], 12 male students (average and standard deviation age was 27 ± 6 years, 3 were left handed and 9 were right handed) who all had at least half a year experience with the SpaceBall performed an assembly task supported by mathematical constraints. All participants had performed the task before in a computer aided design course. Assembly with mathematical constraints means that the 6DOF input device was used simply to change the viewpoint, making it possible to select the surfaces to be connected in the assembly with the conventional mouse. Thus no precision work was performed with the 6DOF input device, which was handled with the subject’s non-dominant hand. This specific CAD task was chosen because it implies a comparatively high amount of 6DOF interaction. The subjects were told to keep their normal work pace and that the execution time had no importance in the test. The participating subjects always began with rate control and then repeated the task with position control. The experiment was assessed on the following criteria: task solving time, spoken comments, and the number and kind of unintended manipulations.
6.1. VIDEO RECORDED USABILITY TEST

Figure 6.1:
Apparatus for both experiments in the qualitative usability test

Figure 6.2: Video recorded usability test set-up for both experiments: in order to record hand movements and virtual object manipulations the cameras $C_1$ and $C_2$ were set up according to the figure.
Figure 6.3: The image from the screen camera $C_2$ was inserted in the upper left hand corner of the hand posture camera image $C_1$.

In the second experiment ten persons (one woman and nine men with the mean age $29 \pm 6$ years, one man was left handed and the rest of the subjects were right handed) without any experience with 6DOF manipulators participated. They were asked to focus the viewpoint on different virtual object locations. The experiment was assessed on spoken comments and the number and kind of unintended manipulations.

6.1.4 Results of the Video Analysis of the First Experiment

Unigraphics allows functions to be entered via mouse or keyboard and furthermore allows different kinds of object representations. Seven subjects utilised this to fundamentally change their strategy on how to solve the task. Because of this the recordings from these subjects could not be used for time measuring purposes. The five subjects sticking to the same strategy needed $179s \pm 34s$ with rate control and $161s \pm 16s$ with position control to solve the task, i.e., no significant differences in terms of completion time were measured ($t=0.96$, $p=0.2$).

In position control mode long distance moves triggered frequent clutching, often 3 to 6 subsequent clutching actions. During the assembly task the subjects clutched between 6 and 55 times (mean and standard deviation is $28 \pm 6$). No unwanted movements of the controlled object was noted due to clutching. No unwanted manipulations were registered in position or rate control mode. During the experiments no changes of arm postures due to
the change of input device were noticed.

### 6.1.5 Spoken Comments

Comments from the *first experiment on position control with SpaceCat*:

- The position control is convenient, intuitive and logical.
- The virtual object is restless.
- For long distances one has to clutch extensively.

Comments from the *first experiment on rate control with SpaceBall*:

- The rate control is convenient as soon as you have learned it.
- The control is continuous and restful.
- The control demands big forces and torques.

Comments from the *second experiment on position control with SpaceCat*:

- The haptic impression of the small forces and torques mediates an impression of high sensitiveness and fragileness.
- The manipulation is fine and convenient.
- Because of the gains the control is very sensitive, and the controlled object dithers continuously.
- The mapping between handle and virtual object is very intuitive and corresponds completely to my expectations.
- The hand cannot completely relax if left on the handle during interaction pauses.
- The clutching demands an effort.

Comments from the *second experiment on rate control with SpaceBall*:

- Fine positioning is difficult – everything is skew.
- The control is not intuitive. It is indirect and like driving on blank ice.
When zooming to see details it is difficult to keep the orientation. The object often disappears out of the view.

According to all subjects, position control was reliable and intuitive. The experienced SpaceBall users especially remarked that position control can be mastered immediately. The rate control however is learned after some hours practice. Furthermore, when zooming on details the image was easier to keep at rest with position control. A drawback in position control was the hand tremor, which was effectively damped in rate control. Generally the subjects thought rotations were better handled using position control whereas the translations were better handled using rate control, especially long virtual object translations which demanded a range of clutching actions in position control mode.

6.1.6 Preferred Device

Of the 12 subjects in the first experiment two preferred the SpaceBall and one the SpaceCat. Nine subjects were not conclusive in their decision.

Of the 10 subjects in the second experiment nine spontaneously preferred the SpaceCat because it is simpler, more intuitive, requires less force and is more precise. One person preferred SpaceBall because no clutching and therefore less effort is needed.

6.1.7 Survey on SpaceCat’s Properties

All subjects from both experiments were asked to comment on forces, torques, clutching, handle size, and height difference between palm support and handle for SpaceCat. The results are summarised in figure 6.4.
6.1. VIDEO RECORDED USABILITY TEST

Generally, the physical properties of SpaceCat were accepted. This includes the size of the handle, the palm support, the workspace and the functionality of the clutching mechanism. One exception is how the subjects felt about forces and torques. Currently the maximum force is 1.5N and the maximum torque is 0.03Nm, which was regarded as too small by about half of all subjects.

6.1.8 Conclusion

For the experienced users in experiment one the control order or the kind of input device did not play a major role when solving the CAD assembly task supported by mathematical constraints. The users could quickly learn to use the new position control input device sufficiently for this task, i.e., no significant performance difference for experienced users was noticed as hypothesised in section 6.1.1. The second hypothesis was also upheld. Nine of ten of the inexperienced subjects preferred SpaceCat to SpaceBall.

A possible explanation for this difference between the groups is, first, that the experienced users already were well acquainted with SpaceBall, which put it in a more favourable position. Second, the inexperienced users were much more focused on the input device assessment, whereas for the experienced users the 6DOF input device only plays a limited role in the performed CAD task. Because of this no strong preferences came out from the experienced users.

The comments of the experienced users, however, reveal some interesting differences between the devices. Position control has its strength in precise control of an object whereas rate control is good for long object translations. Accordingly an optimal 6DOF input device should be capable of both position and rate control. To achieve this SpaceCat is the better candidate: due to its' greater workspace it is applicable to both velocity- and position control.

In this test an assembly task with mathematical constraints was performed. There is reason to believe that similar results would be achieved when testing other CAD tasks. In CAD 6DOF input devices are generally used with the non-dominant hand for tasks not demanding precise manipulation. To account for SpaceCat’s advantages in precise manipulation a visualisation system is a more proper base. Thus, this usability test support the decision to implement SpaceCat for the visualisation tool 3D Studio MAX as specified in section 4.3. A usability test incorporating docking in 3D Studio MAX is described in chapter 7.
6.2 Student Interviews

During an open-door event at the ETH A-level students tested SpaceCat and SpaceBall 3003 FLX with the system in a simplified version of experiment one of the previous section. The students were asked which device they preferred. Furthermore they made statements on how they felt about SpaceCat’s clutching, elasticity, workspace, handle size, and palm support. Half the students started with SpaceCat and the other half with SpaceBall. SpaceCat was tested in position as well as rate control mode, where position control was always tested first. The subjects were asked to move a CAD work-piece between predefined start and end positions with an object in hand metaphor. Before performing the given task the subjects played with the device to get used to the currently active control mode. The experiment lasted between 15 and 20 minutes per subject. One right handed woman, two left handed men and twelve right handed men participated. None of the subjects had previous experience of 6DOF input devices but all had extensive training with the conventional mouse. 11 of the subjects spontaneously preferred the SpaceCat out of which one subject favoured the rate control mode. All subjects preferring SpaceBall had begun the test with SpaceCat. Six of the subjects found SpaceCat’s clutching perturbing in some way. Five subjects stated a strong desire for stronger spring forces and another two found the current spring forces OK or somewhat too small. The workspace was considered too big by three subjects and too small by another three. Generally SpaceCat’s handle size and palm support were rated as good. One subject thought a camera in hand metaphor would have been more appropriate for the task. To summarise the student interviews it can be concluded that all results were in line with the results of the experiments in the previous section.
Chapter 7

Quantitative Usability Test

7.1 The Experiment

In a 3D docking task the input devices SpaceCat and SpaceBall were compared. SpaceCat is an elastic input device that was used in position control mode whereas SpaceBall is a stiff elastic input device used in rate control mode.

The independent variables in the usability test were subject, device, trial number, docking distance, target size, and degree of freedom. Docking distance and target size are summarised in the variable index of difficulty for a Fitts’ Law test (compare equation 3.4). The dependent variables were learning coefficient, task completion time, Fitts’ Law parameters, half way time (i.e., a performance difference measure for the different degrees of freedom), coordination between the degrees of freedom, and clutch characteristics for SpaceCat. All of these variables can be calculated from the movement path trajectories.

It is assumed that the hypotheses from chapter 3.4 are correct. In this test hypothesis 1 (Control Mode and Control Task) and 3 (Physiological Implications on Handling and Learning) are verified. Hypothesis 1 was implemented by comparing the trial completion times for SpaceCat and SpaceBall whereas hypothesis 3 was implemented by comparing the learning coefficients of SpaceCat and SpaceBall.

In this section background information is given on the subjects (section 7.1.4), apparatus (section 7.1.5), experiment design (section 7.1.6), task scene (section 7.1.7), experiment procedure (section 7.1.8) and on how some of the dependant variables are calculated (sections 7.1.1, 7.1.2 and 7.1.3). In section 7.1.1 a description is given on how the trajectories are described mathematically. In the sections 7.1.2 and 7.1.3 it is shown how the dependant
variables *half way time* and *coordination between the degrees of freedom* are calculated from the trajectories. The calculation of the other dependent variables are given with the results of the experiment in section 7.2. Finally in section 7.3 some qualitative results of the quantitative usability test are presented.

### 7.1.1 Mathematical Background of Path Description

An Euclidian motion from $p$ to $q$ can be written in matrix vector notation as:

\[
E : \mathbb{R}^3 \rightarrow \mathbb{R}^3
\]

\[
p \rightarrow q
\]

\[
p = Rq + S
\]

where $R$ is a $3 \times 3$ rotation matrix and $S = \left( \begin{array}{ccc} S_x & S_y & S_z \end{array} \right)^T$ is the translation vector [HL92]. Instead of a rotation matrix the orientation can be described by a normalised Hamiltonian quaternion [Ple89]:

\[
Q = \left( Q_t \begin{array}{c} Q_x \ Q_y \ Q_z \end{array} \right)^T = \left( \cos \theta/2 \ e^T \sin \theta/2 \right)^T
\]

(7.2)

i.e., $Q_t = \cos \theta/2$ and $\left( \begin{array}{ccc} Q_x & Q_y & Q_z \end{array} \right) = e^T \sin \theta/2$ where $e$ is the normalised rotation vector and $\theta$ is the rotation angle.

Let $S(t)$ and $Q(t)$ denote the position of the controlled object at time $t$ and $\hat{T}$ denote start time. The start position of the docking task is defined as $\hat{S}$ and $\hat{Q}(\hat{e}, \hat{\theta})$ and the target (or end) position is defined as $\hat{S}$ and $\hat{Q}(\hat{e}, \hat{\theta})$, which is reached from the start position within a certain tolerance at time $\hat{T}$. The difference between the current position and the target is thus

\[
\Delta S(t) = S(t) - \hat{S}
\]

\[
\Delta Q(t) = Q(t)\hat{Q}^{-1}
\]

\[
\Delta \hat{e}(t) = \hat{e}(t) - \hat{e}
\]

\[
\Delta \hat{\theta}(t) = \hat{\theta}(t) - \hat{\theta}
\]

(7.3)

The difference at the start position is denoted by $\Delta \hat{S} = \Delta S(\hat{T})$, $\Delta \hat{Q} = \Delta Q(\hat{T})$, $\Delta \hat{e} = \Delta \hat{e}(\hat{T})$, and $\Delta \hat{\theta} = \Delta \hat{\theta}(\hat{T})$. If we make the restriction $\Delta \hat{\theta} \in [-\pi/2, \pi/2]$ a simple, numerically stable, and unambiguous measure for the distance to the target in position and orientation of the controlled object can be defined as:
\[ \Gamma = \left( |\Delta S_x|, |\Delta S_y|, |\Delta S_z|, |\Delta Q_x|, |\Delta Q_y|, |\Delta Q_z| \right)^T \] (7.4)

7.1.2 Half Way Time

To measure the over-all performance of the docking task the completion time \( \hat{T} - \hat{T} \) is used. To simplify the notation the start time is set to zero \( \hat{T} \equiv 0 \) and the completion time becomes equal to \( \hat{T} \). The completion time does not reveal in which order the different degrees of freedom approach the target. Therefore in addition to \( \hat{T} \) a new performance measure for each degree of freedom called half way time \( b_h (h \in [1, 6]) \) was introduced:

\[
\min_{b_h} \int_{\hat{T}}^{\hat{T}} (\Gamma_h(t) - \hat{\Gamma}_{h}(t))^2 dt
\] (7.5)

where

\[
\hat{\Gamma}_{h}(t) = \Gamma(\hat{T})_h e^{-\ln 2 t / b_h}
\] (7.6)

i.e., the actual paths \( \Gamma_h \) are compared with the path \( \hat{\Gamma}_{h} \), which would have occurred if humans would embody a first order control system according to the control law

\[
\frac{d}{dt} \hat{\Gamma}_{h}(t) = -\frac{\ln 2}{b_h} \hat{\Gamma}_{h}(t)
\] (7.7)

\( b_h \) is related to the performance index \( b \) in Fitts’ law (see equation 3.4). Fitts’ law can be rewritten as:

\[ W = cA \frac{2^n}{b} e^{-\ln 2 T / b} \] (7.8)

i.e., with increasing movement time \( T \) it is possible to hit a smaller target width \( W \). Setting \( a = 0 \), corresponding to an idealised Fitts’ law without any time lag, and setting \( c = 1 \) instead of \( c = 2 \) as in Fitts’ original formulation [Fit54] the equations 7.6 and 7.8 become identical and the half way time corresponds to the inverse of the Fitts’ performance index. The similarity between 7.6 and 7.8 indicates that the human control performance is similar to a first order control system.

However Fitts’ law does not say anything about the shape of the path. Normally human control systems are modelled poorly by a linear system such as the first order control law in equation 7.7 or the second order control system proposed in Langolf et al [LCF76]. The deterministic iterative corrections model presented by Crossman and Goodeve (summarised in [DM97]) is
an attempt to find a model more closely fitting the observed data. They introduced a linear difference equation describing a number of submovements, each of which covers a constant portion of the distance between the current position and the target. The solution of this difference equation is similar to equation 7.7 but also fails to give a proper description of movements actually observed. As seen in section 3.2.3 human movements are not deterministic but consist of a series of submovements comprising irregular episodes of acceleration and deceleration. A thorough analysis must be based on this microstructure of the movement, i.e., parsing and comparing the submovements. This would demand that a parsing algorithm is written for position as well as rate control and that the submovements are categorised and quantified. This means an initial high amount of qualitative analyses which is not within the scope of this thesis. Therefore, in order to find out if there is any difference in how fast the different degrees of freedom are approaching the target, the simple measure given by equation 7.5 will be used.

7.1.3 Measuring Coordination

One of the goals of multidimensional input is to achieve a more efficient information flow between user and computer. Therefore it is of interest to measure whether the different degrees of freedom are used in a coordinated manner. Below two different ways to do so are presented.

Correlation

The cross correlation between two elements of \( \Gamma \) is given by [Lyn89]:

\[
r_{hh'} = \frac{1}{T - \hat{T}} \int_{\hat{T}}^{\hat{T}} \Gamma^{(t)}_h(t) \Gamma^{(t)}_{h'}(t) dt
\]

where \( h, h' \in [1, 6], h \neq h', \) and \( \Gamma^{(i)}(t) = \frac{d^i \Gamma(t)}{dt^i}, i \in [1, 2, 3, \ldots] \).

The covariance is defined as [Shi91]:

\[
c_{hh'} = \frac{1}{T - \hat{T}} \int_{\hat{T}}^{\hat{T}} (\Gamma^{(i)}_h(t) \Gamma^{(i)}_{h'}(t) - \hat{\Gamma}^{(i)}_h(t) \hat{\Gamma}^{(i)}_{h'}(t)) dt = r_{hh'} - \hat{\Gamma}^{(i)}_h \hat{\Gamma}^{(i)}_{h'}
\]

where \( \Gamma^{(i)}_h = \frac{1}{T - \hat{T}} \int_{\hat{T}}^{\hat{T}} \Gamma^{(i)}_h(t) dt. \)

The covariance is normalised as follows:

\[
\rho_{hh'} = \frac{c_{ij}}{\sigma_h \sigma_{h'}}
\]

where \( \sigma_h = \sqrt{\frac{1}{T - \hat{T}} \int_{\hat{T}}^{\hat{T}} (\Gamma^{(t)}_h(t) - \hat{\Gamma}^{(t)}_h)^2 dt} \)
7.1. THE EXPERIMENT

The following example shows why $i = 1$ is the only reasonable choice for measuring coordination. In figure 7.1 there are two coordinated paths ($\Gamma_x$ and $\Gamma_y$) and one uncoordinated path ($\Gamma$) with the normalised covariances $\bar{p}$, $\bar{\rho}$ and $\bar{\rho}$ respectively.

If $i = 0$ then $\bar{\rho}_{xy} \neq 0$, i.e., although $\Gamma_x$ and $\Gamma_y$ are completely uncoordinated a nonzero correlation result is achieved and thus $i = 0$ is not a feasible choice.

If $i = 1$ then

- $\bar{\rho}_{xy} = 1$ because $\Gamma_x = \Gamma_y$ during the whole path
- $\bar{\rho}_{xy} \approx 1$ because $\Gamma_x \approx \Gamma_y$ during the whole path
- $\bar{\rho}_{xy} = 0$ because $\dot{\Gamma}_x \dot{\Gamma}_y = 0$ during the whole path

i.e., the coordinated paths correspond to paths with high correlation.

If $i \geq 2$ then $\bar{\rho}_{xy} = 0$, because $\dot{\Gamma}_x$ and $\dot{\Gamma}_y$ never have an acceleration, jerk or any higher derivatives in common. Since $\Gamma$ describes a fairly well coordinated path but the correlation yields a zero result the correlation of higher derivatives cannot be used as a coordination measure.

Thus only $i = 1$ corresponds to our intention to measure how efficiently the different degrees of freedom are used simultaneously to reach the target for all paths $\Gamma_x$, $\Gamma_y$ and $\Gamma$ in figure 7.1.

Path Arc Length

An alternative to measuring correlation is to compare the actual path arc length with the shortest distance between start and target:

$$\Delta L = \frac{L_{act} - L_{opt}}{L_{act}} \quad (7.12)$$

where

$$L_{act} = \int_{\Gamma} \sqrt{\dot{S}_x^2 + \dot{S}_y^2 + \dot{S}_z^2} \, dt \quad (7.13)$$

and

$$L_{opt} = \|\dot{S} - \ddot{S}\| \quad (7.14)$$

A similar measure can be defined for the orientation and a total measure could be defined for translation and orientation with an appropriate scaling.
Figure 7.1: Three paths $\tilde{\Gamma}$, $\hat{\Gamma}$, and $\check{\Gamma}$ from the start point $A$ to the target point $B$. $\tilde{\Gamma}$ and $\hat{\Gamma}$ are coordinated in the sense that both of the $x$ and $y$ degrees of freedom are used simultaneously to approach the target $B$ whereas accordingly $\check{\Gamma}$ is completely uncoordinated.

Choice of Coordination Measure

Recently there has been a number of papers on different ways about how to measure coordination. Both correlation and path arc length has been investigated by Zhai ([ZS97] and [ZM98b]). Masliah [MM00] extended the path arc length measure to be valid for measuring any subset of all degrees of freedom. He also introduced a measure similar to what would be achieved by combining correlation and path arc length, but with the correlation replaced with a measure called simultaneity, which can be used for any number of degrees of freedom and accounts only for error reductions. Path arc length is called efficiency by Masliah. Since completion time and half way time could also be called efficiency measures the expression efficiency is avoided in this thesis. Masliah’s efficiency measure is independent of time, so, using Masliah’s terminology, a slow path consisting of many submovements is more efficient than a fast overshooting path consisting of only two submovements (compare section 3.2.3). When users decide whether to use a 6DOF controller the main argument concerns time savings. In this thesis the performance is measured by completion time. Therefore, in order to find out whether the multiple degrees of freedom are actually used in parallel in a constructive manner the correlation is used as the relevant measure of coordination.
Choice of Start and End Position

Correlation as a coordination measure is not invariant to rotations. The result depends on the start and target positions, but also on the visualisation on the computer screen, the position and structure of the input device, and on the hand posture. We are interested in paths using all degrees of freedom. By choosing the same amount of translations along all coordinate axes $\Delta \hat{S}_x = \Delta \hat{S}_y = \Delta \hat{S}_z$, the set-up becomes symmetrical and there is no problem with scaling. The rotation become equally distributed around all axes by setting $\Delta \hat{Q}_x = \Delta \hat{Q}_y = \Delta \hat{Q}_z$. Thus, during this experiment, an ideal path always corresponds to a space diagonal.

7.1.4 Subjects

8 men aged 24, 25, 29, 32, 44, and the remaining ones 27, performed the test. All had computer mouse experience since at least 10 years and used the computer mouse with their right hand. One subject had one year of SpaceBall experience, the others were new to both SpaceCat and SpaceBall. The subjects consisted of three mechanical engineers, two architects, two physicists and one chemist. Four of the subjects were devoted amateur musicians where two played the violin, one the viola and one the cello (by coincidence the instrumentation of a string quartet).

No attention was paid to the time of the day when the experiment was performed. All day times occurred but most subjects came over lunch or in the evening.

Two subjects had to be dismissed: one because he had no 3D perception at all and the second one because he took too long to learn. After one hour these two subjects had solved only one respectively four tasks compared to hundreds of tasks performed by all other subjects, and accordingly they had to be dismissed from the test.

7.1.5 Apparatus

The docking task was performed with two different input devices. The stiff elastic input device SpaceBall 4000 FLX (compare figure 2.3) was used in rate control mode and the elastic input device SpaceCat (compare figure 1.1) was used in position control mode. The virtual objects involved in the task were modelled in the visualisation tool 3D Studio MAX v3.0.

SpaceBall used the SpaceWare driver 9.2 for Windows and the SpaceWare AniMotion software plug-in for 3D Studio MAX v3.x provided by Labtec. For SpaceCat a new driver and 3D Studio plug-in was developed [Wil00].
Another plug in was developed to handle the experiment data, i.e., monitor the motion paths and completion time.

Originally the experiment was planned to include the input device Space Mouse (compare figure 2.1) as well, but because LogiCad3D's Magellan Studio v3.0 form 28 March 2000 contains a bug for the rotation of grouped objects, SpaceMouse had to be excluded from the experiment.

The experiment run on a desktop Compaq PC (Intel Pentium Pro 200 MHz, Windows NT 4.0, 64 MB RAM, Matrox Millenium Graphics Card 8 MB, monitor 17" at resolution 1024x768 pixel). The system reaction time was tested with a SpeedCam+ LITE camera with a time resolution of one frame per millisecond. The screen ran with a screen buildup frequency of 85Hz. The 3D Studio MAX view was updated every third screen buildup yielding approximately 28 frames/s, which gives an impression of a smooth movement. The system reaction time for both SpaceCat and SpaceBall was approximately 0.10s. This time lag was short enough not to be noticed by the subjects.

7.1.6 Experiment Design

The performed paths are denoted with the following tensor:

\[ \Gamma_{nmknjihg} \]  

where the variables are

\[ n \in [1, N = 8] \] – subject identification number (subject id)
\[ m \in [1, M = 2] \] – device id, where \( C=1=\text{SpaceCat} \) and \( B=2=\text{SpaceBall} \)
\[ l \in [1, L_n] \] – index for the set of \( IJK = 12 \) docking trials
\[ k \in [1, K = 3] \] – index for the subset of \( IJ = 4 \) docking trials
\[ j \in [1, J = 2] \] – distance, where \( S=1=\text{short distance} \) and \( L=2=\text{long distance} \)
\[ i \in [1, I = 2] \] – target size, where \( b=1=\text{big target} \) and \( s=2=\text{small target} \)
\[ h \in [1, H = 6] \] – degree of freedom index (according to equation 7.4)
\[ g \in [1, G_{nmknjih}] \] – docking path sample index

The order in which the docking trials were collected for each subject is described by the index \( \xi \), i.e., the collected data is described alternatively by \( \Gamma_{nmknjihg} \). \( i, j, k, l \) and \( m \) are functions of \( \xi \):

\[ l = \xi \div IJKM \] A new set of trials starts after each combination of device, subset, distance and target size have been performed.

\((a \div b \text{ is integer division of } a \text{ and } b)\)
7.1. THE EXPERIMENT

\[ m = (\xi \div IJK + n \mod M) \mod M \]

The input device is changed after each combination of subset, distance and target size have been performed. Every second subject starts with SpaceCat and the rest starts with SpaceBall. \((a \mod b \text{ is congruent to } a \modulus b)\)

\[ k = (\xi \div IJ) \mod K \]

Each subset consist of four trials, all with different combinations of distance and target size. With eight subjects each combination occurs exactly once in a balanced experiment design since \((IJ)! = NK\).

\[ j = j(n, \xi \mod IJK), i = i(n, \xi \mod IJK) \]

The distance and target size combination is different for each subject and is repeated after each set of \(IJK\) trials.

\[ \eta = \xi \mod IJK \]

This variable is used to describe how the geometrical boundaries change over the experiment.

The variables \(i\) and \(j\) were introduced in order test hypothesis 1 (see section 3.4). Furthermore \(i\) and \(j\) make a simple test of Fitts' law possible with the four corresponding indexes of difficulty. The subset index \(k\) was introduced in order to have the difficulties equally distributed. Each subset consists of all indexes of difficulty. The set index \(l\) counts the number of times the set of 12 trials have been performed for each input device. These 12 trials are not changed for a subject and are repeated over and over again for both input devices. By comparing different sets of trials with the same input device a learning curve is achieved and hypothesis 3 can be checked. The reason for the frequent changes between the input devices is to minimise the influence of which input device the subject starts with. Since only eight subjects participated in the investigation and the data was collected at few occasions this was a necessary step to take. Drawbacks are that we cannot study the learning of the input devices separately, we cannot see if there is an asymmetric skill transfer between the input devices, and theoretically we measure properties we are not interested in like the factor how well the subjects can swap between the two input devices.

The signals were sampled at times \(t_{nmklji}\) giving a time discrete path function \(\Gamma_g\) with derivative \(\frac{d\Gamma}{dt} \approx \Gamma_g\) according to common practice in tensor notation [Ram87]. Each docking trial path contains \(G_{nmklji}\) samples. The trial end time is denoted by \(T_{nmklji} = t_{nmklji}G_{nmklji}\).

Since no real time operating system was used, there was no accurate sampling rate. A sample time interval \(t_{g+1} - t_g\) had a mean value of 0.077s. 3% of the time intervals were longer than 125ms and six sample intervals (i.e., 0.0038%) were longer than 250ms, all measuring 428 ms.
7.1.7 Task Scene

The target and cursor were each shown as three rigidly connected boxes arranged in an L-form with the relative positions

\[
(0 0 0)^T, \ (8.5d 0 0)^T \text{ and } (0 4d 7.5d)^T, \text{ where } d \text{ is the length unit in 3D Studio MAX. The last box was coloured differently in order to make recognising the structure easier (compare figure 7.2). The target and cursor boxes had the diagonals } (s_i 2s_i 2s_i)^T \text{ and } (2s_i s_i s_i)^T \text{ respectively in the same coordinate system as used for the relative box positions. The goal of the docking is to bring every cursor box symmetrically attached to the respective target box. The target was considered as reached as soon as each cursor box was completely contained in a box with the diagonal } (3s_i 2s_i 2s_i)^T \text{ positioned symmetrically around each target box, i.e., the end deviation translation was less than } s_i/2. \ s_i \text{ took one of the values } s_{i=b} = d/2 \text{ for a big target or } s_{i=s} = d/4 \text{ for a small target.}
\]

The relative difference between the start and target position and orientations was given for translations by \( \Delta \dot{S}_\eta \) and for rotations by

\[
\Delta \dot{Q}_\eta = \left( \cos \Delta \dot{\theta}_\eta/2 \ \hat{e}_\eta^T \sin \Delta \dot{\theta}_\eta/2 \right)^T
\]

where \( \hat{e} \) takes one of the eight possible values \( \hat{e}_\eta = 1/\sqrt{3} \left( \pm1 \ \pm1 \ \pm1 \right)^T. \)
7.1. THE EXPERIMENT

The start position and orientation was \( \hat{\mathbf{s}}_\eta = -\Delta \hat{\mathbf{s}}_\eta /2 \) and \( \hat{\mathbf{q}}_\eta = 1/\sqrt{\Delta Q_\eta} \), i.e., start and target are symmetrically positioned around the origin.

Short distance is given by \( \Delta \hat{\mathbf{s}}_j = 2.5d \) and \( \Delta \hat{\mathbf{q}}_j = \pi /4 \). Long distance is given by \( \Delta \hat{\mathbf{s}}_j = 5d \) and \( \Delta \hat{\mathbf{q}}_j = \pi /2 \). For the rotations \( \Delta \hat{\mathbf{q}}_\eta \) takes one of the two values \( \Delta \hat{\mathbf{q}}_j \). For the translations all possible distances are described by

\[
\Delta \hat{\mathbf{s}}_\eta = \left( \pm \Delta \hat{\mathbf{s}}_j \quad \pm \Delta \hat{\mathbf{s}}_j \quad \pm \Delta \hat{\mathbf{s}}_j \right)^T \tag{7.17}
\]

i.e., for short and long distance eight positions respectively are possible.

In all there are \( 2^H 2^J \) combinations of start and end position, target size and docking distance. It turned out that for some of the \( 2^H 2^J \) combinations for distance and end position the docking was difficult because of occlusion. Therefore 24 of the possibilities for short distance and 20 of the long distance were removed. A computer program was written to provide a balanced distribution of all possible combinations among the subjects. A start position was not reused until all other start positions had occurred. Furthermore similar start positions were not allowed to follow after each other. This was combined with the selection of distance and target size as described in the previous section.

The camera, through which the subjects observed the scene, had an view angle of 45°, was positioned in \( (0d \hspace{1cm} -240d \hspace{1cm} 65d)^T \), and was directed towards the origin. Three point light sources were positioned in \( (250d \hspace{1cm} -250d \hspace{1cm} 0d)^T \), \( (-250d \hspace{1cm} -250d \hspace{1cm} 0d)^T \) and \( (0d \hspace{1cm} -250d \hspace{1cm} 100d)^T \) with the 3D Studio light strength set to 0.5.

7.1.8 Procedure

The 8 subjects were asked to move the cursor as quickly as possible from the start to the target position. The completion time was measured and presented to the subject together with the best time achieved with the currently used trial parameters \( m \) and \( \eta \) in order to encourage better performance.

In order to avoid biasing from the test leader the subjects got a short test description in written form:

12 docking tasks are repeated over and over again by using alternatively SpaceBall or SpaceCat.

Your task is to dock the cursor with the target as quickly as possible trying to achieve new records with every trial.

No attention should be paid to the fact the SpaceCat is an ETH-development created by your test leader.
For the first half of the subjects this procedure was repeated in a second phase of the experiment one week later in order to see the effect of retention and extended practice. The first experiment phase lasted for 60 minutes whereas the second phase was shortened to 40 minutes.

Before each trial started the subjects were allowed to look at the scene and plan the movement. It is known that assessing the orientation of virtual objects projected on a computer screen provide a certain difficulty [SM71]. To help the subjects understand the movement to be performed the following animation was shown once before every trial:

\[
S_v(t) = S_v + t \Delta S
\]

\[
Q_v(t) = \Delta Q^t \dot{Q}_v
\]

where \( t \in [0, 1] \) is approximately the time in seconds.

The subject touching the input device started the trials. No time limit was imposed on the subjects for the start. The hit of the target (i.e., the end of each trial) was marked with a sound. A different sound was used to indicate when a new record had been achieved.

As we saw in section 3.3.2 we don’t expect the performance to depend strongly of the gains used. The subjects were asked whether they wanted more or less sensitivity for translations and rotations for each input device after every performed test phase.

### 7.2 Quantitative Usability Test Results

#### 7.2.1 Learning Coefficients

A box plot of all trial completion times is given in figure 7.3. Each box comprises a set of \( IJK = 12 \) measurements. The number of performed trial sets \( L_n \) differs for the subjects: \( L_n = 4 \) for \( n \in [1, 4] \) and \( L_n = 3 \) for \( n \in [5, 8] \). The first four subjects performed two phases of 75 minutes on one day and repeated the same on another day. Because of lack of time for the experiments the last four subjects only performed one phase with the three last sets recorded. The SpaceCat results are always plotted prior to the SpaceBall results, although this does not correspond to the order of data collection (compare section 7.1.6).

---

1 The box plot describe the data in the following way: within the horizontal outer lines of the box 50% of the samples are contained. The horizontal line in the box marks the median. The dashed lines mark the range for the upper and lower 25% of the samples. Circles mark outliers.
7.2. QUANTITATIVE USABILITY TEST RESULTS

Figure 7.3: Box plot of completion times for all trial sets. A solid line separates the subjects’ results. A finely dotted line separates the SpaceCat and SpaceBall results (denoted nC and nB on the x-axis) for each subject.
As shown in figure 7.3 the subjects learn to use SpaceCat faster than they learn to use SpaceBall. To find out the learning coefficient \( a_{nmkij} \) for each subject, input device, subset, distance and target size the following model was used:

\[
\log(\hat{T}_{nmkji}) = a_{nmkij}l + b_{nmkij}
\]  

(7.20)

In figure 7.4 box plots of \( a_{kij} \) for each subject and each device are presented, i.e., \( a_{1kij}, ..., a_{N_Mkij} \). The average improvement between two trials \( \hat{T}_{l+1}/\hat{T}_l \) is defined as

\[
\kappa_m = 1 - \exp\left\{ \frac{1}{\text{NKIJ}} \sum_{nki} a_{nmkij} \right\}
\]  

(7.21)

with \( \kappa_C = 14.0\% \) and \( \kappa_B = 6.7\% \). The difference in the input devices is significant \( (p = 0.002) \) according to a Wilcoxon test \( W(a_{nBkij}, a_{nCkij}) = 3425 \).

First, the elasticity difference between input devices provides a difference in proprioceptive feedback. SpaceCat has an advantage with its greater workspace and weaker elasticity. Second, position control is cognitively to prefer in a docking task because it is more direct and corresponds to what we are used to with physical objects. For instance there is a direct correspondence between parallax shifts given visually and the movements that the hand performs with the input device handle.

### 7.2.2 Completion Time

In the following analysis only the last trial set has been used in which the subjects had been able to accumulate a maximum training with the respective device. We define

\[
\Gamma_{nmkjihg} = \Gamma_{nmL,nkjihg}
\]  

(7.22)

and

\[
\hat{T}_{nmkji} = \hat{T}_{nmL,nkji}
\]  

(7.23)

In figure 7.5 a box plot of \( \hat{T}_{nk} \) for each device and task difficulty is presented, where

- \( Sb \) means short distance with big target completion time \( \hat{T}_{nkSb} \)
- \( Lb \) means long distance with big target completion time \( \hat{T}_{nkLb} \)
Figure 7.4: Box plot of the learning coefficients $a_{ij}$ of equation 7.20.
Figure 7.5: Completion time vs. task difficulty for SpaceCat and SpaceBall for short distance combined with big target (Sb), long distance combined with big target (Sb), short distance combined with small target (Ss), and long distance combined with small target (Ls).

*Ss* means
short distance with small target completion time $\hat{T}_{nkSs}$

*Ls* means long distance with small target completion time $\hat{T}_{nkLs}$

According to the figure SpaceCat has its greatest advantage for short distances or small targets over SpaceBall. The average quotient between SpaceCat and SpaceBall completion times is

$$\lambda_{ji} = \frac{1}{NK} \sum_{nk} \frac{\hat{T}_{nCkji}}{\hat{T}_{nBkji}}$$  \hspace{1cm} (7.24)

with $\lambda_{Sb} = 0.51$, $\lambda_{Lb} = 0.89$, $\lambda_{Ss} = 0.57$, and $\lambda_{Ls} = 0.78$. The significance of the differences between the devices according to Wilcoxon tests are:
7.2. QUANTITATIVE USABILITY TEST RESULTS

Figure 7.6: Anova model verification

\[ W(T_{nCkSb}, T_{nBkSb}) = 37 \text{ (} p < 0.001 \text{)}, \quad W(T_{nCkBkb}, T_{nBkBkb}) = 196 \text{ (} p = 0.06 \text{)}, \]
\[ W(T_{nCkSs}, T_{nBkSs}) = 48 \text{ (} p < 0.001 \text{)}, \quad \text{and } W(T_{nCkLs}, T_{nBkBsl}) = 154 \text{ (} p = 0.005 \text{)}. \]

Both categories involving short distances are highly significant and completion times for SpaceCat are on average less than 60% of SpaceBall completion times. This difference between the input devices is in accordance with Hypothesis 1. For short distances the workspace of SpaceCat corresponds to the workspace of the task that allows a fast completion times. This is also true for the two categories involving small targets, where there is a greater need for precise manipulation. Only for the combination long distance with big target there is no significant difference between the devices.

In figure A.1 it is confirmed that the main variance is contained in the device variable and a relatively small proportion of variance in the variables subject and subset. A data inspection was performed on the \( T_{nukij} \)-data set with the factors subject, device, target size, and distance between the start...
and end positions. Figure 7.6 confirms that the $F$-test provides a proper basis for the evaluation. As seen in figure A.2 in the appendix there is a strong interaction between device and distance. This is also easily seen in figure 7.5. For SpaceBall the distance does not make a big difference, which is not true for SpaceCat. Accordingly we had to perform separate variance analysis for trials with long and short distance. As seen in figure A.3 the difference for the devices is significant for the long distance. In the figure A.4 there is an interaction between subject and device, which has been visualised in figure 7.7. Obviously there are some subjects that for short distances are exceptionally fast with SpaceCat combined with being slow with SpaceBall. One possible explanation for this could be that some subjects developed very efficient ways of moving the short distance with SpaceCat, e.g., moving the SpaceCat handle in the inverse direction before the clutch was pressed in order to minimise clutching.

### 7.2.3 3D Fitts’ Law Parameters

The usability test was designed to make a Fitts’ law verification for the used input devices possible. It is directly seen in figure 7.5 that SpaceBall up could not be a Fitts’ Law compliant input device in the performed task. The categories $Lb$ and $Ss$ have the same difficulty index according to Fitts’ law, but have very different completion times for SpaceBall. The difference is significant ($p = 0.0007$) according to a Wilcoxon test $W(\hat{T}_{nBLLb}, \hat{T}_{nBBSa}) = 127$. This is not the case for SpaceCat with $p = 0.34$ and $W(\hat{T}_{nCCLb}, \hat{T}_{nCSSa}) = 335$. Therefore further analysis on Fitts’ Law was only performed with SpaceCat.

In figure 7.8 all completion times with SpaceCat has been fitted to Fitts’ Law. The performance index is $1/b = 0.43$, which is low compared to Fitts’ law measurements in 2D positioning tasks. In order to gain a deeper understanding of positioning in 6DOF-tasks an analysis of the half way time was performed in the following section. The extreme broadness around the fitted line is mainly to be explained by the difficulty to target the depth in a 6DOF docking task.

### 7.2.4 Half Way Time

Half way times were calculated as described in section 7.1.2. To be able to compare half way times for any index of difficulty the half way times were normalised to the completion time according to

$$\beta_{nmkjih} = v_{nmkjih}/\hat{T}_{nmkjih}$$  \hspace{1cm} (7.25)
7.2. QUANTITATIVE USABILITY TEST RESULTS

Figure 7.7: Interactions between SpaceCat (device 1) and SpaceBall (device 2)
Figure 7.8: SpaceCat performance index. Since the results were significantly different for the same index of difficulty for SpaceBall the performance index was only calculated for SpaceCat.
7.2. QUANTITATIVE USABILITY TEST RESULTS

Figure 7.9: Half Way Time. Translations along the x, y and z-axes denoted with X, Y and Z. Rotations around the x, y and z-axes denoted with A, B and C.

In figure 7.9 each box corresponds to $\beta_{nkJi}$ for the different degrees of freedom and the different input devices. The depth (i.e., movements along the y-axis or the direction perpendicular to the surface of the computer screen) is as expected much more difficult to control than the other degrees of freedom for both SpaceCat and SpaceBall. This means that the calculated Fitts’ Law 6DOF performance index is to a great extent a performance index on controlling depth. Note the similarities between SpaceCat and SpaceBall in figure 7.9.

7.2.5 Examples of Trajectories

In this section we look at two sample trajectories from subject number five from the same task given for SpaceCat and SpaceBall in the set of trials
performed last (figures 7.10 and 7.11). The four graphs correspond to translations (left two graphs) and rotations (right two graphs) as well as position (upper two graphs) and velocities (lower two graphs).

Generally, the collected trajectories have little in common with the first order control system assumed in section 7.1.2. The models described in section 3.2.3 seems to hold also in 6DOF control. A good example of this is given in figure 7.10 for the translation and in figure 7.11 for the rotation. These trajectories consist of two submovements. The first fast movement is a typical open loop movement followed by a second regulated closed loop submovement for the fine positioning. The SpaceCat submovements are separated with a clutching of 0.25s, whereas the SpaceBall submovements are more difficult to identify. The maximum velocity for translations is much higher for the SpaceCat open loop submovement. This supports the idea that it is possible to develop a faster work pace with a position control device than a rate control device because of fast open loop movements. The maximum rotation velocity is approximately the same for both devices.

In figure 7.11 we see one example that the depth is difficult to control. The subject begins with a movement in the wrong direction. Obviously the half way time is much worse for the $\Delta S_y$ trajectory than the other trajectories.

7.2.6 SpaceCat Clutch Characteristics

The main obstacle for using position control in combination with long movements of the virtual object is the clutching. Between 10% and 15% in median of the completion time is used for clutching. In figure 7.12 the number of clutch actions as a function of task difficulty and subjects is illustrated. The short movements have a median of one clutch action whereas the long movements have a median of three clutch actions, i.e., although the distance is only doubled the number of clutch actions increased by a factor of three. One reason for this may be unwanted movements caused by clutching. One example of this is given in figure 7.13. Especially problematic is the z direction (i.e., the vertical direction). The handle follows the hand when lifting the hand to begin a new submovement. The difficulty lays in the coordination of letting loose the index finger while still holding the handle steady with the other fingers.

As seen in figure 7.12 the number of clutch actions varies very much among the different subjects. Also the time used for each clutch action varies strongly between subjects whereas the median clutch action lasts for approximately 0.4s independent of task difficulty. Subjects number 2, 3, 5 and 8 have the shortest clutching time. An interesting remark is that exactly these subjects are devoted amateur musicians.
Figure 7.10: Sample SpaceCat trajectory. $\Delta S_x$ and $\Delta Q_z$ is marked with a solid line, whereas the y and z movements are correspondingly marked with dashes and dash-dots. These trajectories clearly consist of two submovements as described in section 3.2.3. The first submovement ends with a clutch action after approximately one second. The first submovement is considerably faster than the second one, indicating an open loop behaviour, whereas the second submovement is a typical slow precision movement which is assumed to be controlled in a closed loop.
Figure 7.11: Sample SpaceBall trajectory. \( \Delta S_x \) and \( \Delta Q_x \) is marked with a solid line, whereas the y and z movements are correspondingly marked with dashes and dash dots. As in figure 7.10 this trajectory clearly consists of two submovements. The second submovement starting after approximately 2s corrects a move in the wrong direction along the y-axis (i.e. the direction perpendicular to the screen surface). This is a typical and reflects the results from section 7.2.4.
Figure 7.12: Number of SpaceCat clutching actions vs. task difficulty and subject. The notches indicate the standard deviation. For the long moves the number of clutch actions increase more than proportionally.
Figure 7.13: Example of how the clutching generates errors. $\Delta S_x$ and $\Delta Q_x$ is marked with a solid line, whereas the y and z movements are correspondingly marked with dashes and dash dots. After 2s the first submovement ends and the clutch is released. This generates an especially big error in the z-direction, with the dash-dotted line springing from below 0.2 to above 0.8 in the upper left figure, i.e., almost the whole first submovement in the z-direction is made reverse unintendedly.
Figure 7.14: SpaceCat clutching time vs. task difficulty and subject
7.2.7 Coordination

The discrete version of equation 7.10 for all trials and all subjects takes the form ([Kur79] page 411):

\[
chh' = \frac{\sum_{nmkji} \Sigma_{h} (\Gamma_{nmkji,g} - \bar{\Gamma}_{nmkji}) (\Gamma_{nmkji',g} - \bar{\Gamma}_{nmkji})}{\sum_{nmkji} G_{nmkji} - 1}
\] (7.26)

where \( \bar{\Gamma}_{nmkji} = \frac{1}{G_{nmkji}} \sum_{g} \Gamma_{nmkji,g} \). By not summing over all \( n, m, k, i \) and \( j \) the covariance for a specific trials, subjects or devices can be achieved.

The discrete version of equation 7.11 similarly becomes:

\[
\rho_{hh'} = \frac{c_{hh'}}{\sigma_h \sigma_{h'}}
\] (7.27)

where

\[
\sigma_h = \sqrt{\sum_{nmkji} \frac{\sum_{g} (\Gamma_{nmkji,g} - \bar{\Gamma}_{nmkji})^2}{G_{nmkji}}}
\] (7.28)

According to the covariance analysis all covariances \( \rho_{hh'} \) for both input devices are very small. Neither SpaceCat nor SpaceBall achieved any covariance greater than 0.25. This is less than the results published by Zhai in [ZS97]. There are two possible reasons for this:

1. The subjects had too little time in the experiment to learn the interaction with the devices. The coordination may gradually improve as the subjects become more experienced.

2. In Zhai’s experiment, subjects were explicitly told to perform coordinated movements, i.e., a kind of tracking task combined with a docking task. Here, subjects only were told to achieve as short completion times as possible.

7.3 Qualitative Results

7.3.1 Sensitivity

The subjects were asked to comment on the control gains after each performed test phase. Their assessments are complete, except for subject number four, and listed in figure 7.15 and figure 7.16. Note that the gains were kept the same for all phases and subjects during the whole experiment.

Some subjects asked for stronger gains the more experienced they became (see subject 1 and 3 in table 7.15). One subject in figure 7.16 also commented that he would like stronger gains the more training he got.
7.3. QUALITATIVE RESULTS

<table>
<thead>
<tr>
<th>Subject</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
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<tbody>
<tr>
<td>Phase</td>
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<td>2</td>
<td>1</td>
</tr>
<tr>
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<td>+</td>
<td>0</td>
</tr>
<tr>
<td>SpaceCat Orientation</td>
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<td>+</td>
<td>0</td>
</tr>
<tr>
<td>SpaceBall Translation</td>
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<td>0</td>
<td>-</td>
</tr>
<tr>
<td>SpaceBall Orientation</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 7.15: Gain change suggestions by the subjects performing trials on two different occasions.

<table>
<thead>
<tr>
<th>Subject</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>SpaceCat Translation</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>SpaceCat Orientation</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>SpaceBall Translation</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>SpaceBall Orientation</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 7.16: Gain change suggestions by the subjects performing all trials on the same day.

Generally the subjects accepted the preinstalled parameters, although more subjects asked for stronger gain for SpaceCat and less gain for SpaceBall. Judging from the gain assessments it seems most likely that the preinstalled gains for both SpaceCat and SpaceBall were near the flat gain optimum according to section 3.3.2.

7.3.2 Qualitative Subject Statements

Five of the subjects preferred SpaceCat and one subject preferred SpaceBall for this specific docking task. One preferred SpaceCat for translations and SpaceBall for rotations and one subject was undecided. The subjects preferring SpaceCat valued especially better precision and better feedback. Some subjects remarked that their preference is only valid for this specific task as the need for position and rate control depends on the task.

Five of the subjects recognised the clutching as SpaceCat’s major weakness. It led to unwanted manipulations and was cumbersome by long distance translations and rotations. Possible solutions are better filters and transfer functions as well as the possibility to switch between position and rate control.

There were no complaints on fatigue, probably because of the short experiment duration and the frequent changes between the two input devices. Two
of the subjects gripped the base of the input device with their non-dominant hand. This was true for both SpaceCat and SpaceBall. Two subjects stated that the spring forces of SpaceCat were too weak and two subjects found them just right.

One of the architects made the unexpected statement that not only positioning and navigation is of interest in architectural applications. He felt a strong need for 3D free form surface design, for instance when manipulating Bezier control points in 3D.
Chapter 8

Conclusion

8.1 Summary of the Test Results

A series of experiments were performed with a commercially available, rate controlled, stiff elastic 6DOF input device called SpaceBall, and a position controlled soft elastic 6DOF input device called SpaceCat in conjunction with a CAD system. CAD is the field of use where 6DOF input devices are predominantly used today. One group of the subjects performing the tests had at least half a year experience with the used CAD system combined SpaceBall and performed an assembly task with mathematical constraints. The other group's subjects had no experience of 6DOF input devices or CAD systems. For the experienced users the control order or the kind of input device did not play a major role when solving the CAD task. For them the functionality of an input device working in position control mode does not provide a major advantage as compared with the currently commercially available 6DOF input devices that work in rate control mode. The result from the inexperienced subjects was different. They preferred overwhelmingly SpaceCat's position control to SpaceBall's rate control. This reaction from new users was also confirmed in additional qualitative tests. The results confirm hypothesis 3 from the literature analysis (compare section 3.4).

In order to test hypothesis 1 a docking experiment requiring more precise manipulation was performed. According to the result, Elastic Position Control is better than Stiff Elastic Rate Control both in terms of completion time and learning. The difference between the completion times is larger for high docking precision and short movements. Thus this usability test supports hypothesis 1 and hypothesis 3. The main obstacle when performing long distance movements in position control are the clutch actions. This is confirmed by the measurements of the clutching times, from the study of
trajectories and by interviews. As expected the most difficult parameter to control was the depth translation, i.e., the translation in the viewing direction. The performance pattern in the different degrees of freedom was very similar for both kinds of input devices.

Because of the different advantages of position and rate control, an optimal 6DOF input device should be capable of both. To achieve this SpaceCat with its softer elastic suspension is the better candidate than SpaceBall: due to its greater workspace it works well in both position and rate control.

8.2 Further Research

Improvement Suggestions for the Performed Experiment

The experiment set-ups generally worked as intended. In the quantitative test there was one task occurring for one subject where the end position and orientation were much more difficult than for the other tasks and thus should have been removed from the list of acceptable end positions, but generally the different end position and orientations did not account for a major part of the variance (compare figure A.1).

One question arising from the test is whether it is appropriate to perform a 6DOF docking task using only a two dimensional projection of the virtual scene. Other experiments have used stereoscopic glasses to enhance perception of depth. There is research however, which has shown that stereoscopic projection improves the 3D perception only marginally [Gei94]. More improvement can be expected by using a viewpoint dependent display to create viewpoint parallax shifts. Further improvements could incorporate shadow parallax or semitransparent objects.

A weakness of the test is that there was no check on whether the cursor was at rest within the specified limits or passed the target position by chance with an uncontrolled velocity. This happened for SpaceCat as well as SpaceBall and has to be improved in a new test version.

Only at one occasion a subject lost sight of the cursor. It happened when working with SpaceBall and was corrected by letting the subject perform the task once more from scratch. A more appropriate way of handling such situations would be to add the time from the first attempt to the time of the second chance.

All data were collected during the subject’s learning phase. It would be of interest to know, whether the result would be the same when the subjects had finished learning. Furthermore a new test could be designed to find out whether an asymmetric skill transfer function is present between SpaceCat
and SpaceBall.

**SpaceCat for Navigation**

The experiments in this thesis support hypothesis 1 and hypothesis 3 in positioning tasks. In a next step it would be valuable to test hypothesis 1 and hypothesis 2 in a navigation task with SpaceCat.

Further questions arise when integrating position control for manipulation and rate control for navigation in the same task. If the "object in hand metaphor" (compare section 3.1) is optimal for manipulation and the "camera in hand metaphor" is optimal for navigation it is unclear if users can quickly learn to switch between these two different metaphors. In navigation tasks it is also not clear how many degrees of freedom are optimal [ZKSS99]. When navigating in architectural models, for instance, it might be of advantage always to have the horizon horizontally in the view, i.e., to allow only five degrees of freedom. A question would be whether users can switch intuitively between five and six degrees of freedom. Finally it is not clear how the spring constants should be chosen to support both position and rate control in a satisfactory manner, assuming that rate control is optimal with a stiffer characteristic than position control.

**Controlling 2D Applications with 6DOF Input Devices**

Using a multidimensional input device for interaction with 2D applications give a potential to use the extra degrees of freedom to speed up interaction. For example translations could be used to move the mouse cursor whereas rotations could be used for scrolling a document in two directions. Furthermore a zoom function could be connected with one degree of freedom.

The clutch can be used for activation, i.e., the role of the left mouse button. This can be implemented in a similar way to what is now used with track pads. A short touch corresponds to a mouse click and a short touch followed by a movement of the cursor corresponds to drag and drop.

The use of an elastic 6DOF input device for 2D selection incorporates two main problems to the transfer function. First, it must be possible to accurately achieve all positions on a large high-resolution screen without clutching. Second, the freely suspended handle doesn’t give any damping of tremor. The conventional mouse has a very efficient mechanical tremor filter in terms of friction between table and mouse while the arm and hand rests on the table surface. Possible solutions to these problems include non-linear transfer functions and rate aided position control. The design of the input device is also extremely important. With a better support for the hand and
fingers than in the present version of SpaceCat the tremor could be reduced significantly. The improvements also involve tuning of spring constants and workspace.

**Other Research Topics**

A currently hot research field focus on *tactile feedback*. A simple way of adding tactile feedback is to use piezo-electric elements. This would make tactile feedback on clutch and virtual button actions possible. More challenging however is the possible use in 3D applications. Tactile feedback could prove to be very useful in assembly or navigation tasks.

Two handed interaction with different kinds of input devices would also bring interesting experiments, e.g., deforming a free form surface. It is known that the dominant and non-dominant hands should be assigned different tasks for optimal performance, i.e., in the task of deforming a free form surface the non-dominant hand would orient the surface while the dominant hand would perform the actual manipulations. According to hypothesis 1 an elastic input device would solve both tasks perfectly whereas an isometric input device would not be suited for the dominant hand work. This is confirmed by how today’s input devices are used [HG98].

Further ideas for future research include standardised 6DOF Fitts’ Law tests, 6DOF tracking tasks with different input devices and trajectory analysis including correlation between the different degrees of freedom.

**8.3 Outlook**

**Contacts with the Industry**

SpaceCat was demonstrated at the CeBit99 in Hannover (see figure 8.1), world’s largest information technology fair with around 700 000 visitors each year. Generally the visitors gave positive feedback. Labtec, the producer of SpaceBall, was given the opportunity to make own usability tests after the fair and found that the larger workspace of SpaceCat compared to SpaceBall does have an effect on issues regarding the learning curve for first-time users, which is in line with the results presented in this thesis.

**Complete Embedding of SpaceCat in 3D Studio Max**

Considering the interest for SpaceCat from computer graphics users and the results presented in this thesis it makes sense to launch SpaceCat on the
market for animation and visualisation tools. This would give a great opportunity to achieve reliable data from a test group of users who work with a software package that supports many different kinds of 3D interaction. In a next development step we extend the 3D Studio MAX plug used in the performed usability test to allow operation in daily work with increased functionality. Manipulation and navigation occur in tasks like assembling parts, positioning virtual cameras, defining camera paths, positioning light sources, and deforming free form surfaces. It will be possible also to control the 2D mouse cursor with the 6DOF input device in order to reduce the need for moving the hands between input devices, and thus to save time. Furthermore, we are investigating the possibility to incorporate "virtual buttons" in SpaceCat. The idea is to combine actions on the SpaceCat handle with clutch or keyboard actions to execute commands. In a first simple version the user moves the handle to the limit in one degree of freedom and gives a short touch on the clutch to trigger the command connected with that position. Preferably commands should be connected to the input device that are logically connected, e.g., adjusting the sensitivity or freezing some degrees of freedom.

The SpaceCat Start-Up Company

During the SpaceCat research project a range of know how was built up which has commercial potential. This expert knowledge is however only a part of the knowledge necessary for an innovation. At universities around
Europe there are numerous of initiatives to combine new research with entrepreneurial know how. During the project a business plan was developed, which made it possible to raise approximately one million Swiss franc of venture capital to hire the right personnel and make the product improvements necessary for the commercialisation. The project have gradually transformed from a research project to a project within the framework of a company competing in the market economy. The university provided an excellent fundament; it is now the task of the founded company to prove the commercial potential of SpaceCat!
Appendix A

Data Evaluation
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Figure A.1: Overview on completion time variance in all degrees of freedom
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**Residuals** | 128 | 15.2377 | 0.1190 |

Significance codes: 0=*** 0.001=** 0.01=* 0.05=.

**Figure A.2:** Completion time ANOVA analysis

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**Residuals** | 64 | 7.4675 | 0.1167 |

Significance codes: 0=*** 0.001=** 0.01=* 0.05=.

**Figure A.3:** Completion time ANOVA analysis for long distance
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Significance codes: 0=*** 0.001=** 0.01=* 0.05=.

Figure A.4: Completion time ANOVA analysis for short distance
Bibliography


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[LCF76] Gary D. Langolf, Don B. Chaffin, and James A. Foulke. An investigation of fitts' law using a wide range of movement am-


Brief CV

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Date of birth: 4 May 1968
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Employment:
- March ’97 – present: Managing the SpaceCat project at the Swiss Federal Institute of Technology in Zürich (ETHZ).
- Jan ’96 – March ’97: Centre for Integrated Production (ZIP), ETHZ. Preliminary study on product and process development.
- Nov ’93 – Oct ’94: Ingenieurbüro Kull AG, Switzerland. Developed software of warehouse material flow systems.

Education:
- April ’94 – April ’96: School of Industrial Engineering and Management, ETHZ. Courses: Operational Organisation, Product and Process Innovation, and Work Psychology.
- Dec ’93: Master of Science at the School of Engineering Physics, RIT, Stockholm, Sweden.
- June ’92 – Dec ’92: Scholarship at Abteilung für Automatisierungstechnik GWE, Siemens, Germany. Developed a DC/DC-Adapter.