Master Thesis

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Design and Development of a Haptic Device Prototype for 3D Virtual Environments

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Design and Development of a Haptic Device Prototype for 3D Virtual Environments

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Title of the paper

Design and Development of a Haptic Device Prototype for 3D Virtual Environments

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Abstract

In the last decade, presentation and rendering of virtual 3D environments have reached a great degree of realism. Stereoscopic displays and projections provide a spatial impression or even immersion. Combined with 3D sound systems the effect is further enhanced.

In contrast, haptic rendering and interaction still is mainly an area of research. Few systems convey a tactile or kinesthesia perception by imposing pressure upon small areas of the human skin or by exerting force on muscles and joints.

This master thesis deals with requirements and construction of a kinesthetic system in a 1D force-feedback setup. Along with the design and development phase requirements are given for an installation in a CAVE.

Stephan Plaschke

Thema der Diplomarbeit

Entwurf und Entwicklung eines haptischen Prototypen für 3D virtuelle Umgebungen

Stichworte

Haptik, Taktile- und kinästhetische Wahrnehmung/Displays, 3D virtuelle Umgebung, CAVE, BLDC-Motorsteuerung

Kurzzusammenfassung

Möglichkeiten zur Darstellung und Abbildung virtueller 3DUmgebungen sind in den letzten Jahren weit vorrangeschritten. Stereoskopische- Bildschirme und Großwandprojektionen vermitteln einen räumlichen Eindruck. Drei dimensionale Soundsysteme unterstützen den virtuellen Eindruck zusätzlich.

Bei haptischen Interaktionen und Darstellungen ist dagegen vor allem noch immer Forschungsbedarf. Einzelne Systeme vermitteln einen taktilen oder kinästhetischen Eindruck, indem z.B. Druck auf Hautpartien oder eine Kraft auf Muskel und Gelenkpartien ausgeübt wird.

Diese Masterarbeit befasst sich mit den Anforderungen und dem Aufbau eines Systems zur Darstellung kinästhetischer Eindrücke in einem 1D Kraftrückkopplungs-Aufbau. Während der Durchführung werden die Anforderungen weiter entwickelt und für eine Anwendung in einer CAVE-Anwendung spezifiziert.

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Acronyms

1D	one dimensional
2D	two dimensional
3D	three dimensional
AC	Alternating Current
API	Application Programming Interface
ARM	Advanced RISC Machine
BLDC	Brushless Direct Current
CAVE	Cave Automatic Virtual Environment
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
DC	Direct Current
DIP	Dual in-line package
DOF	Degree Of Freedom
DE-9	D-SUB 9 Pin Socket
EIA RS-232	Electronic Industries Alliance Recommended Standard 232
EIA RS-485	Electronic Industries Alliance Recommended Standard 485
GPIO	General Purpose Input/Output
HAW	University of Applied Science Hamburg
HCC	Human Computer Communication
HCI	Human-Computer Interaction
HD	High Definition
HMI	Human Machine Interface
IEEE	Institute of Electrical and Electronics Engineers
IDE	Integrated Development Environment
ISDN	Integrated Services Digital Network
ISP	In-System-Programmer
JTAG	Joint Test Action Group
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
MCU	Microcontroller Unit
MHz	Megahertz
MIPS	Million Instructions Per Second
MMLab	Multi Media Systems Laboratory
MSP430	Mixed Signal Processor, Member of the 430 MCU Platform
PC	Personal Computer
PCB	Printed Circuit Board
PDA	Personal Digital Assistant
RISC	Reduced Instruction Set Computers
ROM	Range of Motion
ROR	Rotate Right
rpm	rotations per minute
R/C	Radio-Controlled

RX	Receiver
SD	Secure Digital
SPI	Serial Peripheral Interface
SPIDAR	SPace Interface Device for Artificial Reality
TWI	Two-Wire Interface
TX	Transmitter
USB	Universal Serial Bus
UART	Universal Asynchronous Receiver/Transmitter
VDP	Visual Decision Platform
VE	Virtual Environment

1. Introduction

Haptics is compared to vision or acoustics a less known subject. It involves mechanical contact with optional thermal and pain intensive receptions. In every situation haptics helps to understand the outside world. It contains more information, a higher resolution and a better absorptive capacity compared to vision and acoustics.

A impressive demonstration of haptics relevance in omnipresent life can be experienced in the "Dialog im Dunkeln" exhibition in Hamburg. Here, visitors explore blindfolded the meaning of haptics demonstrated by blind exhibition guides. Another omnipresent example is the driving of a vehicles. Every steering and control action is based of the touch sense. This makes haptics so interesting for many different applications as teleoperations, simulators or Virtual Environments (VEs) [19].

Teleoperation implies the operation of a machine at a distance. Thereby the human controls and the machine executes the commands. Most commonly associated with robots, as the Mars-robot "Spirit", teleoperation can be used for a wide range of applications where a machine is operated at a distance.

A meaningful example is the work of an engineer. To complete his tasks all his senses must work together, first of all the sense of touch and vision. In case one sense is not precise enough or fails, the worker is able to use his other senses in substitution for the lost one. When the object he handles is not in his field of view, the engineer needs the sense of touch in supplement or substitution to his sense of vision to complete the task. This shows the need of the human touch in teleoperation. Further, more input channels also save energy by reducing the error count and the time a task takes to complete. Existing teleoperation systems have no or only limited haptic feedback and the display is two dimensional (2D). These limitations are the reason why teleoperation is useless for maintenance, reparation and related applications at the moment [36].

Besides teleoperation, VEs are another important field of application. Thereby haptics connects the VE with the human sense of touch. Current VEs like a Cave Automatic Virtual Environment (CAVE)[1] installation have either limited or no haptic feedback. Regarding the immersive point of view[2] this is an essential problem. The ability to provide the user with haptic feedback is a powerful way to improve the level of realism of a VE [3].

The absent haptic feedback leads to a misinterpretation in VEs. For example, a user tries to grab a virtual ball. Without haptic feedback there are only visual and acoustic methods to let the user know he is in contact with the ball. Also, there is no barrier or mechanism to keep the user from passing through the ball. [36].

The above mentioned examples show obviously why haptics is finding its way from theoretical considerations into real time tasks. This is reflected in various scientific publications and readings. Further, it is a result of the approximately perfect quality from visual and auditory representation. These two perceptual channels were analyzed and a subject of many scientific publications and developments during the last century. Current visual output devices like High Definition (HD) projectors provide the user with a high-quality visual representation. Supported

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[1] A CAVE installation is a VE where the user is surrounded with three, four, five or six walls.

[2] Immersion is the modified state of consciousness the user experiences by being surrounded in a virtual environment.

by three dimensional (3D) sound systems with six (Cinema 5.1 for home use) up to twenty four speakers (Hamasaki 22.2 part of Ultra High Definition Video), a proper immersive impression for those two channels is reached. The next step for a realistic representation is to open a new sensory channel: the sense of touch, presentable haptics [17].

The haptic feedback is provided by haptic systems which are generally called *haptic displays* or *haptic devices*. They are mounted to the floor, ceiling, wall or carried by the user and are sorted in at least two main classes: time-invariant and reconfigurable displays. The first one always generates the same haptic feeling. As example the surface of a wooden plate. Grooves and elevations generate the same haptic feeling. This is called *haptic texture*. On the other hand reconfigurable displays are able to modify the haptic impression in any way the displays type allows [19].

The haptic representation generated by current displays is good but they limit the Range of Motion (ROM) immensely. Different strategies were developed to create haptic feedback with a wide ROM. First of all, devices are mounted to parts of the user's body. These devices create a good haptic feedback by the use of pneumatic or hydraulic actuators[3]. However, the haptic feelings are limited due to the contact between the body parts and the device even when no feedback is desired.

Another approach is to limit the contact between skin and device so that only contact occurs when feedback is required. Thereby robot arms follow the user's motion and only touch those parts of the body where contact is required. This involves complicated control mechanism and bulky robot arms [17].

To provide haptic feedback in free space the university of Tokyo has developed a haptic display based on ultrasound, named the Airborne Ultrasound Tactile Display. Haptic feedback is created without attaching a device to the user's body with a wide ROM. The ultrasound transducers are packed in a hexagonal arrangement and apply a maximum force of 2.9 gf, respective 28.44 mN [17].

The optimal approach might be based on a ground referenced device (see chapter 2.4.2) where the controller is connected via strings to a cubic frame. This constellation allows at least three (three translation axis) up to six (three rotation and three translation axis) Degree Of Freedom (DOF) and a wide ROM. The idea, invented by professor Makoto Sato, is named SPace Interface Device for Artificial Reality (SPIDAR) [35]. Later on, Haption, a spin-off of CEA[4], developed a scientifical system on the same concept called INCA 6D[5]. The wide ROM provided by the haptic display allows various simulations and trainings. Therefore, this approach is the base idea for the concept of this master thesis.

With such a haptic display and the CAVE of the Multi Media Systems Laboratory (MMLab) easy simulations can be realized. As example the sawing of a wooden log, where the control element of the haptic display represents the saw, is imaginable. Another approach is a tire change at a car. Thereby the control element represents the impact wrench to loose or tighten the wheel nuts. This two simulations need a haptic display with one DOF and a CAVE for visualization to be successfully.

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[3] A actuator is the part of a haptic system where the force is generated.

[4] Commissariat à l'énergie atomique - French Nuclear Research Agency

[5] Visit `http://www.haption.com` for more information.

1.1. Goal of this Study

The theoretical goal of this master thesis is the analysis of haptic feelings created by a haptic display. With this knowledge the design of a haptic display is developed. It will be dimensioned for a horizontal usage with one DOF and provide a wide ROM. The practical goal will be to build this developed haptic display in hardware.

The design complies with the conditions of the CAVE installation in the MMLab at the University of Applied Science Hamburg (HAW). The idea of this master thesis is to support the CAVE and the MMLab with a fully assembled haptic device.

The idea is derived and simplified with respect to the research of professor Makoto Sato with his SPIDAR concept [35] and the INCA 6D system from Haption.

1.2. Practical Outline

The practical task of this master thesis includes the development, design and testing of a haptic device with respect to the gathered requirements.

The work-flow is planned as following:

- ♢ **Conception phase**
  The work on the master thesis starts with the development of the concept. A technical analysis will be performed, the requirements will be refined and the system components, protocols and software will be designed.

- ♢ **Hardware design and development**
  The hardware components will be selected, the layout for the Printed Circuit Board (PCB) will be drawn and the PCB will be produced.

- ♢ **Mechanical construction**
  The components of the mechanical construction will be selected, the engineering drawings will be sketched and the mechanical parts will be built.

- ♢ **Firmware design and development of the controller**
  The firmware for the controller will be written and the controller will be programmed. Therefore, it will be the first hardware commissioning and a stand alone test will be performed.

- ♢ **Software design and development for the PC application**
  The design and development of the Personal Computer (PC) application will be done. First test scenarios will be performed and therewith the requirements will be revised.

- ♢ **Evaluation and test**
  Every part of the system will be tested separately. Afterwards, component assemblies will be connected and the behavior of the complete system will be tested. Foreign requirements will be checked and evaluated.

2. Basics

In this chapter the theoretical background is described in order to understand the development process within this document. The first part describes physical conditions. The second part shows the functionality of existing haptic displays and also presents hardware components needed for the development process.

2.1. Haptics

Haptics in general is known as the sense of touch of the human body. "*The word haptic comes from the Greek word hapthesthai, meaning "to touch", but is used to refer to both force (joint/-muscle) and tactile(skin based) feedback.*" [3]

The human sense of touch is a combination of the position of bodily parts known as *kinaesthesia* as well as *tactile perception* whereas tactile perception involves pain and temperature perception. Figure 2.1 illustrates the human senses. Thereby the sense of balance has a special status, because it is not part of the conventional human senses [19].

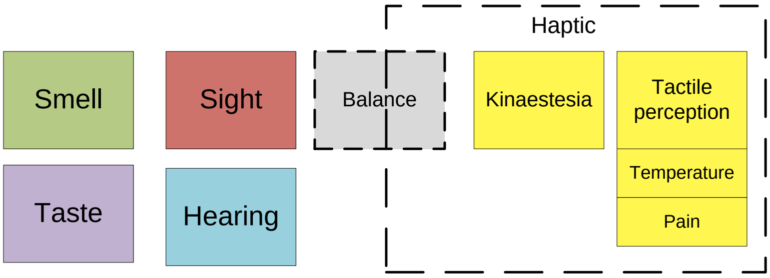

Figure 2.1: *The human senses (Based on [19])*

2.1.1. Kinaesthesia

Kinaesthesia is generally known as "Force Feedback" or "proprioception" and is by now called an "intelligence". Basically, it is the intelligence to take control of the human body's movement and the ability to handle objects skillfully. It provides information, perceived by receptors in the muscles and tendons, that contains movement, position, weight and torque of different bodily parts. Without this information our body parts would feel as if they were not attached to our body. Like tactile perception, kinaesthesia can be both, active and passive [3].

These abilities do not seem very complex. But this is a disbelief. As a test straighten your arm to the side. Then close your eyes, bend your arm and touch your nose. Without any information about the position of your body parts this would be impossible. With closed eyes no visual information is present and the concentration is on the human sensory system, mainly on kinaesthesia. This intelligence allows the body to perform actions without any information perceived by other senses.

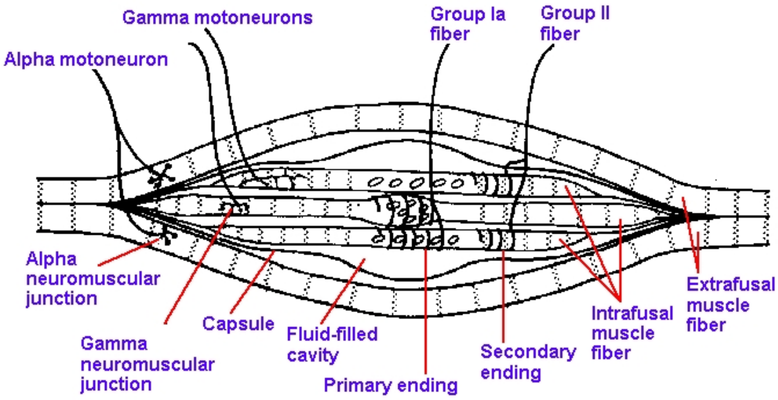

Figure 2.2: *Anatomy of a muscle spindle [29]*

Receptors of muscles and tendons differ. In muscles receptors are called "muscle spindle". The anatomy of a muscle spindle is shown in figure 2.2. The spindles are 4 mm to 7 mm long and embedded in the extrafusual muscle fiber, the regular muscle fiber. When the muscle fiber shortens or lengthens the spindles also shorten or lengthen and convey length information to the central nervous system. With this information the brain determines the position and angle of each body part without visual information [29].

Besides the passive operation spindles can also control muscle fiber length. This is achieved through activating the gamma motoneurons (also figure 2.2) on the intrafusual muscle fiber. The reaction is a contraction of the intrafusual muscle fiber and this contraction lengthens the extrafusual muscle fiber. This information is sent to the central nervous system, activating the alpha motoneurons (see figure 2.2) and again activating the extrafusual muscle fibers. This procedure is done until the muscle fiber is relaxed [29].

The receptors in the tendons are called "Golgi tendon organs" or "neurotendinous spindle". Figure 2.3 shows the anatomy. The Golgi tendon organs are suited at the junction of tendons and muscles, the musculo-tendinous junctions. They convey information about tensions generated by muscles during contraction or exertion [29].

A muscle contains many extrafusual fibers in it but only a few Golgi tendon organs. This is due to the fact that one Golgi tendon organ is arranged with only a few muscle fibers (between seven and ten). When the muscle is stretched, tension is applied to every muscle fiber. The information from the few Golgi tension organs represent the information for the whole muscle [29].

During exertion the endings, the sensory terminals, are compressed. As a result, nerve impulses are generated and fired straight to the central nervous system. The potential frequency is respective to the force applied to the muscle [29].[6]

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[6] A detailed animation can be found online at the University of Alberta, Arthur Prochazka's Lab [31]. More information about muscle spindles and tendon organs can be found in Michael D. Mann - The Nervous System In Action [29].

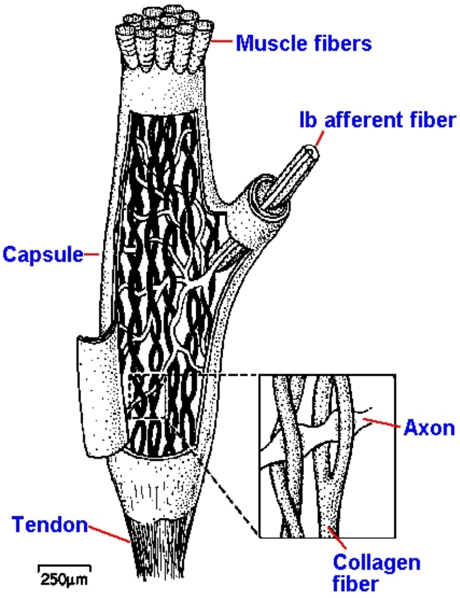

Figure 2.3: *Anatomy of a Golgi tendon organ [29]*

2.1.2. Tactile Perception

Tactile perception is perceived through nerve endings located under the surface of the skin. These nerve endings, or receptors, provide information about heat (thermoreceptors), pain (nociceptor), surface texture and pressure (mechanoreceptors) [36].

The anatomy of the human skin is illustrated in figure 2.4. Each layer consists of different receptors for different perceptions.[7]

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[7] For further information about the anatomy of human skin see Burdea - Force and Touch Feedback for Virtual Reality [4] or Kandel - Principles of Neural Science [18].

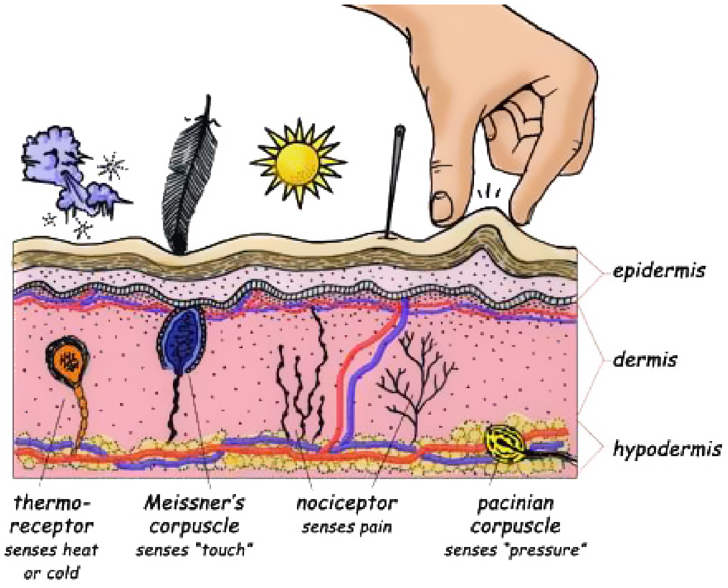

Figure 2.4: *Sense organs in the human skin [1]*

- ◇ **The Meissner's corpuscles** are suited in the outer layer of dead skin cells, the epidermis. They are egg-shaped and perceive light touch, for example by deforming the corpuscles. Electric activity is detected by electrodes connected to the corpuscles. The greater the deformation the greater the electric potential. Below 50 Hz the Meissner's corpuscles have their highest sensitivity. They are categorized as *rapidly adapting receptors type I*, significantly they have multiple Meissner's corpuscles end-organs [18].
- ◇ **The Pacinian corpuscles** are suited in the lower layer, the hypodermis. Pacinian corpuscles are categorized as *rapidly adapting receptors type II*, which means they have multiple Pacinian corpuscles. Their function is similar to the Meissner's corpuscles, except their highest sensitivity frequency. Here it is 250 instead of 50 Hz [18].
- ◇ **The Thermoreceptors** are suited in the middle layer, the dermis. They perceive relative and absolute changes in temperature. Temperature receptors for cold and warm are known. Warm receptors react with an increase of their action potential during warming and a decrease during cooling. Cold receptors react contrary to warm receptors. During cold stimuli sensibility of each receptor and the motor skills are limited [18].
- ◇ **The Nociceptors** are also suited in the dermis. They are split into three different groups: thermal-, mechanical- and chemical-nociceptors. The first group is activated by temperature changes, the second by pressure or mechanical deformation and the last by spices. All of them work on the same principle. When a threshold value is reached an electric potential is induced which leads to pain [18].

Tactile perception arises from two different stimulations. One implies active stimulation from the outer world, the other involves active movement of the body. These stimulations are called passive and active touch.

- ◇ **Passive touch** occurs when a resting part of a body has contact with an object. The object can be a moving or a stationary object. A tear running down the cheek or a coin pressed into someones hand are examples of passive touch [37].
- ◇ **Active touch** involves the active exploration of objects and is also known as haptic perception. For the brain it is the fastest way to identify unknown objects. Moving a finger over a surface results in several information like edges, curves or surface texture. With this information the human brain is rapidly able to identify the object. Active touch involves kinaesthesia as well (see chapter 2.1.1) [13].

2.2. Human-Computer Interaction

Human-Computer Interaction (HCI) is the research of interaction between human users and computers. The goals of the HCI research field are the improvements of interaction between human and computer as well as the improvement of the communication and cooperation between humans. In figure 2.5 the wide range of different research fields which are involved in HCI is illustrated [32].

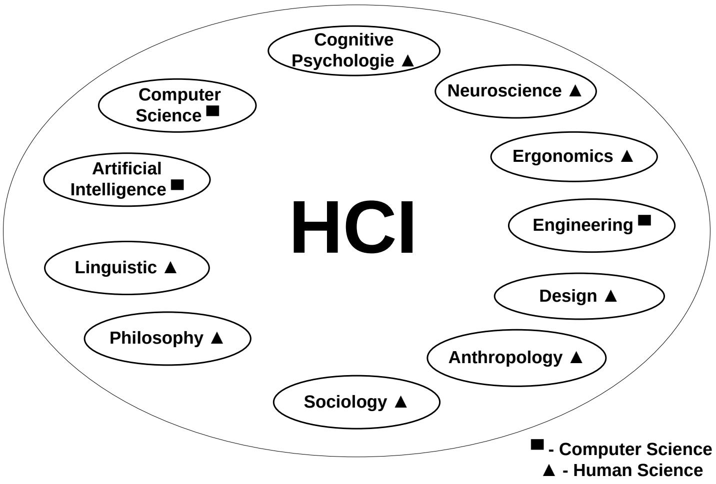

Figure 2.5: *Human-Computer Interaction [32]*

The focus of HCI is the user interface that includes hardware and software, the Human Machine Interface (HMI). Therefore, studies in the human as well as in the machine fields are required as both work closely together. On the human side sociology, design disciplines, linguistics, cognitive psychology, neuroscience, ergonomics, anthropology and philosophy play a big role. On the machine side engineering, artificial intelligence and computer science are relevant. For HCI to be successful, people with different technical backgrounds need to work together due to the HCIs multidisciplinary requirement [32].

A comprehensible way to explain HCI is to demonstrate the need for Human Computer Communication (HCC), the communication between user and system (see figure 2.6). Here the user forms his goals depending on his input options, which, on the other hand, are limited by the input device. Afterwards, the system provides feedback to the user, that again is limited by the feedback device. This whole HCC process requires various translations. First of all, after the user has translated his goals into physical actions, the input device in turn translates these actions into electronic signals processable by the system. Based on the current system state and the signals, the system produces a digital output for the user. This process is called transfer function. Further, the output device translates these digital outputs into a form the user can perceive, such as tactile perception or light. Finally, the user translates these perceptions into a reasonable semantic representation [3].

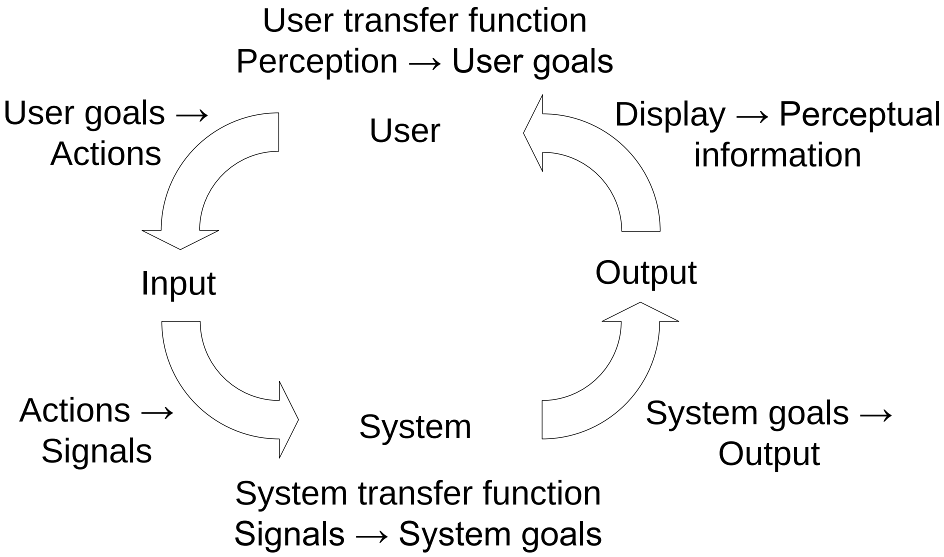

Figure 2.6: *Human-Computer Communication*

The communication process shown in figure 2.7 can easily refer to a common example, in which the input device is a joystick and the output device a Liquid Crystal Display (LCD). The transfer function of the system is represented by a computer game. The goal of the user is as a matter of course to play the game, for example walk through a special area in the game. Thereby the direction, in which the user wants to move, is translated into electronic signals by the joystick. The system then deciphers the signals and calculates the direction as well as the distance the avatar moves in the game. Finally, the LCD displays the output and the user can perceive the information.

In VEs haptics is a way to couple the virtual world with the human sense of touch. Current VEs like CAVE installations or simulators have either limited or no haptic feedback. Providing a user in those VEs with haptic feedback is a powerful way to improve the realism of the virtual world.

An example is the welding simulator ARC+ from 123 Certification Inc. This simulator is used to train workers on different welding equipments with materials that are difficult to handle, as cast steel, aluminum or thin iron sheets. With these simulators workers with a low level of experience train to work on these materials. Afterwards, they work on real materials with real equipment. This increases productivity and efficiency.[8]

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[8] Visit http://www.123arc.com for more information.

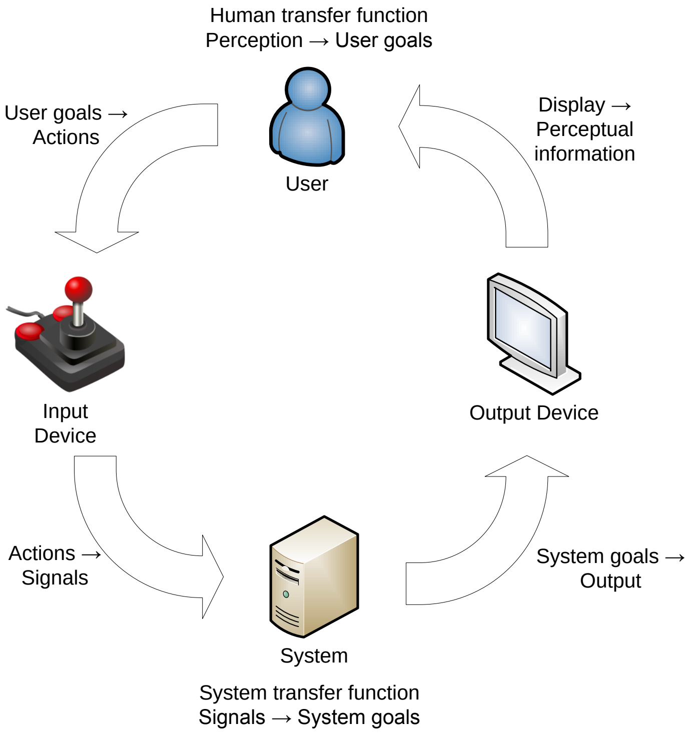

Figure 2.7: *Human-Computer Communication example (based on [3])*

A further example is the endoscopic surgery simulator. In modern surgery, endoscopic surgery plays an essential role. The patient has many advantages from this type of surgery. This kind of operation is a big challenge for the surgeon. He needs good skills in remote operations and good interpretations of 3D information on a 2D screen. These skills have to be trained constantly. In real surgeries amateurs train slowly and start in easy situations. When it is getting complicated an experienced surgeon resumes. This is inalienable for the patients health but for training it means slow progress. By the means of qualitative surgery simulators the training becomes much easier, harmless for the patient and faster. At the Department of Medical Informatics at the University Medical Center Hamburg-Eppendorf a 6 DOF simulator is developed. It is used to simulate and train lumbar punctures. As haptic device Sensable's Phantom Premium device with 6 DOF is used [11].

The two examples show that haptic feedback is highly important in training situations. Other applications as remote controlled operations (maintenance) also need this kind of feedback. The biggest challenge is to create high quality feedback. Poor quality feedback may limit the immersive experience or mislead the learning process.

2.3. Haptic Systems

Haptic systems are comparable to regulator circuits in control engineering. Their different components are illustrated in block diagrams, such as figure 2.8, that shows a haptic device, a haptic controller and a user. By definition a haptic device is a system which provides the user with haptic feedback and consists of one or more haptic controllers.

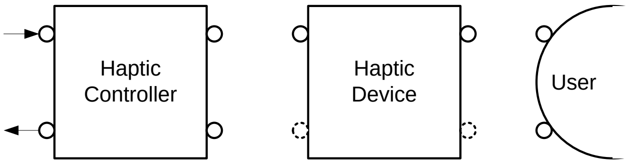

Figure 2.8: *Components of a haptic system block diagram [19]*

2.3.1. Characteristics

The Mechanical Impedance $\underline{Z}$ describes the complex coefficient between force $\underline{F}$ and velocity $\underline{v}$ or rather torque $\underline{M}$ and angular velocity $\underline{\Omega}$. In haptic systems analysis $\underline{Z}$ is known as display-impedance or interface-impedance $\underline{Z}_D$ and represents the impedance on the mechanical output (e.g. controller, joystick). The user-impedance $\underline{Z}_H$ is the simplified approach of the mechanical influence of the user. A high $\underline{Z}_H$ or $\underline{Z}_D$ refer to a "rigid" or "inert" system, whereas a low impedance to a "smooth" system or user [19].

$$\underline{Z} = \frac{\underline{F}}{\underline{v}} = \frac{\underline{M}}{\underline{\Omega}} \tag{1}$$

The Transparency $\underline{T}$ of a haptic system is defined by *Lawrence* in [27] as the factor between mechanical input impedance of the interface $\underline{Z}_{in}$ and mechanical output impedance of the device $\underline{Z}_{out}$.

$$\underline{T} = \frac{\underline{Z}_{in}}{\underline{Z}_{out}} \tag{2}$$

$\underline{T}$ is termed as the only established, frequency-dependent characteristic of a haptic system. With a value close to one the system has no effect on the input impedance. The mechanical properties of the virtual object are realized without any influence of the mechanical part of the device [19].

2.3.2. Haptic Interaction

The communication between a device and a user is called haptic interaction. Thereby, the interaction can be both unidirectional and bidirectional as illustrated in figure 2.9. Tactile perception only allows unidirectional interaction, whereas kinaesthesia allows uni- as well as bidirectional interaction. As an example a standard *QWERTY* keyboard has a raised dot or a bar on the *F* and *J* key which results in a tactile haptic interaction [19].

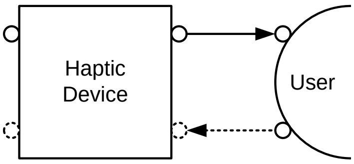

Figure 2.9: *Haptic interaction block diagram [19]*

2.4. Haptic Display

Haptic display is a generic term for haptic devices. A haptic display provides the user, depending on the type of display, with kinaesthesian and/or tactile perception by interacting in VEs.

2.4.1. Characteristics

Haptic displays have different characteristics and types which help to describe and review them. The most common characteristics are haptic presentation capability, resolution and ergonomics.

Haptic presentation capability represents the type of perception, the ROM a haptic display offers and the force/perception a haptic device provides on which parts of the users body [3].

Resolution of a haptic display can be divided into spatial and temporal resolution. The first one refers to the sensitivity of the body part the device addresses. For instance, a fingertip's spatial resolution is much higher than the resolution for the arm. Temporal resolution on the other hand refers to the refresh rate of the device. To provide quality output a frequency of 500 Hz to 1000 Hz is necessary. Low refresh rates can affect quality by causing unintended vibrations and making virtual objects feel softer then intended [3].

Ergonomics is needed to guarantee a user's safety as some haptic displays deploy the user with extremely high forces. If a software error occurs, the user's health can be in danger. Further, the weight and design of the device is important for high usability and user safety [3].

2.4.2. Types

Through the years many haptic displays have been developed. However, they all are categorized in five groups mainly based on the type of force the device offers to the user. The kind of actuator represents a subcategory. Actuators are the components that generate the force or the tactile feedback. Different kinds are present like electro-mechanical, pneumatic, hydraulic, current and elastomer based actuators. In the following the five groups of haptic displays are introduced.

Ground-referenced displays are mounted to the wall, ceiling, desk or ground. The force generated is connected to the ground. Mechanical components and the fixed connection to a surface limit the ROM of these devices. Many different kinds like pen-based force feedback, force-reflecting joysticks, string devices and robotic arms are known. Typically, electro-mechanical, pneumatic and hydraulic actuators are used [3].

Figure 2.10: *Ground-referenced haptic display from Haption*[9]

Joysticks and steering wheels are well known implementations of ground referenced devices. The robust and inexpensive design and the high usability make them perfect for the consumer market. Other devices, like pen-based ones, are precise, complicated and expensive. Most computer users are not even aware of the existence of these devices. Figure 2.10 shows the VIRTUOSE 6D35-45 from Haption, a haptic device which applies forces to the hand, elbow and shoulder.

Body-referenced displays are connected in some way to the body of the user. Compared to ground-referenced devices, body referenced devices allow more freedom in motion for the user. Therefore, design and weight are more important criteria. The weight a user can carry and still act naturally is limited. Mostly, electro-mechanical or pneumatic actuators are used [3].

Body-referenced devices are built in two different variants. The first variant, the arm exoskeleton, is similar to a ground-referenced arm exoskeleton except that it is connected to the back of the user. The second variant is a hand-force-feedback device as shown in figure 2.11. This variant uses strings or pneumatic actuators to apply forces to the part of the body, for instance each finger of a hand. The disadvantage of this display is the time needed to put it on and calibrate [3].

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[9] Image available online at `http://haption.com`.

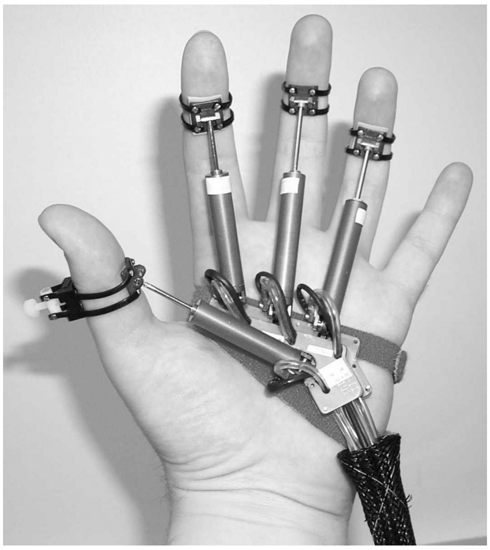
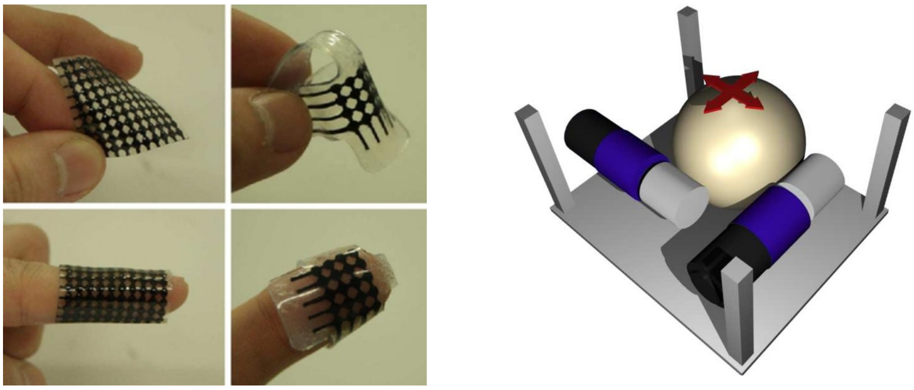


Figure 2.11: *Body-referenced haptic display [2]*

Tactile displays stimulate the tactile receptors located in human skin. Figure 2.12 shows two different categories of tactile displays. The first is based on pressure exposed on the human skin through different kinds of actuators. A tactile display with soft actuators is depicted in figure 12(a). This kind is based on dielectric elastomer's and electroactive polymers which expands when electric voltage is applied.

An example for the second category is shown in figure 12(b). These displays use methods like rotating spheres to apply shear forces to the skin. Shear forces are generated by moving over a surface. This approach is new and still not completely investigated.[10] The best tactile display would be a combination of these two types.



(a) Band-Aid-Size Tactile Display [26]

(b) Sphere-Based Tactile Slip Friction Display [12]

Figure 2.12: *Two different tactile displays*

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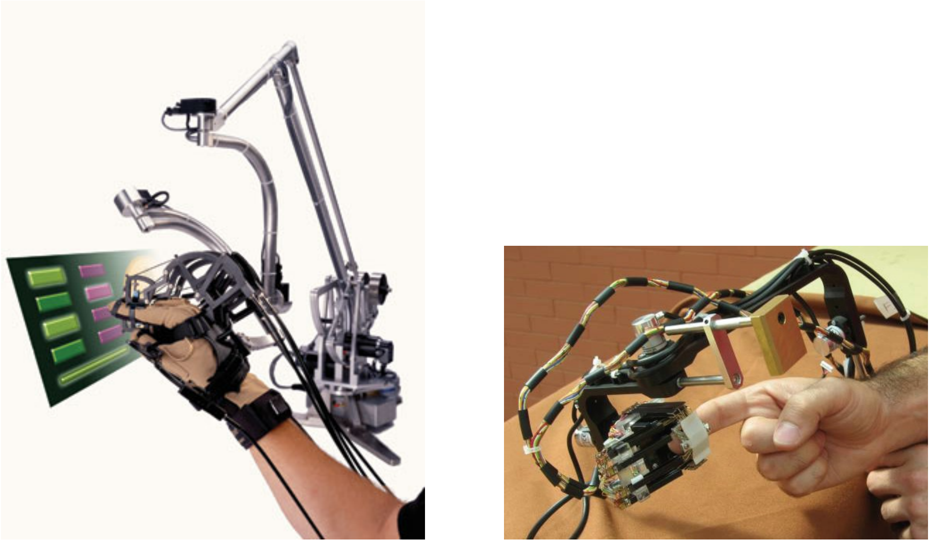
[10] For further readings see Fritschi, Ernst and Buss - Integration of Kinesthetic and Tactile Display [12].

Passive displays in VEs are real existing objects, for example a tennis ball fixed to a glove (figure 2.13). It is used for a "Tin Can Alley" simulation [34] developed at the HAW in the MMLab.[11]

Figure 2.13: *Passive haptic display*

Hybrid displays involve more than one of the types introduced previously. For instance, a combination of a body-referenced and ground-referenced device, shown in figure 2.14(a). These devices are often used for trainings or in simulators. They apply heavy forces connected to the ground and a feeling as if the hand of the user touches the interpretation of a virtual object.



(a) Cyberforce combination device from Immersion Corporation (Source: Immersion Corporation)

(b) Integrated force-feedback and tactile perception device [28]

Figure 2.14: *Two different hybrid displays*

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[11] Another example is a paint-brush in a painting application. A natural paint-brush is used in combination with a ground referenced haptic device as controller [38].

As a second example of a hybrid device, figure 2.14(b) shows a combination of tactile perception and ground-referenced forces.[12]

Hybrid devices create stronger haptic sensations than single devices but need more computing time. Computing time is still a big issue because it is rare in VE. For a good haptic feeling a refresh rate of 500 Hz - 1000 Hz is necessary for a force device. For this reason most devices concentrate on one haptic perception.

2.5. Hardware

Hardware needed for this project involves mechanical and electrical components. Electronic components imply electronic engines, controlling units for the main system and the electrical engine and PC adapters. Mechanical components involve transmission and tackle.

2.5.1. Embbeded Systems

Embedded systems are computer or microcontroller designed for a special purpose, they are "embedded" in a system to execute particular tasks. The task is to control, operate or monitor the system. Depending on the system it is also used to interact with the environment.

Nowadays different forms of embbeded systems are used in almost every electrical device. The complexity of the device defines the operating system used in embedded systems. Small systems get by without an operating system, bigger systems use special types like QNX, Windows CE or Linux.

The design of embbeded systems succumb strict limitations. Minimal costs, minimal place requirement, minimal power consumption and a minimum memory required are essential for a reliable and effective embedded system. Enhancements of older microcontrollers can be useful to keep software and to reduce development time.[13]

2.5.2. Microcontroller

In common control and monitoring systems Microcontroller Units (MCUs) are used for the central system control. Besides a Central Processing Unit (CPU), memory and General Purpose Input/Output (GPIO) most microcontrollers employ interfaces like Universal Serial Bus (USB) or Universal Asynchronous Receiver/Transmitter (UART). Which kind of MCU is used depends on the application. Real time systems need fast units which allow them to run a real time operating system. Therefore, a good choice is the Advanced RISC Machine (ARM) MCU family. These microcontrollers are used in smart phones and Personal Digital Assistants (PDAs).[14]

Other applications need a microprocessor which draws only a little current. In these applications a microprocessor of the Mixed Signal Processor, Member of the 430 MCU Platform (MSP430) family is a good choice. Controllers from the MSP430 family have a minimal current consumption from $250\mu A/$Million Instructions Per Second (MIPS). The negative effect is less computing power.[15]

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[12] This device is part of a cloth simulator called HAPTEX.

[13] Source: `http://www.embedded.com`

[14] Source: `http://www.atmel.com/`

[15] Source: `http://www.ti.com/`

For an effective solution a microprocessor is needed which combines computing power with low current consumption and enough control interfaces. A reliable microprocessor family is the Atmel AVR. These MCUs provide enough computing power, memory and interfaces for further development.

2.5.3. Interfaces

Every MCU has a different amount of interfaces. On every microprocessor a definite amount of GPIO is given. Thereby input/output pins from the MCU run on different logic levels to control or monitor external devices. Other common interfaces such as UART or USB run on different levels and need a converter.

Joint Test Action Group (JTAG) is the commonly used name for the Institute of Electrical and Electronics Engineers (IEEE) 1149.1 Standard Test Access Port and Boundary-Scan Architecture. Nowadays JTAG is also used for MCU debugging. Most current microprocessors provide a JTAG interface. Development of embedded systems requires debuggers with JTAG to perform single stepping and breakpointing.

UART is a type of asynchronous transmitters/receivers which translates parallel to serial data. In combination with standards like Electronic Industries Alliance Recommended Standard 232 (EIA RS-232) it is used for serial communications between two devices (e.g. PC→PC or PC→MCU).

Standards like Electronic Industries Alliance Recommended Standard 485 (EIA RS-485) benefit from a multi-user network which make them useful in industrial environments.

USB is an interface to establish connections between a host controller and devices. It is developed for PCs to replace former serial communication interfaces with a faster, more reliable and more user friendly interface. Usually a PC represents the host and PC peripherals the clients.

For older systems serial-to-USB converters are developed. This kind allows MCUs to establish a USB connection without knowledge about the USB protocol. The driver on host side provides a communication port which has the benefit of uncomplicated programming on PC side.

2.5.4. Electrical Motors

Electric motors convert electric power into mechanical force. Few motors achieve translational motion, this kind is known as linear actuators. The common use is a circular motion. Developed in the early 18th century electric motors began their triumphant success in many different facilities. Since then the functionality is based on the same principle, the Lorentz force. Based on their electric power supply two types exist, Alternating Current (AC) and Direct Current (DC) electric motors. The principle is similar for both motor types.[16]

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[16] For further readings about electrical motors see [10].

DC Electric Motors are driven by direct current. The DC motor generates the rotating magnetic field in the rotor. The stator magnetic field is generated by permanent magnets or, on larger motors, by windings. The rotor windings are supplied through slip rings.

The most common type is the brushed DC electric motor. The basic design, the wide power spectrum and the good start-up behavior makes it a perfect solution for most applications.

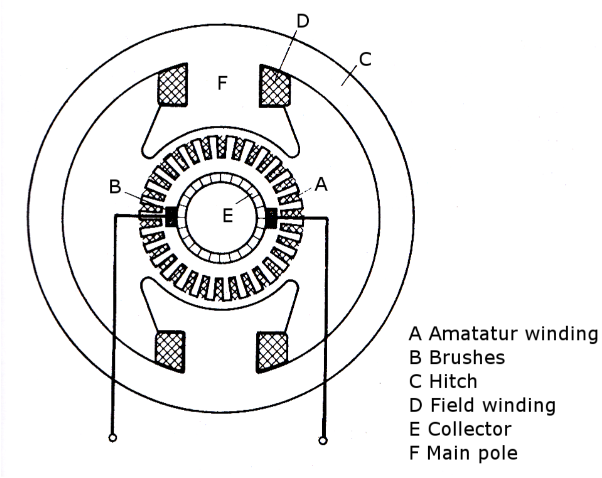

Figure 2.15: *Operating of a DC motor (based on [30])*

Figure 2.15 shows the principle of a brushed DC motor with field windings in the stator. By powering the armature windings a magnetic field is generated. The north pole of the armature is pushed away from the stators north pole. When the armature becomes horizontal the commutator changes the direction of the current and with it the magnetic field of the rotor changes. The process repeats continuously [10].

Such type of motors pose the problem of electric brush sparks. This results in high-frequency interferences on supplier side. To avoid high-frequency interferences Brushless Direct Current (BLDC) motors are developed. Instead of a mechanical commutator and brushes it has an electronic commutation system. The rotor consists of permanent magnets. Hall sensors detect the position of each of them. In relation to the position the windings of the stator are switched on and off to produce a proper rotary motion. The use of permanent magnets limits the BLDC motor power. Current to torque and voltage to rotations per minute (rpm) are linear relations by these kind of motors [10].

AC Electric Motors are driven by alternating current. Compared to the DC motor the AC motor generates the rotating magnetic field in the stator not in the rotor. Two kinds exist, the synchronous and the induction motor. The synchronous motor rotates with exactly the supply frequency or a submultiple of it. The magnetic field of the rotor is generated by a permanent magnet or by current delivered through slip rings. When the stator electric field starts rotating, the rotor immediately follows the electric field. Depending on the number of pole pairs the rotation velocity is similar or a submultiple of the supply frequency [10].

The induction motor runs a bit behind the supply frequency. It has a passive rotor and an active stator. By comparison with a generator the stator is the primary and the rotor the secondary side. The rotor current, and therefore the magnetic field of the rotor, is induced by the magnetic field of the stator windings. The rotation of the stators magnetic field causes a rotational motion on the rotor. Two variants exist: The first one is a squirrel-cage rotor. It has shorted bars of solid copper and/or aluminum. The resistance of the rotor is always little and unemployable. The second variant, a slip ring rotor, has windings connected to slip rings. During start-up resistors are connected in series to the rotor windings to limit the current by increasing the resistance. When the windings are shorted, the behavior is similar to the squirrel-cage rotor [10].

2.5.5. Transmission

A transmission provides velocity and torque between a rotating power source and powered components. The most common application is the automobile gearbox. There the transmission adapts wheels and engine with different levels of torque and velocity. Transmissions are also used on pedal bicycles, motorbikes and everywhere else a rotation power source is used to power components.

Transmission can be categorized into rigid and non-rigid transmissions. Non-rigid transmissions, as shown in figure 2.16, use belts or chains to transmit velocity and torque. This kind of technique is used on some motorcycles or bicycles but mainly in industrial facilities. The utilized belts consist of rubber with steel strings in it. This makes them cost-effective, quiet and reduces power loss. During start-up the belt is stretched a little and the machine starts smoothly. Non-rigid transmissions with toothless belts also prevent the power source from overload. Different kinds of belts are utilized nowadays: flat belts, round belts, vee belts, ribbed belts, film belts and further special belts [9].

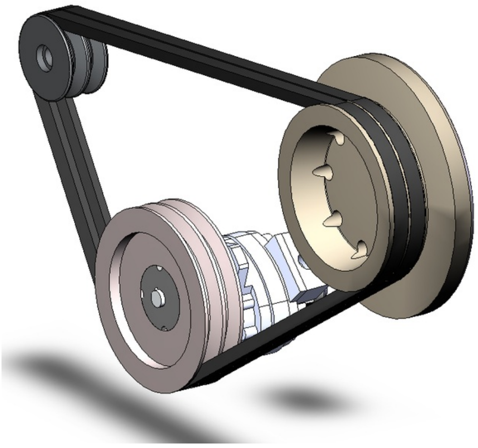

Figure 2.16: *Non-rigid transmission (Source: Wikipedia)*

Rigid transmissions use gearwheels in different combinations. Figure 2.17 shows an example of a Radio-Controlled (R/C) car gearbox. This kind is louder and in most cases more expensive than the non-rigid transmission. Furthermore, the start-up behavior is jerky. The advantages are the higher power transmission and the rigid connection from load and engine. However, rigid transmissions are not secured against overload by nature. External subsystems are needed for an overload protection, which makes the system more expensive, complicated and high-maintenance. They are used in gearboxes, motorcycles and in some industrial facilities [9].

Figure 2.17: *Rigid transmission (Based on [25]))*

3. Requirements Analysis

In this chapter requirements for the to be developed haptic device are defined. The requirements are developed by analyzing the needs of the device with respect to safety, user interaction and ergonomics. Further, considerations for an CAVE assembly in the MMLab are made.

3.1. Basic Functional Principle

As described above, the main goal of the haptic device is to support the user with a good haptic feeling at one DOF with a wide ROM. In order to fulfill this criterion two types of haptic devices are possible. The first commonly used type consists of body-reference displays, where the display is in some way connected to the body of the user. The force is applied through strings or by an arm exoskeleton. For this implementation body-referenced displays are inapplicable, because of their advanced design, their complicated control system and the weight the user would have to carry.

The second type is a ground-referenced display, in which the disadvantages from the body-referenced design have no effect any more. The assembly on the floor, the plain design and the basic control system are main benefits of this display type. The challenge is to support the user with a wide ROM. For this purpose the research of professor Makoto Sato with his SPIDAR concept [35] is very helpful. The idea is a system, where the control element is free in space, only attached by strings. Each string is connected to an actuator. Depending on the amount of actuators and strings this design allows up to six DOF and a ROM only limited by the string length.

In case one DOF is desired two actuators are required. The actuators are mounted on the ground in force direction. String guides are used to allow the user to walk freely in the area without considering the moving sense of the device. The strings are connected to actuators and tightened to the control element. Moving the controller element results in string reduction or extension that the actuators has to compensate. The basic design of the control element with force impact and moving sense is shown in figure 3.1.

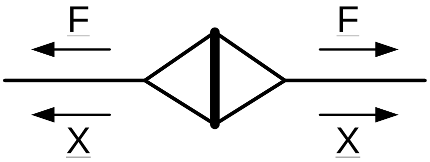

Figure 3.1: *Force impact and moving sense on the control element*

In general, it is a handle connected on each side to strings. The moving sense equals the force impact. Besides the direction of the force, the user is able to walk freely in the operating range of the system. Thereby, the user has to pay attention to the direction of the force. With only one DOF the system is not able to be aware of the position in the room. Moving across the direction of the force is detected by the system as moving on the direction of the force. This ends in wrong force signal computing. In order to solve this problem an optical tracking system[17] can

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[17] See chapter 8 for more information.

be used but is not dealt with in this master thesis.

3.2. Basic Requirement Analysis

The development of a common device is subject to several design rules and conditions. The successive analysis of needs is the theoretical part of this chapter. The following sections pay attention to the characteristics of a haptic device (for an explanation see chapter 2.4.1).

3.2.1. Flowchart

System development starts with the theoretical design of the system. Thereby a flowchart helps to understand the functionality of the system and gives an overview of requirements. A standard haptic system with visual content is illustrated in figure 3.2. There the user interacts with a control element. The position information is transformed into digital signals and transferred to the haptic controller and the visual system, where the modified haptic and visual representation is computed. The visual and haptic device transforms the data into a representation the user can deal with.

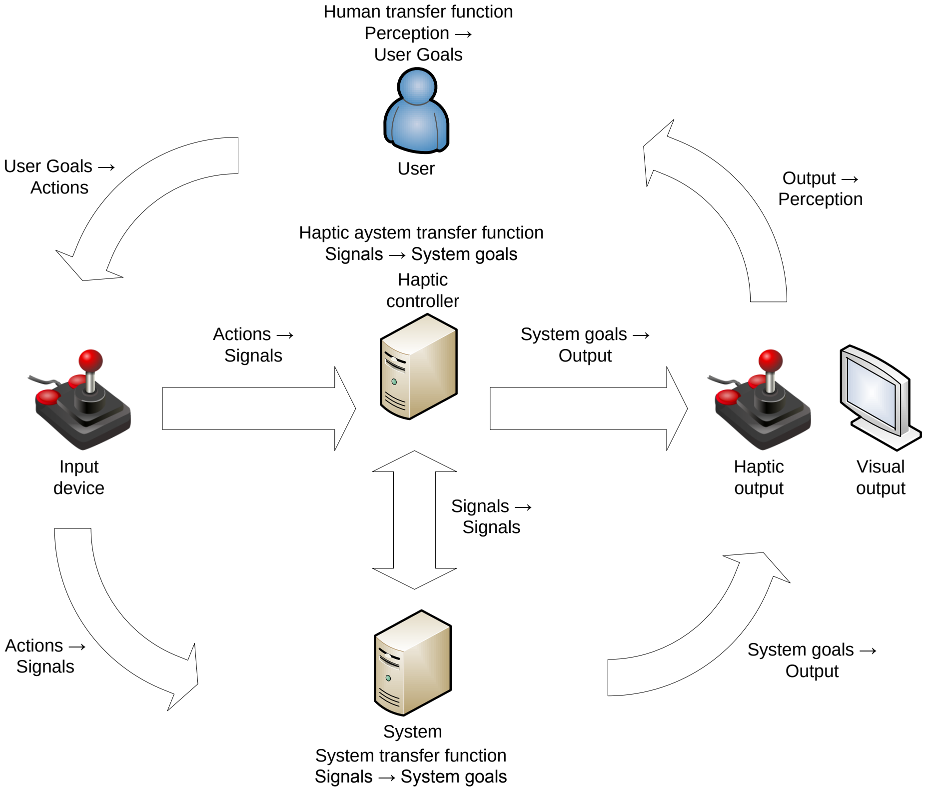

Figure 3.2: *Haptic and visual system overview*

A flowchart of the haptic system as described before is illustrated in figure 3.3. First of all, the simulator starts and generates the virtual content. As in this example it is the regular case that a haptic system has visual and haptic content. Detecting the position of the control element, respective the user, is done next. At this point the main loop starts. Every action is assigned to a system component. This flowchart consists of three haptic components: simulator, controller and device.

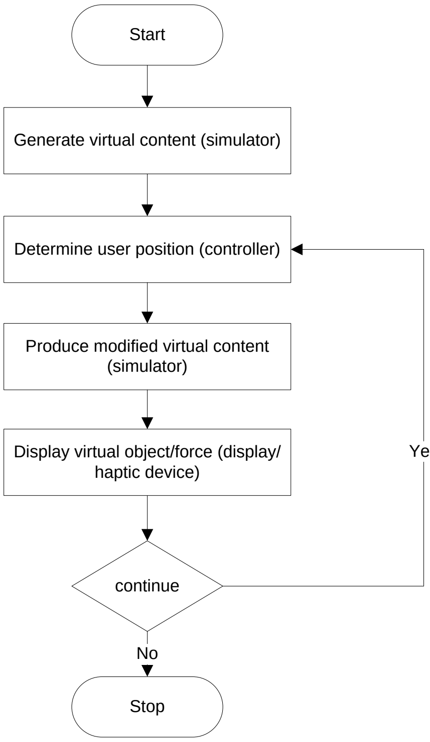

Figure 3.3: *Haptic system flowchart*

3.2.2. System Block Diagram

In the next step, a block diagram is created with the help of the flowchart. Each component is analyzed and transferred into a part of the block diagram. As the descriptions of theoretical and practical developments differ, the definition of *haptic device* and *haptic system* could be misleading.[18]

As before, the haptic system to be developed consists of three components, shown in the block diagram in figure 3.4. From left to right, the first component is the haptic simulator, a software located on a standard PC-system, where the data for the visual and haptic representation is computed. The second component, a haptic controller based on a microcontroller subsystem, deciphers the signal from the simulator and controls the electric motors from the haptic device. The last component of the system is the haptic device, where the interaction between user and system occurs. In this case the name haptic device combines three components: the electronic motors, transmissions from rotational to linear motion and the control element.

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[18] For a better understanding of definitions in block diagrams see [19].

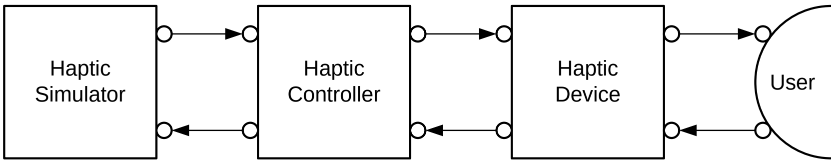

Figure 3.4: *Haptic system block diagram [19]*

Figure 3.5 illustrates the block diagram of the haptic device including signals for force and motion. The haptic interaction is bidirectional, force as output and motion as input. The actual haptic data is computed in the PC-software and translated into a signal representative force. This signal ($\underline{F}_{Sig0}$) is transmitted to the haptic controller and translated into force direction and strength. The sequent signal ($\underline{F}_{Sig1}$) is transmitted to the haptic device. The signal representative force ($\underline{F}_{Out}$) is generated by electric motors and transferred through cable winches to the control element.

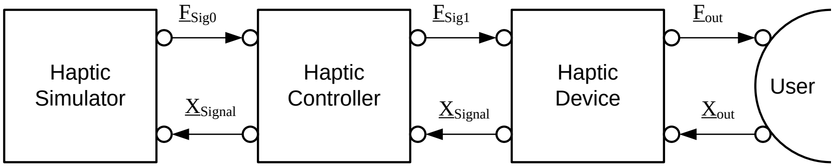

Figure 3.5: *Block diagram with signal paths (based on [19])*

The input signal path starts at user side. Linear motion ($\underline{X}_{Out}$) is transferred to the haptic device. Sensors in the electronic engine detect the rotary motion and transform the signal into a digital representation ($\underline{X}_{Signal}$). This digital signal is sent via the haptic controller to the haptic simulator. With this motion information the simulator computes the new haptic and visual data.

As described in chapter 2.3.1, the major characteristic of a haptic system is transparency $\underline{T}$.[19]

3.2.3. Mechanical Network

Besides block diagrams mechanical networks are an important theoretical method to describe a mechanical system. Each mechanical component is split into its basic characteristics. The basic characteristics are:

Physical Variable	Symbol	Unit
Force	F	N
Velocity	v	$\frac{m}{s}$
Torque	M	Nm

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[19] A value as close as possible to one is desirable.

Mass	m	kg
Inertia	Θ	$kg \cdot m^2$
Rotatory Attenuation	d	$\frac{N}{s \cdot m}$
Mechanical Impedance	$\underline{Z}$	$\frac{N \cdot s}{m}$
Radius	r	m

Table 3.1: *Mechanical network characteristics*

A mechanical network description with one DOF is shown in figure 3.6. An electrical motor is used as torque source $\underline{M}_0$ with rotor inertia Θ and rotatory attenuation d_R from bearing and transmission. At the spindle with the radius r the rotary motion is transferred into linear motion with force $\underline{F}_0$ and velocity $\underline{v}_0$. The mass m defines the weight of the control element. The force applied to the user ($\underline{F}_{out}$) is dependent on the user impedance $\underline{Z}_H$ and the sum of all single impedances.

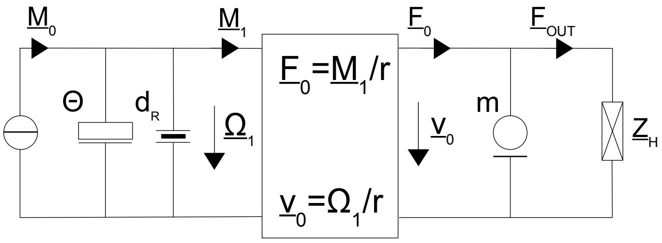

Figure 3.6: *Mechanical network [19]*

Although the impedance of the system should be as low as possible, impedance from rotor, bearings and transmissions are always present. For an effective system motor torque and gear ratio must be sufficient to compensate the system impedance.

3.2.4. Simplified Mechanical Network

Simplified mathematical models are inalienable for a better understanding and for system verification. However, in this special case up to now no standardized and approved method to simplify a mechanical network exists.[20] The method from *Kern*[21] is used for this work. It transfers the mechanical network model (figure 3.6) into a simplified model (figure 3.7), that now consists of an ideal force source ($\underline{F}_0$), an unknown mechanical impedance from the display ($\underline{Z}_D$) and the user impedance ($\underline{Z}_H$) [19].

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[20] Own research and mentioned in [19].

[21] See [19] chapter 4 page 88 - 89.

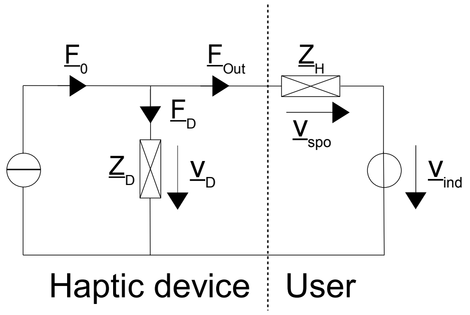

Figure 3.7: *Simplified mechanical network (Based on [19])*

The nodal equation of the simplified mechanical network is

$$\underline{F}_0 = \underline{F}_D + \underline{F}_{out} \tag{3}$$

Haptic perception $\underline{K}$ is defined as followed[22]

$$\underline{K} = -\frac{\underline{F}_{out}}{s\underline{Z}_H} \cdot \underline{G}_{FIP} \tag{4}$$

Equation (3) resolved to $\underline{F}_{out}$ and inserted into equation (4) results in

$$\underline{K} = \frac{\underline{Z}_D \cdot \underline{v}_D - \underline{F}_0}{s \cdot \underline{Z}_H} \cdot \underline{G}_{FIP} \tag{5}$$

Equation (5) defines the complex haptic perception of the simplified mechanical network and is a solution regarding the torque source. For the design process a solution regarding the interaction is needed. This is done by using $\underline{v}_D$ as a sum of user and device velocity [19]

$$\underline{v}_D = \underline{v}_{spo} + \underline{v}_{ind} \tag{6}$$

Further, device velocity $\underline{v}_D$ is replaced by the impedance and integrate $\underline{v}_{spo} = \underline{x}_{spo} \cdot s$ results in

$$\frac{\underline{F}_D}{\underline{Z}_D} = \underline{x}_{spo} \cdot s + \underline{v}_{ind} \tag{7}$$

With the help of equation (3) and $\underline{F}_{out} = \underline{Z}_H \cdot \underline{x}_{spo} \cdot s$ equation (7) turns into

$$\underline{F}_0 - \underline{v}_{ind} \cdot \underline{Z}_D = \underline{x}_{spo} \cdot s\,(\underline{Z}_D + \underline{Z}_H) \tag{8}$$

Solve equation (8) to $\underline{x}_{spo}$ and relating with equation (4), the result is a description of an arbitrary haptic system with the user as torque source.

$$\underline{K} = -\underline{x}_{spo} \cdot \underline{G}_{FIP} = \frac{\underline{v}_{ind} \cdot \underline{Z}_D - \underline{F}_0}{s\,(\underline{Z}_D + \underline{Z}_H)} \cdot \underline{G}_{FIP} \tag{9}$$

This method implies a direct measurement of the user and haptic display impedance and therefore is discussed later in this work.

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[22] See [19] chapter 4 page 89.

3.2.5. Working Point

The working point is a specified point in the characteristic curve of the system. This point is defined by the characteristic of each haptic system component and external hazards. Two different types exist, the stable and the instable state. Depending on the type of system (electrical or mechanical) a stable working point is defined as quiescent point[23] of the system (electrical) or the point where input and output torque is balanced (mechanical). This is the stable point, the rest of the characteristic curve is instable.

The to be developed haptic display consists of electrical and mechanical components. The electrical working point is not in the point of interest because the haptic display is defined as force output system. Therefore, the mechanical working point is in focus.

In idle mode the haptic device needs a defined output force to compensate the weight of the control element and to control the winding mechanism. On the other hand, the force should be as low as possible to keep the counteracting force lower than the force a user is willing to spend[24]. Additionally, the rotational motion speed is important. With low rotational motion the reaction time to wind up the strings is too slow. Too fast rotation can cause injuries to the user.

3.3. Haptic Display Characteristics

Referring to chapter 2.4.1 the common characteristics of a haptic display are the presentation capability, resolution and ergonomics. The requirements for these three characteristics of the haptic display are described in this chapter.

3.3.1. Presentation Capability

The haptic presentation capability is the most important characteristic of a haptic device. It describes the type of perception, the body parts the device is designed for and the ROM.

The basic functional principle is described in chapter 3.1. Following from this the device to be developed is an active kinaesthesian haptic device. It applies force only to the arm and the hand. The force shall be high enough to simulate the handling of objects, for example mechanical tools. A comparable device, the INCA 6D from Haption, has a continuous output force of 15 N and a maximum output force of 40 N [33].

Also a compensation of the control element's weight is necessary. Without this compensation the control element sticks to the ground when not in use.

Further the device is categorized as *ground-referenced haptic device* (see chapter 2.4.2). These devices create a physical link between user and the mounting point of the device. Here, actuators and controllers are mounted on the floor. This has the advantage of a light weight control element and no component is attached to the user.

As mentioned before, the device should offer a wide ROM. It results on the dimension of the CAVE where the final assembly is planned. This is the minimum required ROM and should not limit the maximum ROM for other installations. Therefore a wide ROM is specified as an area of 2 m × 2.65 m. Summarized the requirements are:

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[23] Normally used in connection with transistors or vacuum tubes.

[24] This force is represented as system impedance described in chapter 3.2.3.

- ♢ Active kinaesthesian haptic device
- ♢ Provide output force on arm and hand
- ♢ Continuous output force of approximately 15 N
- ♢ Minimum ROM of 2 m × 2.65 m
- ♢ Compensate weight of the control element

3.3.2. Resolution

The resolution of a haptic device consists of two properties, spatial and temporal resolution. Spatial resolutions refer to the location of the stimuli. As an example, a device designed for the forearm needs a lower spatial resolution than for a fingertip. However, spatial resolution is dedicated to tactile displays and therefore it is not discussed in this master thesis [3].

Temporally resolution refers to the refresh rate of the device. With a temporal resolution of 50 Hz every two milliseconds the input position and output force is updated. For tactile devices low refresh rates are sufficient. Whereas kinaesthesian devices need a much higher refresh rate, up to 1 kHz, to provide good haptic feeling. Lower refresh rates then 50 Hz may cause vibrations [3].

The refresh rate of the device to be developed should be as high as possible but at least 50 Hz. Therefore, adequate components for data acquisition and processing as well as communication are needed.

3.3.3. Ergonomics

Ergonomics plays a vital role in the design of haptic displays. Force and tactile information are generated and have a close relationship to the user. Kinaesthesian haptic displays often use electric motors, at which the force can cause injuries to the user. Tactile haptic displays on the other side use current or heat to stimulate the user's receptors. For a safe user interaction a careful use of current or heat is necessary. These cases show the strong need of a good safety system of the haptic display [3].

The haptic display to be developed uses electric motors and transmissions to generate motion. High forces are applied to the control element. Therefore, an adequate control mechanism need to be integrated into the controller of the haptic display. Two quantities needs to be controlled:

- ♢ Current
- ♢ Velocity

Current control is needed to protect the device from overheating and a too high output torque. It also provides the user with protection against high forces. Via velocity control the input and output velocity is regulated. Rapid user interaction can damage the system, whereas fast system response can cause injury to the user.

Further, the design of the control element is very important. A poorly designed control element can give the user a distorted haptic feeling. Also, an easy replacement of the control element is desired. A mechanism that easily connects and disconnects the strings from the control element is also necessary.

3.4. Actuator

The main aspect of the actuator is an adequate output force on the control element in order to give the user a good haptic feeling. In the complete assembly the actuator is the major component. Here, electric power is transformed into linear motion, respectively force. An actuator consists of at least two components. The first component transforms electric power into rotary or linear motion. Linear motion can be used without transformation, whereas rotary motion is transformed into linear motion and afterwards transferred to the control element. This is done by the second component, the transmission.

3.4.1. Electrical Motor

As mentioned before, two types of electrical motors exist, linear and rotary motional. The motor is the part of the system that generates the torque of the system. A well dimensioned motor is the basis for a working device. High output torque results in high output force and can cause injuries to the user. Whereas a motor with low torque generation cannot fulfill the requirements for a high output force of the device. Further, motor and transmission need to be aligned to achieve an adequate output force.

Other significant characteristics are type and range of the power supply, operation mode and the motor dimension. For a practical assembly in the CAVE, motor and transmission should be as small as possible. The range and type of the power supply and the operation mode plays a secondary role in this case.

In addition to a straight system design, the motor controller should be a subsystem of the haptic controller. This guarantees an easy replacement of the motor without changing other system parameters or components. Summarized, the demands on the electrical motor are:

- ◊ Adequate torque generation
- ◊ Small dimensions
- ◊ Suitable motor type
- ◊ Separate motor controller

3.4.2. Transmission

Transmission, the second part of the actuator, transforms rotary motion into linear motion and provides a mechanism to wind up the strings. Referring to the previous chapter, transmission and motor need to be aligned. With a given output force and motor torque the gear ratio can be calculated. Thereby maximal output force should be higher then the desired output force on the element to protect the motor from overheating.

Further, quiet operation is necessary for a good immersion. Acoustic interference can reduce the immersion in a VE. Also small dimensions are essential. Summarized the demands on the transmission are:

- ◇ Convenient gear ratio
- ◇ Low noise level
- ◇ Low friction loss
- ◇ Small dimensions

3.4.3. Mechanical Design

The main goal of this master thesis is a working prototype of a haptic device. Therefore a prototype with electrical and mechanical components has to be designed and build. Former chapters described the electrical motor and the transmission. Further, a mechanism to wind up the strings is mentioned. It consist of a spindle with a rollback mechanism. Adequate mountings need to be designed. Moreover, string guides are needed. Without these the strings might get tangled up. In the end construction drawings are made for the production of the components. Summarized the demands for the actuator design are:

- ◇ Plain and rugged build-up
- ◇ String guides
- ◇ Construction drawings

3.4.4. Temperature Control

Every system with electrical and mechanical components, especially transmissions, electrical motors and motor controllers, produces heat. Therefore, considerations about temperature control are essential. The engine power, the time and mode of operation are the relevant facts. As longer the engine runs as more heat it produces. Furthermore, common operation of the system includes workload against the linear motion produced by the actuator. This results in intense load for the system and causes high power consumption of the electric motor. Which in turn involves the motor control unit that provides the current for the electrical motor.

To calculate the need of a temperature control, heat loss and heat flow are compared. With a higher heat loss than flow a temperature control is required. The temperature control can be realized as a stand-alone or subsystem.

3.5. Communication

The haptic display to be developed is a distributed system. It consists of different subsystems, whereas each of them has different tasks to fulfill. Components with different requirements shall work together and communicate on one channel. Constant and fast information exchange is required in order to reach haptic refresh rates up to 1 kHz. Also the possibility to extend the system is essential. Summarized the demands on the communication system are:

- ◇ Compatible to microcontroller- and PC-systems
- ◇ High transfer rate
- ◇ Reliable communication
- ◇ Expandability

3.6. User Interface

The main goal of a user interface is to support the user with relevant information and give him the option of configuration. For a haptic display this means displaying system status and allowing control of the simulation. User interfaces are split into two categories, direct and indirect user interaction. Direct interaction is achieved with the unit itself and indirect with a configuration tool running on a PC.

The haptic display to be developed requires the possibility to start, stop and reset the device. Further, the system status needs to be displayed. In addition to an error-notification display, the user requires an emergency stop to guarantee user safety. Therewith the complete motor system is disconnected from the power supply. Therefore, these essential requirements shall be fulfilled:

- ◇ Start, stop and restart the system
- ◇ Emergency stop
- ◇ Display system status

No properties of the device should be changed. The communication type and speed as well as the number and address of the devices are static. Therefore, no indirect interaction is implemented.

3.7. Use Case

The idea for this master thesis is derived from the needs of a haptic display in a CAVE. The display should be as simple as possible and provide only one degree of freedom. This will allow simple simulations and trainings in a CAVE.

A representative simulation is the sawing of a wooden log. The log, the pruning saw and the area is visualized in a CAVE. The control element represents the pruning saw handle. By moving the control element on the x-axis the saw is moving forwards and backwards. When the saw touches the log a force against the moving direction is applied. This force represents the sawing resistance of the wooden log. Therefore, moving only on one axis is sufficient and only one point is needed where the force has to be applied. Only the moving direction is needed to set the correct force direction.

Another example of a very simple haptic simulation is shown in figure 3.8. Three points are given and connected by two lines. By moving through the coordinate system a defined force at each point on the lines is applied to the user[25].

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[25] This case does not involves the direction of the force.

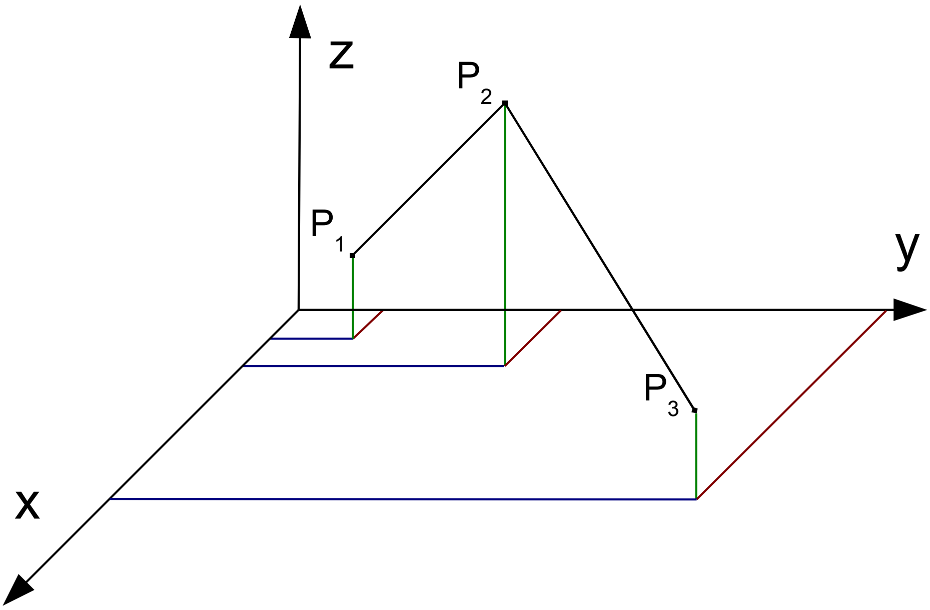

Figure 3.8: *Three-dimensional space*

Transforming this case into an one dimensional (1D) representation gives several positions on the x-axis which cross the lines in the 3D space. Each of them has a defined force value. The example from figure 3.8 is transformed and illustrated in figure 3.9.

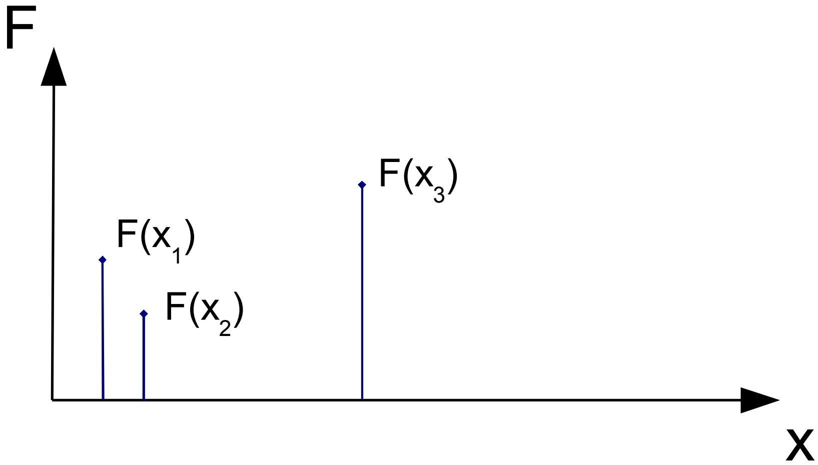

Figure 3.9: *Force at defined x-positions*

Both examples need different points where the force has to be applied. They can be static, time or counter dependent. The sawing example needs a counter in the software which detects the moving of the saw. Each time it reaches the end, the counter is incremented. Depending on the counter values, the force is applied either a bit earlier or later as the wooden log is rather round shaped than squared. Therefore the saw runs in either earlier or later. The second example can be both, time or counter dependent. The time can represent the y- or z-axis. Therefore a 2D space can be realized.

With the final goal of an installation of the haptic device in the CAVE of the MMLab at the HAW, some additional considerations have to be made. Figure 3.10 shows the installation in the CAVE. Therefore, a smooth winding mechanism and a high positioning resolution is important as well as a constant force output. Further, the haptic feeling is described by analyzing the user impression and comparing with the desired impression.

The basic design involves a wide ROM, necessary to act in the CAVE. The projection area of the CAVE in the MMLab has a size of 2 m × 2.65 m and 2 m in height. With the device in his hand the user shall be able to work in almost the entire area. Therefore, the strings need a sufficient length and clearance to wind up on the spindles. In order to reach an adequate height for the control element a bracket on each side is required. String guides force the strings and allow the user to walk freely in the area. In the end an easy and rugged build-up is preferred.

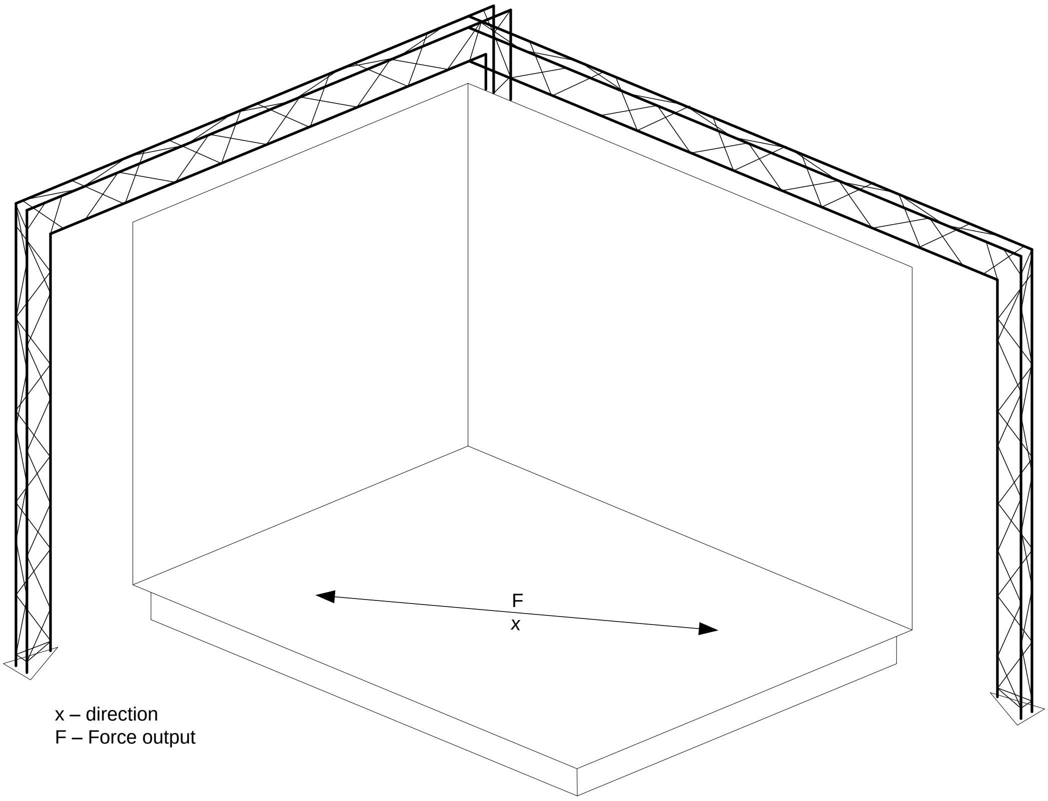

Figure 3.10: *Use case in the CAVE*

Moreover, the design of the control element plays an important role. With a fixed handle the position can only be detected on the x-axis. Moving on the y- or z-axis cannot be detected by the system due to the design of the haptic display. With the aid of a link system a handle can be mounted movable on the control element. This handle can be moved on the x-, y- or z-axis without moving the control element and therefore without changing the force output. With the help of an optical tracking system the position can be determined to allow manipulation in the scene. This is only meant to be a consideration for further work, but is not subject of this master thesis.

Summarized the demands for an assembly in the CAVE are:

- ♢ Sufficient string length
- ♢ Dimensioned spindles
- ♢ String guides
- ♢ Easy, rugged build-up
- ♢ Bracket

4. Technical Analysis

In this chapter the hardware for the haptic device is specified with respect to the requirement analysis from chapter 3. The decision for each component is illustrated and explained in detail. Also test cases are defined within this chapter.

4.1. System Examination

In chapter 3.1 the basic functional principle is defined. Now, with the help of those developed requirements, a more detailed specification is elaborated. Some basic questions have to be answered in the beginning. At the end of this chapter a requirements specification is established. Afterwards, the characteristics of the developed device are compared to the requirements worked out in this chapter.

DOF - The haptic device has to provide the user with horizontal translational DOF. Thereby motion towards the horizontal axis is neither blocked nor compensated by the device. Further, no rotatory DOF is provided by the device at all.

ROM - The ROM provided by the device is an area of approximately 1.8 m × 2.5 m × 1 m with a working angle of 75 ° as shown in figure 4.1. A higher working angle is construction-related not achievable because screens and framework of the CAVE of the MMLab limit the free space for the strings.

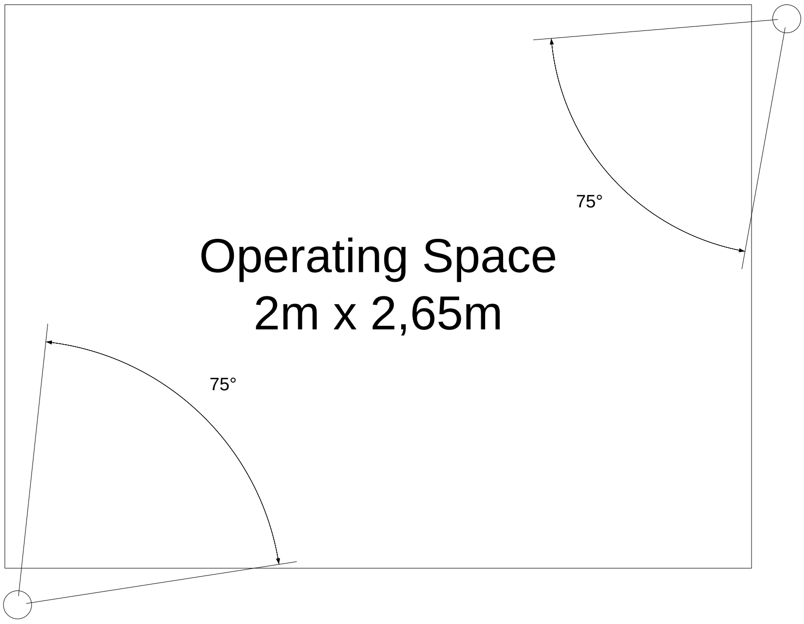

Figure 4.1: *Operating space and angle*

Resolution - As explained in chapter 3.3.2, the temporal resolution should be as high as possible. A minimum of 100 Hz is requested.

Output force - Chapter 3.3.1 brings up the INCA6D as a comparable device. This device has a continuous force output of 15 N and a maximal force output of 40 N. For a good haptic feeling this is the minimum requirement for the device to be developed. On the other hand a minimum output force of 0.5 N is desired. That is used to compensate the weight of the control element.

With above information a full requirements specification for the device is developed in table 4.1. Later in chapter 7 the results of the validation are compared to these requirements.

Type[a]	Description	Dimension	Comment
D	Number of DOF	one	Limitation to one degree of freedom
D	Force reference	Ground referenced	
D	Minimal operating space	1.8 m × 2.5 m×1 m	Specified operating space of the CAVE
R	Maximal operating space	2 m×2.65 m×2 m	Full size of the CAVE
D	Minimal temporal resolution	50 Hz	Refresh rate of the device
D	Minimal cut-off-frequency	static	
D	Maximal velocity of the control element	50 mm/s	Limitation for safety reasons
D	Maximal continuous force output	15 N	Comparable to the INCA6D
R	Maximal continuous force output	20 N	
D	Maximal force output resolution	0.5 N	Maximal output force resolution
R	Maximal force output resolution	0.1 N	Higher accuracy of the force output during simulation
D	Maximal force output	30 N	Maximal force output over a short period, limitation due to safety reasons

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[a] R = request; D = demand

D	Positioning resolution	2 mm	Accuracy of the positioning system
R	Positioning resolution	1 mm	Comparable to a optical tracking system
D	Type of control element	Joystick	

Table 4.1: *Requirements specification*

4.2. Control mode

The structures of common kinaesthesian haptic devices are based on transmission behavior of a mechanical impedance $\underline{Z} = \underline{F}/\underline{v}$. The device generates an output force and receives a position change as input. Systems with such a structure are called *open loop impedance controlled systems*, an illustration is shown in figure 4.2. The force signal $\underline{S}_F$, generated in a PC-system, is converted by a driver $\underline{G}_{ED}$ (haptic controller) and transformed into output force $\underline{F}_0$ by an actuator ($\underline{G}_{D1}$). This force is superimposed by a noise signal $\underline{F}_{noise}$, generated by the user interaction $\underline{X}_{out}$ and produced by the mechanical properties $\underline{G}_{D3}$[26]. The sum of both ($\underline{F}_0$ and $\underline{F}_{out}$) is the output force $\underline{F}_{out}$. Further, a motion sensor $\underline{G}_{D2}$ generates the position input signal $\underline{S}_x$.

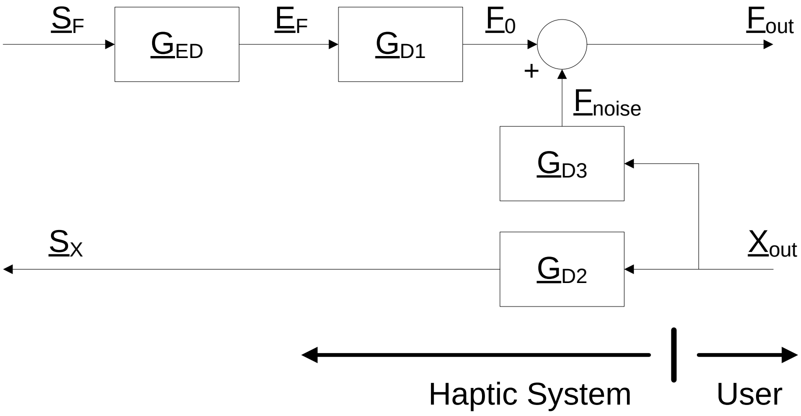

Figure 4.2: *Open loop impedance controlled circuit (based on [19])*

As explained open loop impedance controlled systems only need the position as input. As no control and regulation of the output force $\underline{F}_{out}$ is done, no force sensors are involved in the controlling. Therefore, the system is relative simple and cost effective.

The advantage for the development of the haptic device is a simple control mode with only position detection. This is commonly done by sensors in the electrical motor. Therefore, no additional sensors are needed for this design.

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[26] Mechanical properties are mass inertia and friction of the device.

4.3. Haptic Controller

As illustrated in figure 3.2, the haptic controller controls component communication between PC-system and output devices (actuators). Therefore, a sufficient processing speed of the microcontroller used for the haptic controller is necessary. Also components for the communication or the possibility to connect these are needed. Hence, an adequate design of the PCB for the controller is essential. Further, different peripherals for input and output are required, such as a LCD to set state messages and push-buttons for user input.

To fulfill all these requirements during the development process, a working and proved development board is a good choice. Afterwards, a new PCB can be designed with only the peripherals that are required.

4.3.1. Development Board

The haptic controller is based on a development board from Laser & Co. Solutions GmbH and called MK3. The advantage of a development board is that no hardware needs to be designed during the development process. Moreover, many different hardware components are usable on this development board. If the design changes, for instance if another communication standard is used, other components on the board can be used or external modules can be easily connected. This saves a lot of development time and costs. The MK3 board offers the following peripherals [14]:

- Microprocessor mounted as a plug-on module
- Communication interfaces: UART, Two-Wire Interface (TWI), Serial Peripheral Interface (SPI) and USB
- Output devices: one graphical LCD (64 × 128 pixel), eleven Light-Emitting Diodes (LEDs), one speaker, one 7-segment-display
- Input devices: three buttons, one joystick, eight Dual in-line package (DIP) switches, three analog inputs, one photo sensor
- Every GPIO is brought out to a socket
- Power supply over USB or external power supply
- Programmable through integrated USB programmer

On the MK3 the microprocessor is mounted with a plug-on module that has several advantages and is illustrated in the following chapter. The user interface is described in chapter 4.7 and the functionality of the used input and output devices are explained. Further, chapter 4.6 deals with the communication system and explains the used interface.

4.3.2. Microcontroller

The microcontroller is developed by ATMEL and called ATmega 2560. This type of microcontroller is an 8-bit high performance, low power consumption megaAVR with performance approaching 1 MIPS per Megahertz (MHz) at a maximum of 16 MHz. The high amount of memory and several peripherals are the advantages [6].

The microcontroller is mounted on a plug-on board called *Stamp 256 PLUS*. The advantage of a plug-on board is that in case of a damaged microprocessor only the plug-on board needs to be replaced. Also an easy system integration can be done by using a custom baseboard. The Stamp 256 PLUS offers the following properties [15]:

- ◇ Microprocessor: ATmega 2560
    - 16 MHz
    - 256 Kb FLASH
    - 8 Kb SRAM
    - 4 Kb EEPROM
- ◇ Micro Secure Digital (SD) card slot
- ◇ Mini USB port
- ◇ In-System-Programmer (ISP) and JTAG interface

In addition to the already mentioned advantages the Stamp 256 PLUS offers also a mini USB port and a micro SD card slot. With the additional USB interface a debug interface is realized. Relevant state information and debug messages, only visible for the developer, are sent without interfering the bus communication. The micro SD card slot can be used to store state, debug and error messages, configuration files as well as operating hours of the haptic device. Afterwards, the data can be analyzed on a standard PC and be used for further development of the device.

4.4. Actuator

4.4.1. Electrical Motor

The electrical motor is the component that generates the torque. Therefore, it is the most important component and several considerations for the selection have to be done. First of all, the type of motion the electrical motor generates is selected. Linear or rotary motion motors are available. Linear motion motors have the benefit of a direct power transmission, but on the other hand the range of operation is highly limited. With a rotary motor the range of operation is unlimited. However, it needs a transformer from rotary to linear motion. Because of the limitation of the operation range by a linear motion motor a rotary motion motor is selected.

Secondly, the type of electrical motor is chosen. Two different types are available, AC and DC motors. They differ mainly in their application field resulting from their type of energy conversion and the electric power supply. Moreover, the motor control unit differs from type to type. AC motors are often used for simple control tasks in a rough environment, especially unregulated three phase AC motors with a delta-wye switch. DC motors on the other hand are often applied in small devices like computer equipment or toys. The less dangerous voltage level and the possibility to operate from accumulators without special voltage conversion approve their application in commercial devices.

For the haptic device a block commutated three phase BLDC motor from QMOT has been selected.[27] BLDC motors are commonly used and very popular in similar applications. As the demand for these motors is huge and the supply is big as well, the controller units and motors are easy to obtain. Further relevant characteristics are the safety-low voltage of 24 V, the high continuous output torque of 0.125 Nm and the small dimensions of 42 mm×42 mm×61 mm [21].

The controller unit is a general BLDC motor controller module (TMCM-160) from TRINAMIC Motion Control GmbH & Co. KG. Its small form factor allows the integration as a plug-on module on the haptic controller or the installation in the actuator close to the electrical motor with a baseboard (BB-160). The basic functionalities are torque and velocity control and a hall sensor based positioning mode. With the selected motor the positioning mode has a resolution of 15 °.[28] The module can be remote controlled via EIA RS-232 or EIA RS-485 [22].

4.4.2. Transmission

In previous chapter, it was explained in detail which type of electrical motor is used. Besides the electrical motor, the transmission is the second component of the actuator. Here, the rotary motion is transferred to the spindle and transformed into linear motion. Also, the linear motion generated by the user is transformed into rotary motion and then converted into linear coordinates.

Three main conditions of the transmission are set. First of all, quiet operation is needed. This also involves low friction loss. Hence, the best choice is a belt transmission. The belt consists of rubber with steel straps inside. With mounted belt pulleys a quiet operation and a low friction loss power transmission is achieved. Their only disadvantage is the wearing-out. This is based on their construction and can be compensated by a retighten mechanism.

Further, the belt pulleys are exchangeable and therefore a belt transmission provides a variable gear ratio. This allows to align the system afterwards and enables a flexible configuration of the device. The formula for the gear ratio in conjunction with the number of teeth is

$$i = \frac{z_{output}}{z_{drive}} \tag{10}$$

The number of teeth for the belt pulley mounted to the electrical motor is z_{drive}. Therefore, a gear ratio higher than one is needed to enhance the output force.

Finally, a high resolution for the detection of the user's position is needed. This can be done by increasing the rotating speed at the electrical motor. A higher rotating speed refers to more sensor impulses per spindle revolution. More impulses refer to a higher resolution. Hence, the angular frequency ω needs to be calculated. It is defined as

$$\omega = 2 \cdot \pi \cdot f \tag{11}$$

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[27] For detailed specification see the data sheet of the motor - QMOT QBL4208-61-04-013 [21].

[28] Standard eight pole motor with 120 ° hall effect angle.

Here f is equatable to the rotating speed n, which is calculated through the formula for the gear ratio in conjunction to the rotating speed.

$$i = \frac{n_{drive}}{n_{output}} \tag{12}$$

Formula 12 solved to ${n_{drive}}^{29}$ and relating with equation 11 results in a formula for the angular frequency in conjunction with the gear ratio.

$$\omega = 2 \cdot \pi \cdot (n_{output} \cdot i) \tag{13}$$

The outcome of equation 13 is that the gear ratio i refers to a multiple higher rotating speed n_{output} of the motor. This increased rotating speed results in a higher resolution for the position detection. The resolution is higher with the factor i.

A gear ratio of $i = 3$ is selected for the device to be developed. The belt pulley on the motor shaft has 10 teeth, whereas the belt pulley on the spindle shaft has 30 teeth. With respect to chapter 4.4.1 a torque on the spindle shaft which is three times higher than before $(0,125\,\mathrm{Nm} \cdot 3 = 0,375\,\mathrm{Nm})$ is achieved. The resolution of the position detection is now 5 ° instead of 15 °.

4.4.3. Mechanical Design

Different mechanical components are needed for the actuator design. A plain design and a rugged assembly are the main considerations. The motor, transmission and spindle dimensions are important factors for the design. Additionally, the space between motor and spindle has to be adjustable in order to be able to stretch the toothed belt (chapter 4.4.2).

This results in two independent mountings, one for the motor and one for the spindle. The motor mounting is made up of an unequal leg angle steel profile where one bracket is mounted to the ground and the other one provides drill-holes for motor shaft and mounting screws.

The spindle mounting consists of two unequal leg angle steel profiles assembled as u-shape. One side of each is mounted to the ground and the other provides drill-holes for the spindle shaft and the bearing bracket. The spindle shaft is mounted with ball bearings between the brackets. Adequate ball bearings have an inner diameter of 8 mm. The diameter of the spindle shaft is equal to the inner diameter of the ball bearings. This assembly is as simple but also as functional as possible.

The spindle design is more complicated. Different requirements have to be fulfilled. First of all, a lightweight design is essential. This can be achieved by using aluminum as base material. Further, a sufficient spindle dimension is required to wind up the string and the spindle shaft should not exceed a length of 10 cm. For a high force output the spindle diameter should be as small as possible.

With the selected spindle shaft diameter of 8 mm the minimum spindle diameter is 10 mm. For the assembly a diameter of 12 mm is selected. Hence, the circumference of the spindle is

$$c = 2 \cdot \pi \cdot r = 2 \cdot \pi \cdot 6\,\mathrm{mm} = 37.699\,\mathrm{mm} \tag{14}$$

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[29] In this case the rotating speed n_{drive} refers to the user interaction.

Ball bearings have an average width of 10 mm, the belt pulley a width of 22 mm. With some additional space between spindle and ball bearings, a maximal length of 40 mm (l_{sp}) for the spindle is achievable. The maximal assumable string diameter (d_{st}) is 1 mm. Herewith the string length for one wrapping (l_w) is

$$l_w = c \cdot \frac{l_{sp}}{d_{st}} = 150.796\,\mathrm{cm} \tag{15}$$

To achieve an operating space of 1.8 m×2.5 m in the CAVE, 3 m have to be winded up (l_{work}) on each spindle. With a maximal string diameter of 1 mm and a length for one wrapping of l_w, the wrapping height (h_{wc}) is

$$h_{wc} = \frac{l_{work}}{l_w} \cdot d_{st} = 2\,\mathrm{mm} \tag{16}$$

With 10 mm spindle height the dimension of the spindle is sufficient. This calculation disregards the string diameter on the circumference calculation because the dimension of the spindle is compared to the maximal requirements of the device. By adding the string diameter to each wrapping the circumference is enhanced and the wrapping height is reduced resulting in an insufficient calculation.

The detailed construction drawings of the motor and spindle mounting, the spindle and the full assembly can be found on the CD, chapter A.

4.4.4. Force Output

As illustrated before, the force output of the system is dependent on the torque output of the electrical motor M_0, the gear ratio i and the length of lever arm l. With respect to the device design, the length of lever arm is the radius of the spindle ($l_{rspindle}$). Consequently, the output force of the system is defined as

$$F = \frac{M_0 \cdot i}{l_{rspindle}} \tag{17}$$

The length of lever arm should be as small as possible to achieve a high output force. The former section describes the mechanical design. The minimal diameter of 12 mm for the spindle is developed. With a rated output torque from the electrical motor (chapter 4.4.1) and the gear ratio from the transmission (chapter 4.4.2) the maximal continuous output force is

$$F = \frac{0.125\,\mathrm{Nm} \cdot 3}{6\,\mathrm{mm}} = 62,5\,\mathrm{N} \tag{18}$$

By changing the position and the following winding the diameter is changed from a minimum of 6 mm (spindle radius) to a maximum of 7 mm (spindle radius plus string layer). As a result a minimal continuous output force can be calculated.

$$F = \frac{0.125\,\mathrm{Nm} \cdot 3}{7\,\mathrm{mm}} = 53.571\,\mathrm{N} \tag{19}$$

Compared to the requirements in chapter 3.3.1, the continuous output force is sufficient. Due to the difference between minimal and maximal length of lever arm, an effective control mechanism for the output torque of the electrical motor is required in order to achieve a constant output force.

4.5. Surveillance

The system consists of different components which produce heat, force and motion. Therefore, adequate control mechanisms are implemented in the haptic or motor controller.

4.5.1. Current Control

Current control is done in each of the motor controller units. The maximal motor current is configured via EIA RS-485 and regulated through the output driver.[30] Further, every power supply (for the development board and the motor control units) has its own current regulation in form of a fuse. Therefore, no other current control is implemented in the haptic controller.

4.5.2. Temperature Control

Mechanical and electrical systems produce heat. Depending on the heat generation of each component, passive or active temperature control is needed. The former chapter described the output force generated by the system. According to this the electrical motor runs only with fifty percent of the rated torque. Therefore, an active temperature control is unnecessary. Further, a belt transmission is used that does not need any temperature control at all. In spite of that, the temperature of the electrical motor is measured and in case of an overheating the device is shutting-down immediately.

4.5.3. Velocity Control

Chapter 3.3.3 explained the need of a velocity control. In chapter 4.1 the maximal velocity of the control element was defined as 50 mm/s. In order to achieve this the position change per second is measured in the haptic controller. In case of a velocity higher than this threshold, an emergency shutdown is immediately performed by the haptic controller.

4.6. Communication

For a communication between different subsystems various communication standards are available. Each standard has its advantages and disadvantages. The major demands on the communication system for the haptic device are: high transfer rates, reliability and expandability.

Expandable communication systems are typically designed as a serial bus system. Instead of a point to point communication a bus system is a multiuser communication where every user has a unique bus address. All users use the same communication wires and process the data simultaneously. Two different types exist, the master-slave and the multi-master principle. The first one is the conventional system. Here one bus member is the master, the others are slaves. The master starts the communication and the addressed slave responds. The disadvantage of the master-slave principle is that only the master can initiate the data transfer. Although multi-master systems do exist, the complex communication control makes them impracticable for most applications.

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[30] See [22] for a detailed block diagram.

The data exchange on a bus system differs from a point to point system. The data is included in a communication protocol. Depending on the communication standard, a protocol interpreter is given in hardware or has to be implemented in software. At least the address of the sender and receiver is part of the protocol. Common protocols also involve some kind of error correction. This additional data is called data overhead. The transfer rate has to be sufficiently high to compensate this. For a bus system it might be interesting to know the maximal protocol rate f_{Pmax}. It can be described as

$$f_{Pmax} = \frac{BAUD}{P_{length}} \tag{20}$$

BAUD is the bit rate of the communication system and P_{length} the protocol length[31].

The BLDC motor controller module (TMCM-160) works with a standard EIA RS-485 transmitter/receiver. The maximal practicable bit rate is 115.2 kbps. The protocol used with the TMCM-160 has nine byte protocol length.

$$f_{Pmax} = \frac{115200\,\mathrm{bps}}{9\,\mathrm{byte}} = 1600\,\mathrm{Hz} \tag{21}$$

A maximal protocol rate of 1600 Hz for the communication system is reached. At first view, the protocol rate in the example seems to be more than sufficient for the haptic device. On closer examination of the requirements it is obvious that a temporal resolution of 1 Hz involves at least six data transmissions. With the protocol rate in the example a temporal resolution of approximately 266 Hz is possible.

Despite an insufficient transfer rate the EIA RS-485 bus with common master-slave operation was selected. The high flexibility, the reliable communication and the easy use of this communication standard prevail. Also the already existing communication system on the TMCM-160 is an important factor for the EIA RS-485 bus.

A bus structure for the device to be developed is illustrated in figure 4.3. The controller and the PC system are suited at the top and the motor controllers at the bottom. The address range is from *1* (controller) to *n*, whereas the EIA RS-485 bus has in general 32 as maximum 256 users.

The haptic controller uses the internal UART with an EIA RS-485 converter on a separate PCB[32] to connect to the bus. The PC-system connects via a USB to EIA RS-485 converter [33] to the bus. The motor control units use the integrated EIA RS-485 converter.

4.7. User Interface

The controller board, selected in chapter 4.3, provides one graphical LCD, a 7-segment-display, a speaker, eight DIP-switches, three push-buttons switches and one joystick. Further, every GPIO is present as external socket and allows to connect external hardware.

The design requires at least four push-buttons: three to control the simulation (start, stop and restart), suited on the board and one external button, connected to the GPIO and mounted close

---

[31] The protocol length consist of overhead and data.

[32] Schematic and layout of the communication PCB can be found on the CD (see chapter A).

[33] USB-2-485 Interface Converter from TRINAMIC Motion Control GmbH & Co. KG [24]

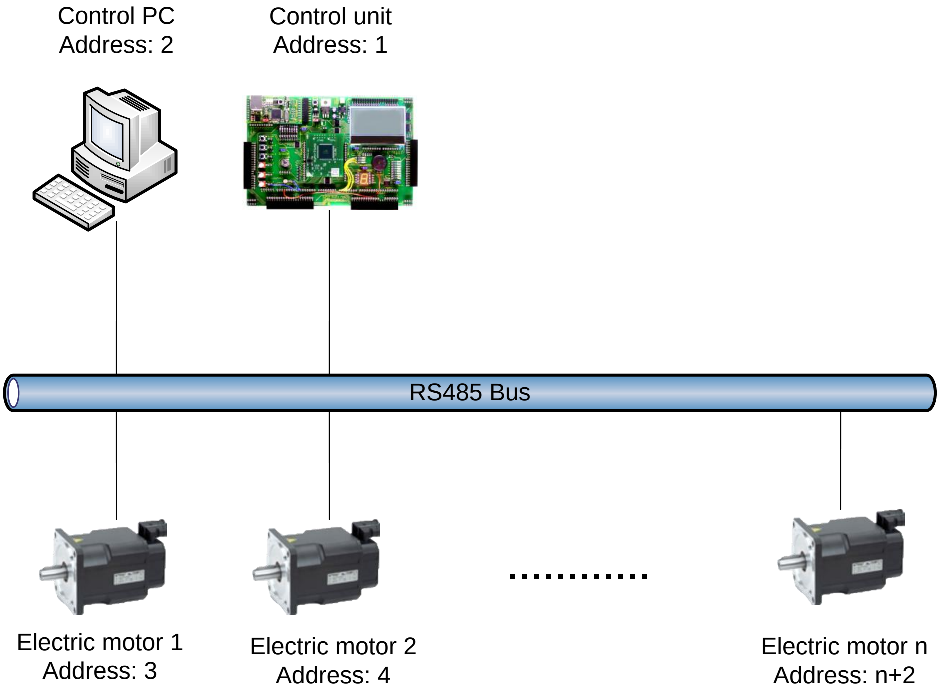

Figure 4.3: *Communication bus structure*

to the workspace of the device, as an emergency stop. Further, attention should be paid to the bounce behavior of the buttons. Adequate debounce mechanisms have to be developed. The graphical LCD is used to display the system state.

Moreover, the joystick can be used to skip through the system state information, the DIP-switches to configure the number of users on the communication bus and the speaker to generate an acoustic signal in case of an error. These considerations are additional and not part of the work. They might be implemented but they are not necessary for a working design.

4.8. Assembly in the CAVE

To achieve an installation in the CAVE, at least two actuators, two brackets, strings and one control element is needed. The design of the actuator was developed in previous chapters. The assembly in the CAVE is shown in figure 4.4. The brackets are mounted to the floor between framework and screen. On each side approximately 0.5 m free space is given, which is sufficient space for the assembly. On each bracket an actuator is mounted. To the top of the bracket some kind of string guide is attached, preferable a deflector roll. The strings are fixed to the actuator, routed by the string guides and tightened to the control element.

In the first assembly the control element is a handle connected on both sides to the strings. Further simulations may have different requirements on the control element. Therefore, a mechanism for an easy replacement of the control element is used (figure 4.5). This component is called *snap swivel* and may be known from fishing. The ring on the left is tightened with a *Grinner* knot to the string of the actuator. The snap fit on the other side is used to fix the control

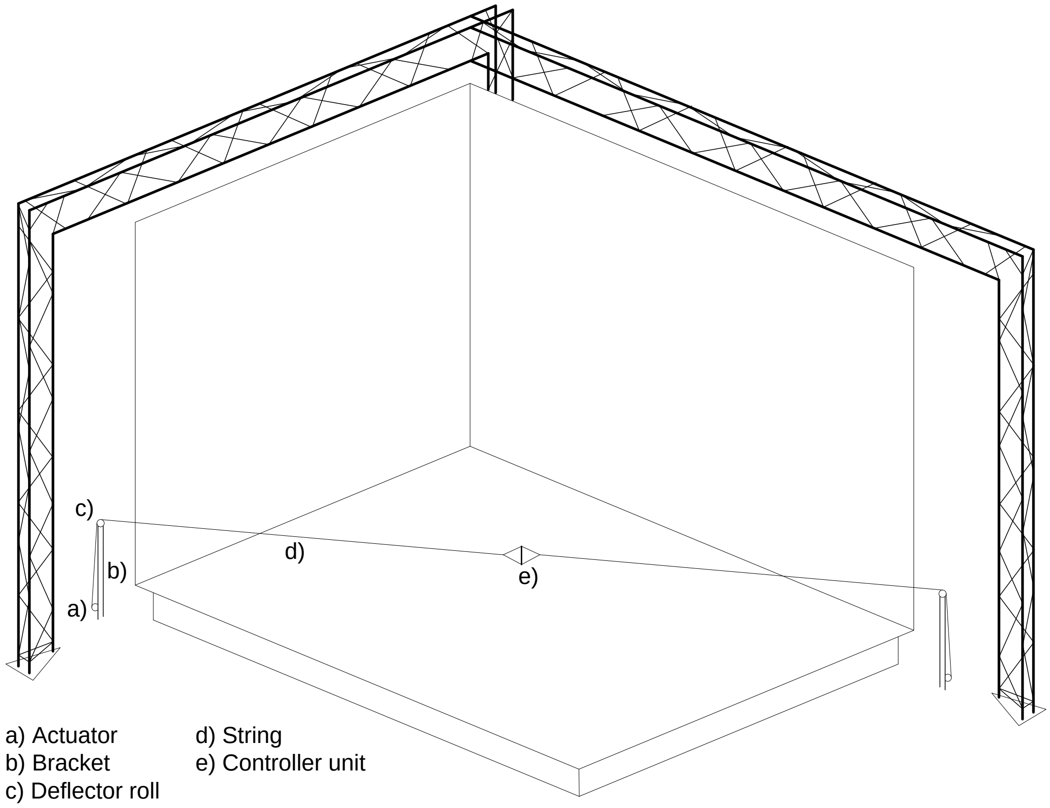

Figure 4.4: *Assembly in the CAVE*

element. Additionally, the pivot in the middle prevents an undesirable tangling.

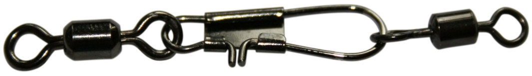

Figure 4.5: *Fastening for the control element (snap swivel)*

During the test phase strings persist of nylon with a diameter of 0.25 mm. For testing and small simulations their bearing force of 7 kg is sufficient. To guarantee user safety, the nylon strings are replaced by copolymer strings with a diameter of 0.4 mm and a bearing force of 12 kg. These strings are also colored in yellow for a better visibility in the CAVE.

4.9. Test Cases

Every system implementation needs to be tested for correct and secure behavior. A test case is a set of conditions under which the system is tested and analyzed whether it works correctly or not. Therefore, different test cases are defined for electrical and mechanical components of the device.

4.9.1. Power Consumption

The first test case is the measurement of the power consumption of each component of the device. This is important to guarantee user's safety and a high life cycle for each component. Further, significant specifications are indispensable for an electronic device and have to be verified.

The system involves three components: the haptic controller, the actuator and a standard PC. The PC is not analyzed as it is already tested from the manufacturer. The other components are tested by adding a current measurement device between power supply and component. A special firmware is written for the haptic controller where every component operates at full capacity to achieve a maximal power consumption. Further, the development board provides two different types of power supply: external power supply and powering over USB, which both have to be tested. Therefore, two different measurements are necessary. One with 5 V for USB powering and the other one with a voltage from 9 V up to 12 V for powering over an external power supply. With a power consumption below 100 mA the device can be specified as a low power USB device with the benefit of a safe usage with every USB controller.

The actuator is tested under three conditions: First, in idle mode with only the motor controller unit as load, secondly, with the minimal continuous torque and last with the maximal torque of the motor. This data is necessary to provide enough power for the system.

4.9.2. Range Of Motion

The ROM is tested by walking through the defined area. An interference free user interaction must be provided by the device. The winding has to be done smoothly with the strings directed from the string guides. Also the working area has to be barrier free. The most important direction is straight between the actuators in line of the force.

4.9.3. Positioning Resolution

The resolution of the positioning is tested by moving the control element over a defined distance. Measuring the distance and comparing it to the position data form the haptic controller gives an overview of the positioning resolution of the device. This measurement is done at different positions in the working space. The resolution might vary because the circumference of the spindle is changing.[34]

4.9.4. Output Force

The output force is tested with a common force meter. Therefore, one actuator is connected to the force meter and runs with defined torque, respective force. The result is compared to the expected force. Furthermore, the force is measured on different positions to analyze the output behavior of the device.

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[34] Chapter 4.4.3 illustrates the problem with the changing circumstance of the spindle.

4.9.5. Simulation

To complete the test phase two different simulations are defined. They are part of a standard simulation which runs in the CAVE. For each one an appropriate simulation routine is developed.

Arithmetically Increasing Force Output The force which is applied by extending a spring is called spring load. This force is increasing arithmetically to the distance x(see figure 4.6). It starts on a defined position with the minimal force of the device. At the end the maximal force of the device is applied to the control element.

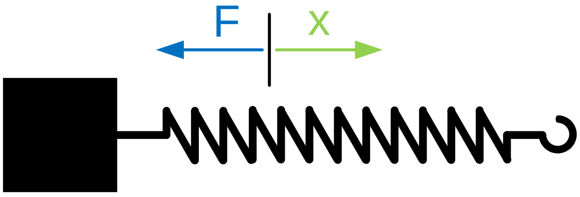

Figure 4.6: *Test case: Arithmetically increasing force output*

Abrupt Force Output The second test routine deals with a fulminating force. On a defined position a high defined force is applied to the control element (see figure 4.7). In reality this can be a hard object like a wall or the door of a car.

Figure 4.7: *Test case: Abrupt force output*

Time Dependent Abrupt Force Output The last test routine is based on the former routine enhanced with the parameter *time*. It changes frequently the position of the force output between two defined positions. This time dependent behavior can be interpreted as a second axis (see chapter 3.7).

5. System Design and Implementation

In this chapter previously acquired knowledge is formed into a specific design. Hardware and software are designed and developed. The decisions made during the development process are illustrated.

5.1. System Design

The system design starts with the analysis of the requirements and the definition of a covenant design, which is already done in chapter 3 and specified in chapter 4. This information helps to develop a specified block diagram of the system. In a block diagram each component is represented by a block and each block fulfills a specified task. The block diagram of the haptic device to be developed is shown in figure 5.1.

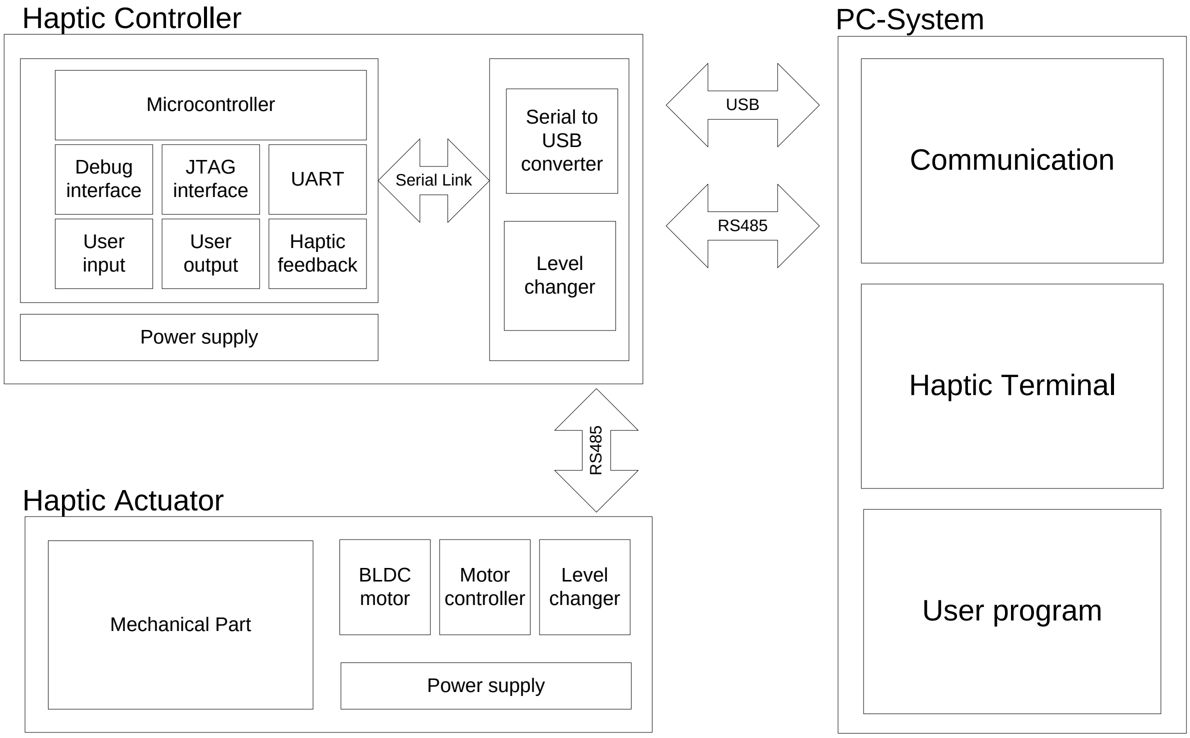

Figure 5.1: *System block diagram*

The haptic controller consists of three different blocks. The first one is the controller logic which consists of a microcontroller with different interfaces (debug, JTAG, UART and user input[35]) and logic components (user output and haptic feedback). Further, the communication interface is connected with a serial link to the microcontroller. It converts the serial signal into the required signal (USB and EIA RS-485). The last component is the power supply, which is in this case an external power supply unit.

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[35] User input involves the buttons on the board and the external button connected to the special PCB.

The second block, the haptic actuator, consists of five components: the level changer for the EIA RS-485 bus, the motor controller, the BLDC motor, the power supply and the mechanical part with the transmission, spindle and control element. For the high current consumption of these components a laboratory power supply is selected.

The last block is the PC-system. This component includes the communication interfaces (USB and EIA RS-485), the haptic terminal and the user program. The latter is the software which computes and displays the haptic and visual data.

Therefore, the haptic display to be developed needs at least the following components:

- ◇ One haptic controller
- ◇ One PC-system with a user program running that computes the haptic representation
- ◇ Two haptic actuators

5.2. Haptic Controller Firmware

The firmware for the haptic controller is written in *C* and developed in the *AVR Studio*.[36] Like the system design every software and firmware development starts with analyzing the needs of the system and defining a covenant design (requirements analysis). Components with shared resources are identified and centralized. Hence, a flowchart is developed and the actual development process begins. A project is created and the source code is written.

Nowadays, the requirements for the programmer have changed extremely. Modern computers are powerful and memory is less expensive. Further, current compilers optimize code better than a skilled programmer. Therefore, saving memory and computing time is no longer the prime importance. Creating applications which are easy to validate, maintain and as general and flexible as possible[37] are the main aspects in software engineering today. Further, the *Modularity Programming Paradigm* forces the programmer to split the program into appropriate small subprograms that perform a well defined task. However, too many subprograms raise the execution time to an inappropriate level because of too many procedure calls [5].

The flowchart for the haptic controller is depicted in figure 5.2. The program starts with the initialization of each component. This includes the setting of internal register for GPIO, UART, timer and interrupts as well as initialization of external components like the graphical LCD and the SD card. Further, the EIA RS-485 bus is scanned for connected users, a connection is established to each and they are verified. If the system passes each test, the system state will be set to "true" otherwise it will be set to "false".

After the initializing process the main routine starts with a request for the internal button state. The buttons perform *start, stop and reset* of the haptic device. The reset performs a reinitializing process which may be necessary in case one of the users was not connected or ready in the first case. Next, the system state is determined. If the system state is "false", the system cycle will be interrupted and start with the request for the button state. This continues until the system state is "true".

---

[36] Integrated Development Environment (IDE) from Atmel for the AVR microcontroller family.

[37] This makes the code reusable.

If the system state is "true" it will continue with a request for the emergency button state. This button starts or stops the simulation immediately. The state is determined by an external interrupt source. By touching the button an interrupt is triggered and a global flag is set.

The last inquiry deals with the simulation state and the sampling time. When the simulation is stopped it breaks and jumps back to the beginning of the main loop. If the simulation is running and the sampling interval is expired, the motor position will be determined and the velocity will be checked with the position information from the last sample. If it exceeds the velocity threshold the simulation will be stopped immediately. Otherwise the data is routed to the PC software where a reply with the actual haptic information is computed and sent back. Then the actual and the previous haptic information are compared. If they differ, the new settings will be sent to the motor control units. Afterwards, the program continues at the beginning of the main loop.

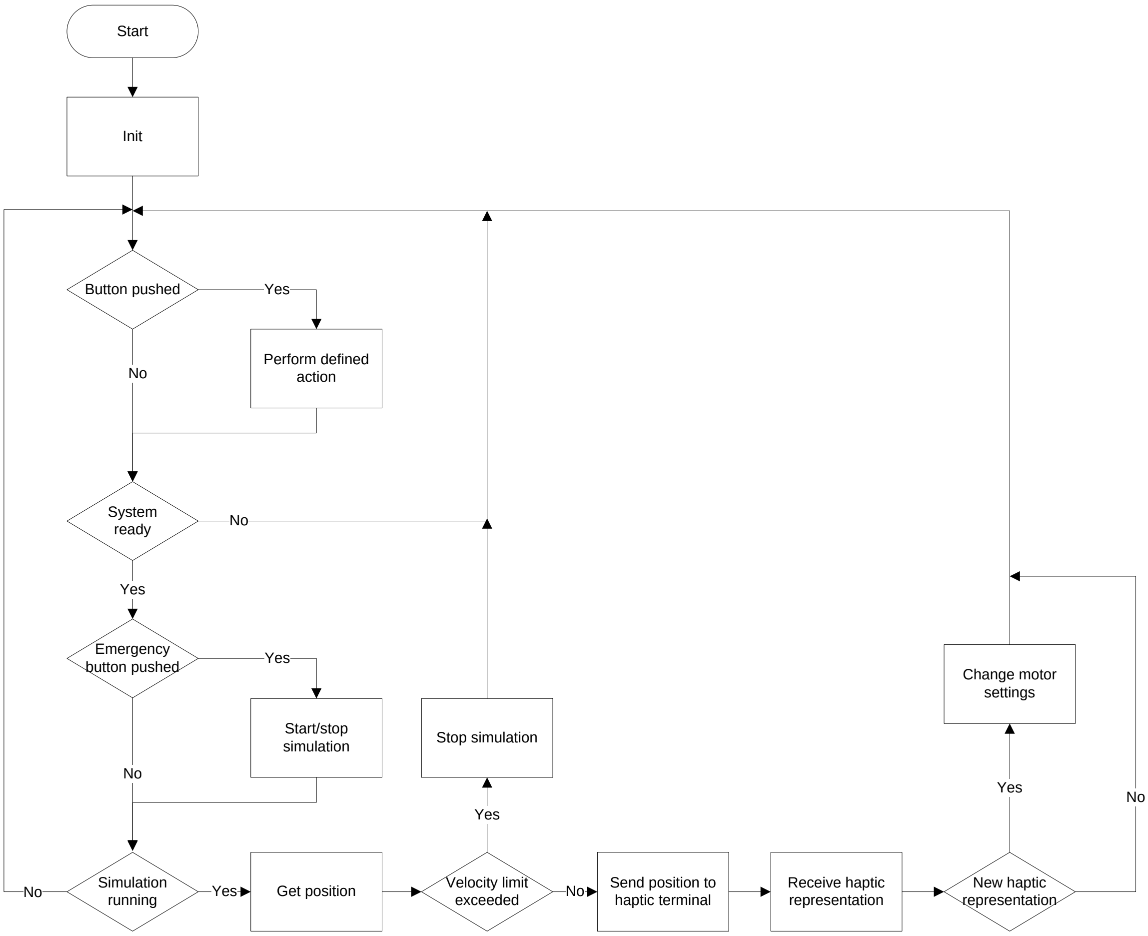

Figure 5.2: *Flowchart haptic controller*

The sampling interval is measured with an internal timer interrupt. When this interrupt is triggered, a global flag is set for the expired sampling time. The sampling interval can be easily adjusted by changing the timer frequency. During the test phase the sampling interval is set to

1 Hz. For normal operations the interval is increased stepwise until the performance limit of the EIA RS-485 bus is reached.

5.2.1. Interface Protocol

The communication between haptic controller, haptic terminal and motor control units uses the TMCL 9 byte protocol from TRINAMIC [23]. The data packages of master (command bytes) and slave (reply bytes) differ.

Command Byte Assignment An overview of the command bytes is illustrated in table 5.1. The first byte always represents the bus address of the receiver. The following three bytes (byte 1-3) are reserved for instructions with optional parameters stored in byte 4-7. The last byte is the check sum of the complete datagram.

Byte	Comment
BYTE[0]	Module address
BYTE[1]	Command byte / Instruction number
BYTE[2]	Type byte (e.g. parameter number)
BYTE[3]	Axis byte (always set to zero for a one axis module)
BYTE[4]	optional parameter (MSB)
BYTE[5]	optional parameter
BYTE[6]	optional parameter
BYTE[7]	optional parameter (LSB)
BYTE[8]	Check sum (1 byte sum of the complete datagram)

Table 5.1: *Command bytes of the interface protocol [23]*

Reply Byte Assignment An overview of the reply bytes is given in table 5.2. Compared to the command data package, the reply data package starts with the host address followed by the module address. The next two bytes represent the actual status and the last received command byte from the host.[38] Followed by four reply bytes, containing the response of former instruction, it also ends with a check sum.

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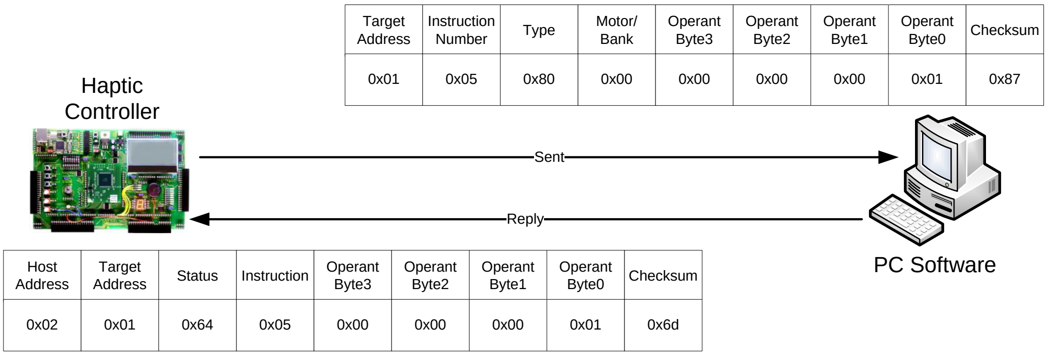
[38] This allows to allocate the reply at the host.

Byte	Comment
BYTE[0]	Host address
BYTE[1]	Module Address
BYTE[2]	Status
BYTE[3]	Last command byte which was received by the module
BYTE[4]	Reply (MSB)
BYTE[5]	Reply
BYTE[6]	Reply
BYTE[7]	Reply (LSB)
BYTE[8]	Check sum (1 byte sum of the complete datagram)

Table 5.2: *Reply bytes of the interface protocol [23]*

An example of a simple transmission is shown in figure 5.3. The haptic controller activates the remote control for the PC software. The device replies with its state information instead of the normal reply defined in the TMCM protocol.



Target Address	Instruction Number	Type	Motor/ Bank	Operant Byte3	Operant Byte2	Operant Byte1	Operant Byte0	Checksum
0x01	0x05	0x80	0x00	0x00	0x00	0x00	0x01	0x87

Host Address	Target Address	Status	Instruction	Operant Byte3	Operant Byte2	Operant Byte1	Operant Byte0	Checksum
0x02	0x01	0x64	0x05	0x00	0x00	0x00	0x01	0x6d

Figure 5.3: *Communication example between PC and haptic controller*

Additional Features Besides the operations described in the manual [23], extra features for the communication with the PC software are implemented. The interface protocol is retained and few commands are modified. These commands are shown in table 5.3.

Command	Comment
5	Get state of the PC software
6	Send position, reply with force information in reply[4-7]
136	Get version number of the haptic terminal

Table 5.3: *Modified communication command list*

5.2.2. Velocity Control

To guarantee user safety some safety circuits and mechanisms are implemented (see chapter 4.5). Current control is realized in the hardware. In contrast, velocity control is realized in the software. The position change between two measurements is compared. In case of an exceeding of the velocity limit the simulation is stopped immediately. The corresponding flow chart is displayed in figure 5.4.

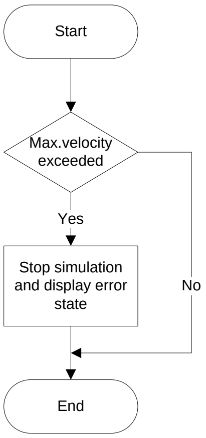


Figure 5.4: *Flowchart of the velocity control*

With equation (14) the circumstance c of the spindle is calculated. Further, the standard motor axis resolution of motor controller unit combined with BLDC motor is 15 °. The positioning resolution is denoted as integer value in the microcontroller. The distance for each integer value can be calculated by using the following formula

$$l_{xdegree} = \frac{15\,^{\circ} \cdot c}{360\,^{\circ}} = 1.571\,\mathrm{mm} \tag{22}$$

With the transmission ratio of three (see chapter 4.4.2) the distance is reduced to 0.524 mm. The maximal permitted velocity of the device is 50 mm/s (see table 4.1 on page 37). With an interim temporal resolution of 10 Hz of the haptic device the distance between two samples is

$$l_{sample} = \frac{50\,\mathrm{mm/s}}{10\,\mathrm{Hz}} = 5\,\mathrm{mm} \tag{23}$$

Therefore, the position value can be decreased by ten during one sample period. By exceeding this value the haptic device is switched off immediately.

5.2.3. Debounce

Besides the actual information processing one routine is running in the background. The routine is used to debounce the single-throw switches on the development board. This is necessary because every single-throw switch bounces with an own *internal frequency*. Depending on the button style the duration of bounce is between a few microseconds up to 20 ms. The ones mounted on the development board are micro single-throw switches which have an average duration of bounce below 1 ms.

The routine used for this job is from Peter Danneger.[39] The used interrupt is the overflow interrupt from the 16 bit timer/counter 5 of the microcontroller with a release time of 1 ms. The working principle of this routine is a simple 2 bit counter for each controlled input pin. This counter is realized through two 8 bit variables (ct0 and ct1) shown in figure 5.5.

	Joy pressed	Joy left	Joy down	Joy right	Joy up	Button 3	Button 2	Button 1
ct1 (bit7:0)	Bit 1	Bit 1	Bit 1	Bit 1	Bit 1	Bit 1	Bit 1	Bit 1
ct0 (bit7:0)	Bit 0	Bit 0	Bit 0	Bit 0	Bit 0	Bit 0	Bit 0	Bit 0

Figure 5.5: *Debouncing counter register*

During each interrupt call the state of every input pin is determined and the counter increased or reseted. If one pin has four times the same state a global variable will be set. This variable is used in the main routine to determine whether a single-throw switch is pushed and has to be cleared afterwards to start the counter again.

5.3. Haptic Controller Hardware

The hardware of the haptic controller is based on the development board MK3 described in chapter 4.3.1. The single-throw switches, an external input for the emergency switch, a UART and the LCD are used. Two external PCBs are connected and complete the assembly. One is designed for the communication and the other to connect the external button. The haptic controller with the external devices is shown in figure 5.6. The button on the left is the emergency button connected to the external button PCB.

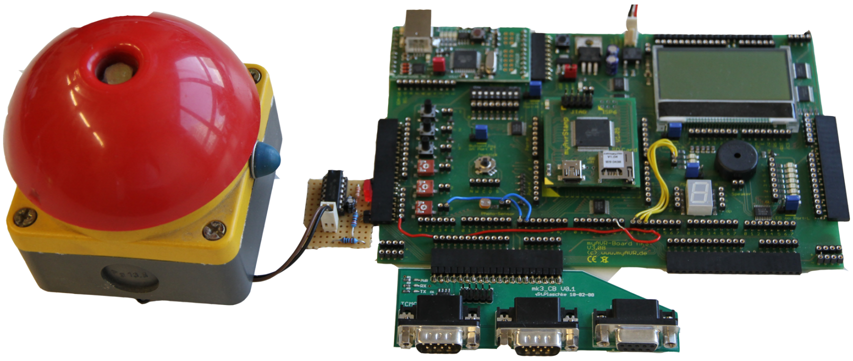


Figure 5.6: *Haptic controller with external device*

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[39] The code is written by Peter Dannegger and can be found online [8].

5.3.1. Visual Output

The visual output of the haptic controller is realized with the graphical LCD with a resolution of 64 x 128 pixels. It is mounted in the upper right corner of the development board (see figure 5.6). For a better visualization in dim environments it has an integrated back light. The resolution allows eight lines with sixteen characters. The status information is displayed line by line. When the last line is written, the display is cleared and it continues writing in the first line.

The information visualized on the LCD is only common state information. First, it starts with the boot sequence. Thereupon only error and operation mode informations are displayed. With the information on the display only a correct work flow can be checked. There is no influence given on the haptic display output.

5.3.2. User Input

The single-throw switches on the left of the development board (see figure 5.6) are used to control the haptic device. Further, an external emergency switch is used to stop the simulation immediately. The single-throw switches are numbered from one to three where the first is at the top of the design. The upper single-throw switch is used to reset the haptic device, the second to start the simulation and the last to stop the simulation. They are debounced in software which is described in chapter 5.2.3.

The external emergency switch is connected to the external input PCB. Pushing it the haptic device executes an emergency stop which can only be deactivated by pushing the button again.

5.3.3. External Input PCB

An external input for the emergency switch is needed and realized as an external interrupt input source. This allows an instant break of all running processes and an emergency stop of every motor. Therefore, a small PCB is designed which is connected to an external socket. This socket is free-utilizable and fitted on the left of the development board. The connection to the microprocessor is done with a loose connection. A LED on the PCB indicates the operating state. Further, a debouncing circuit is included because measurements prove the bouncing behavior of the emergency switch. The debounce function illustrated in chapter 5.2.3 only works for common digital GPIO and not with external interrupt inputs. Hence, a debouncing solution is realized in hardware.

Several methods are known to debounce a single-throw switch in hardware. A cost-effective and reliable method is shown in figure 5.7. A simple R-C low-pass filter in combination with an inverter is used. The values for each component are calculated and shown in table 5.4. With an opened single-throw switch the capacitor is charged over R_1 and R_2 and the output of the inverter is set to "0" after reaching the high level threshold voltage.[40] If the button is closed the capacitor discharges over R_2. After reaching the low level threshold voltage the inverter output is "1". Hence, volatile voltage fluctuation is suppressed.

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[40] A threshold voltage is the voltage where the current is higher than the cut-off current.

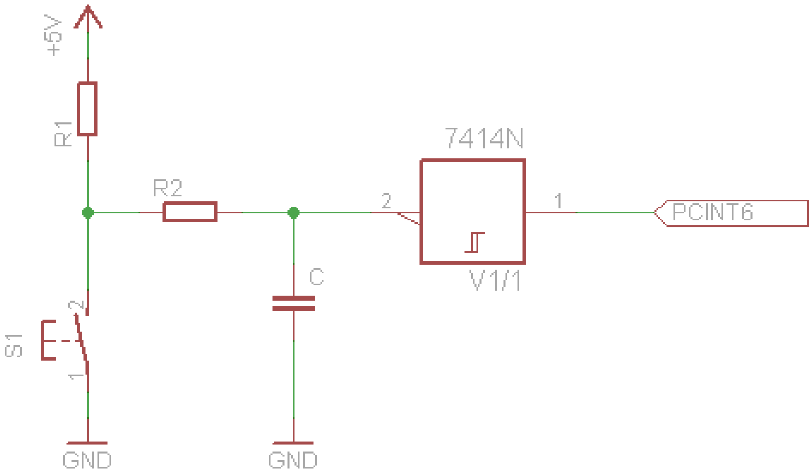

Figure 5.7: *Schematic of the debouncing solution*

For an adequate dimension of each component, the formula for the discharge voltage of the capacitor is analyzed first.

$$U_c\left(t\right) = U_0 \cdot e^{\frac{-t}{R_2 \cdot C}} \tag{24}$$

With $U_c(t)$ equals the low level threshold voltage U_N and solve this equation for R_2

$$R_2 = \frac{-t}{C \cdot \ln\left(\frac{U_0}{U_N}\right)} \tag{25}$$

The debounce time t is measured with maximal $10\,\mathrm{ms}$ (see figure 6.3(a) on page 67). The system is construed with $t = 20\,\mathrm{ms}$ for safety reasons. The supply voltage $U_0 = 5\,\mathrm{V}$ and the capacity of $C = 1\,\mu\mathrm{F}$ are given. Further, the low level threshold voltage of the used *74HC14* is $U_N = 2\,\mathrm{V}$. Therefore, a value of $22\,\mathrm{k}\Omega$ is calculated for R_2.

Secondly, the formula for the charging process of the capacitor is analyzed.

$$U_c\left(t\right) = U_0 \cdot \left(1 - e^{\frac{-t}{(R_1+R_2) \cdot C}}\right) \tag{26}$$

With $U_c(t)$ equals the high level threshold voltage U_P and solve this equation for $R_1 + R_2$

$$R_1 + R_2 = \frac{-t}{C \cdot \ln\left(1 - \frac{U_P}{U_0}\right)} \tag{27}$$

The value of R_2 is calculated with equation (25). The values for U_0, C and t are the same as assumed before. Further, U_P is 2.3 V. Hence, a value of $10\,\mathrm{k}\Omega$ is calculated for R_1. With this circuit the single-throw switch can be used without any bouncing behavior at the microcontroller input. The specifications of the debouncing solution are illustrated in table 5.4.

Variable	Value	Comment
U_0	5 V	Supply voltage
t	20 ms	Debounce interval
C	1 μF	Capacitor
R_1	10 kΩ	Charging resistor
R_2	22 kΩ	Discharging resistor

Table 5.4: *Debounce solution specifications*

5.3.4. Communication PCB

The communication PCB is mounted on the lower left side of the development board (see figure 5.6). To be interference-proof it is connected by a circuit path straight to the microcontroller GPIO. For the transmission the UART of the microcontroller is used. The communication standard[41] for the RS-485 bus is the same as used by the UART. The difference is the signal level. To transform the signal, a level changer[42] from Linear Technologies is used. Further, one low-power LEDs is connected to the RX and TX wires of the UART to realize a transmission indicator.

Besides the level changer a communication socket is suited on the communication PCB. The socket is connected to the GPIO of the microprocessor. Intended for digital outputs they can be used for several applications, for example for an emergency stop for the motor control unit.[43] Thus, an emergency stop can be executed even when the bus communication is disturbed. However, the disadvantage is a second cable to each motor control unit.

The last components on the communication PCB are three D-SUB 9 Pin Sockets (DE-9s). With the level changer they complete the EIA RS-485 bus. The pin out of the USB to EIA RS-485 converter and the motor control units are different. Therefore, they are labeled and not interchangeable.

5.4. PC Software

The developed PC software is called *Haptic Terminal* and written in *C#* with Microsoft Visual Studio 2008. The block diagram of the software is depicted in figure 5.8. It consists of two different modules, the communication and the user interaction. The data exchange is reduced to a minimum due to performance reasons. The user interface only gets the positioning data to display the actual state of the communication module. The communication module on the other hand gets the settings for the two serial interfaces.

The flow chart of the haptic terminal is illustrated in figure 5.9. Basically, it is a routine which monitors the data stream on the EIA RS-485 bus. After receiving a data packet the bus address byte is compared first. In case of a matched bus address the haptic terminal verifies the Cyclic Redundancy Check (CRC) byte to check if the data packet has been received correctly and completely. Next, the positioning information is stored and compared to the values of the

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[41] The communication standard is the bit pattern of the signal.

[42] The level changer is a low-power RS485 interface transceiver (*LTC 485*) [7].

[43] The motor control unit provides a hardware stop [20].

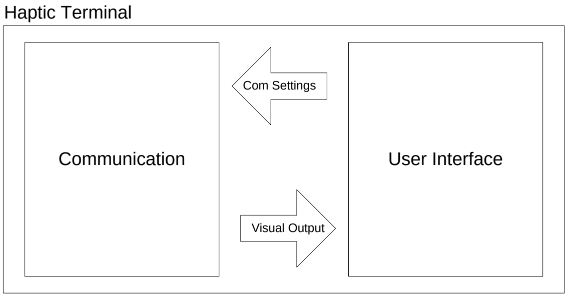


Figure 5.8: *Block diagram of the PC software*

counterforce on the left and right. If there is no overlapping with the counterforce limits only zeros are sent to the haptic controller. With an overlapping the strength of the counterforce is calculated and sent to the haptic controller. The counter force is calculated in two different ways. First, the strength is linear to the immersion depth, that means the counterforce raises linear to the distance the user is above the counterforce limit on the right or left. Secondly, an abrupt force output with a high force at a defined position.

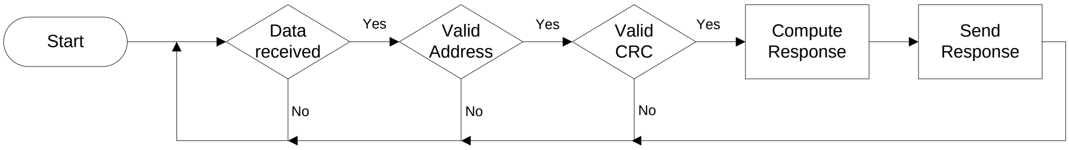


Figure 5.9: *Flow chart of the PC software*

5.4.1. Communication

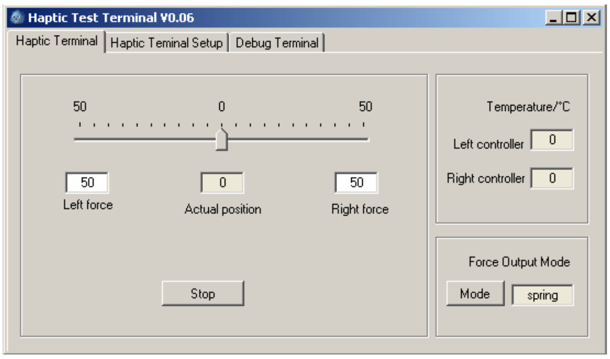
The communication module includes two serial interfaces. One for the USB-2-RS485 interface converter and one for the USB to serial interface converter. These interfaces address the internal USB to serial drivers from Windows to provide a standard serial interface. This allows an easy implementation of a USB communication without knowledge of the USB protocol. This is a great advantage because of the complexity of the USB protocol.

The communication for one serial interface is realized as a manager in the *C#* code. This is reasonable because each interface has its own manager and they work parallel to each other. Therefore, a lot of computing time is saved and the response is generated faster.

Both serial interfaces are set by default to the communication mode described in chapter 4.6. As default serial port three is used for the debugging interface and serial port six for the EIA RS-485 interface. On exit each value is stored in a configuration file which is loaded at startup.

5.4.2. User Interface

An overview of the haptic terminal interface is shown in figure 5.10. The software consists of three different tabs. The first tab contains a slider for the position information with two input



50
Left force

0
Actual position

50
Right force

Temperature/°C
Left controller 0
Right controller 0

Force Output Mode
spring

Figure 5.10: *Haptic Terminal interface*

fields for the counterforce position on the left and on the right. The middle position of the slider is the zero point. The force output defined in the input fields begin with "0" (middle position) and end with "50" (left or right limit). Further, the force output mode selector with one button and one notification field is placed at the lower right corner. The button is used to switch between the different simulations. The time dependent abrupt force output mode has one significant change, the right and left limit is faded out. This is done because this mode has defined force output positions and no possibility to change them. Last information field is the temperature control of each motor control unit. During a simulation the internal temperature of each motor control unit is requested and displayed here. For performance reasons during the development this feature is switched off. To start or stop the simulation on the bottom a button is placed.

The second and third tab containing the settings for the EIA RS-485 bus and debug interface. Further, each tab holds a screen to display relevant state information and debug messages.

Normally, the user interface is located centered on the screen. For undisturbed operation the haptic terminal can be minimized to the system tray. There, every action can still be performed with a right click on the icon.

5.5. Actuator Implementation

The actuator consists of two different component types, electrical and mechanical. Electrical components are the motor and the motor control unit. The mechanical components are the mountings, spindle and transmission.

5.5.1. Motor Controller

The motor control unit consists of two different PCBs, a baseboard [20] and the controller [22]. The baseboard is connected via a DE-9 connector to the EIA RS-485 bus. The power supply and the electrical motor[44] are connected via low voltage connectors to the baseboard. LEDs give a visual output for power supply, overheating, reaching the current limit and the rotational speed of the motor. Further, it contains control elements for analog motor control. These options are disabled and only the remote controlled option is enabled [20].

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[44] Three wires for the motor coils and five for the hall sensors.

On the baseboard the controller is mounted as a plug-on module. It is connected with two sockets to the baseboard. One socket is used for communication[45] and the other one for supply and motor controlling [22]. The remote control via EIA RS-485 is realized with the TMCM interface protocol described in chapter 5.2.1 and in the programmers manual [23].

5.5.2. Electrical Motor

The electrical motor is a BLDC motor with eight poles and three phases. The motor shaft is fitted with ball bearings. The supply voltage is 24 V with a maximal current of 10.6 A. The maximal rotation speed is 4000 rpm with a maximal output torque of 0.38 Nm. The wires for the motor coil and the hall sensors are connected to the baseboard with low voltage connectors [21].

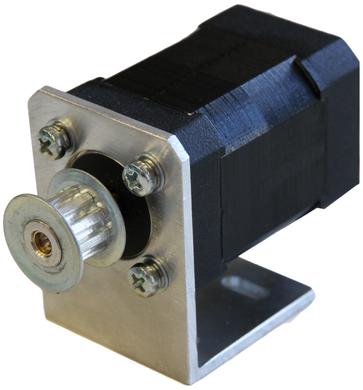

Figure 5.11: *Electrical motor with belt pulley*

5.5.3. Motor Mounting

As described in chapter 4.4.3 the motor mounting consists of an unequal leg angle steel profile. On the base plate it has long holes to adjust the device to tighten the belt. The motor is inserted through the hole and mounted to the plate. On the motor shaft the belt pulley for the transmission is mounted. The assembled device is shown in figure 5.11.

5.5.4. Spindle

The design of the spindle and its mounting is described in chapter 4.4.3. This design is entirely assumed and realized. An assembled spindle is depicted in figure 5.12. The string is coiled in two layers onto the spindle. The belt pulley is mounted on the spindle shaft.

5.6. Control Element

The design of the control element developed during this master thesis has a compact design. A wooden handle has strings tightened to the top and the bottom which end in a swivel on each

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[45] Communication also includes the analog motor control from the baseboard.

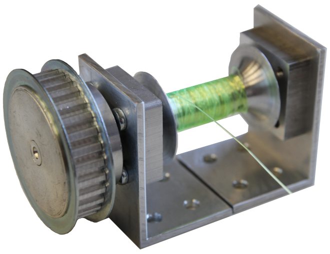

Figure 5.12: *Spindle with mounting and coiled string*

side. Each swivel is connected to a snap swivel tightened to the string of an actuator. This constellation distributes the user with a consistent force on the handle.

6. System Integration

In this chapter the hardware components and the software modules are tested and validated with the defined test cases from chapter 4.9. First, every component is tested individually. Afterwards, the device is assembled piece by piece and tested as a complete system.

6.1. Power Supply

Consequently, hardware validation starts with the power supply. Here, the power consumption of each electrical component is measured over the complete supply input range. The measurements are performed as described in chapter 4.9.1.

6.1.1. Haptic Controller

The power supply of the development board (MK3) used for the haptic controller provides two variants. The first one is from an external power source with an input voltage range from 9 V to 12 V. Therefore, the voltage is raised in 0.1 V steps and the current is measured. The result of the measurement is a constant power consumption over the whole input range and shown in table 6.1.

The second option is to supply the MK3 through the USB port. This can only be done safely, if the device's power consumption is below 100 mA[46]. If the USB port has to provide more current, it has to be declared in the USB protocol by the device. This functionality is not implemented in the USB transceiver mounted on the MK3. Therefore, the device can only be powered over USB if the maximal power consumption is below 100 mA. The measurement is also illustrated in table 6.1. A firmware is written exclusively for these two tests.[47] Thereby every component works on full load.

Supply	Voltage	Current
USB	5 V	186.6 mA
External	9-12 V	187.4 mA

Table 6.1: *Haptic controller power consumption*

The result of the measurements is a power consumption higher than 100 mA. As, a safe use of the USB bus is not guaranteed and the device cannot be categorized as low power USB device, an external power supply is needed for the haptic device.

6.1.2. Actuator

In addition to the haptic controller the actuator is the second component of the haptic device drawing current. The motor control unit and the motor are powered from the same source with 24 V. The motor is defined with a rated current of 3.47 A up to a maximum of 10.6 A. The maximal output current respectively torque is not desirable for a safe use of the haptic device.

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[46] The maximal current for a *low power device* on the USB bus.

[47] This firmware can be found on the CD and is called HC_pc0.1.

Therefore, the power supply has an internal current breaking at 5 A. In order to guarantee the developed output force from chapter 4.1 four measurements are done and illustrated in table 6.2.

Operation mode	Voltage	Current
Stop mode[a]	24 V	60.5 mA
Maximal speed, no load	24 V	0.234 A
Idle mode[b]	24 V	0.32 A
Continuous force output (15 Nm)	24 V	0.59 A
Maximal force output (30 Nm)	24 V	1.94 A

Table 6.2: *Actuator power consumption*

[a] Stop mode - each motor is powered off.

[b] Idle mode - weight compensation of the control element with no interaction.

As shown in table 6.2 the maximal current for the device is 1.94 A. Hence, each power supply is set to a maximum of 2 A.

6.1.3. Haptic Device

The power consumption of the haptic device is the sum of the power consumption of each separate component. For a specification only the maximal value is relevant. With the measurements done in former chapters the power consumption of the haptic device is calculated and shown in table 6.3.

Operation mode	Power consumption
Stop mode	4.509 W
Idle mode	12.918 W
Continuous force output (15 Nm)	34.597 W
Maximal force output (30 Nm)	99.397 W

Table 6.3: *Haptic device power consumption*

With the results of table 6.3 the maximal power consumption of the haptic display is 99.397 W.

6.2. Heat Dissipation

In electrical and mechanical devices the heat dissipation might be crucial. Lost heat from electrical components and frictional heat from mechanical components may overheat the device. Successive damage or limitations in the usability of the system are possible. Therefore, a long term measurement of heat dissipation at motor and motor controller is necessary. The test setup consists of one actuator with the string tightened to a force meter[48]. With a constant velocity of 1000 rpm the output force is calibrated to the different values. With this constant output force the temperature is gathered over a period of ten minutes. This period represents the time

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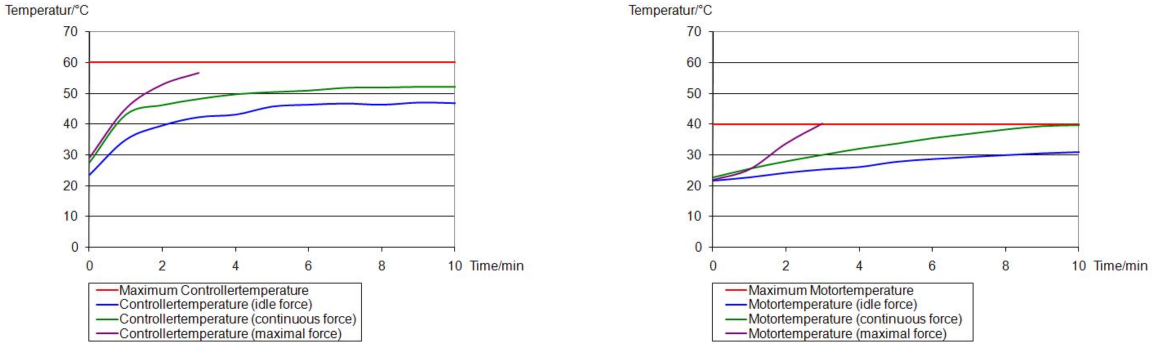
[48] The force meter is the 283-483 spring force meter from Kern with 50 N maximal force and an accuracy of 0.3 %.

a simulation takes time and is sufficient for the specification of the haptic display. The output force of the actuator is measured with the force meter and compared to the calculated force by measuring the current and using the torque constant[49] from the manual. The analog inputs from the baseboard are used to control the output torque. The controller heat measurements for the three output modes in relation to the time are shown in figure 6.1(a), measurements for the motor in figure 6.1(b).



(a) Controller heat dissipation measurement

(b) Motor heat dissipation measurement

Figure 6.1: *Heat dissipation measurement*

The measurements are taken over a period of maximal ten minutes. The highest motor and controller temperature is shown by the red line. If the maximum is reached before the maximal time is expired the measurement will be stopped immediately. The temperature at the idle mode is increasing very slowly. The motor temperature reaches 31 °C, the controller temperature stops at 46 °C. Therefore, no temperature control is needed in this mode. Whereas the temperature at the maximal force output reaches the maximum limit after three minutes. Hence, a temperature control is necessary for the motor and controller because during a simulation the force output will change frequently and no cool down period exists. The temperature control is realized with a fan that generates a constant air flow over the motor and controller and is assembled at each actuator.

6.3. Communication PCB

In chapter 6.1.1 the power consumption of the haptic controller was measured. That result has no significance for the mode of operation of external hardware. Therefore, a test routine[50] is written to allow communication between haptic controller and PC. Basically, it is an *echo* program on the controller activated on PC side with an open source serial terminal program.[51] This test includes the function of the communication system as well as a measurement of the response time (t_d) of the haptic controller.

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[49] The torque constant defines the output torque in relation to the input current.

[50] This firmware can be found on the CD and is called HC_rec0.1.

[51] The terminal program is called HTerm [16].

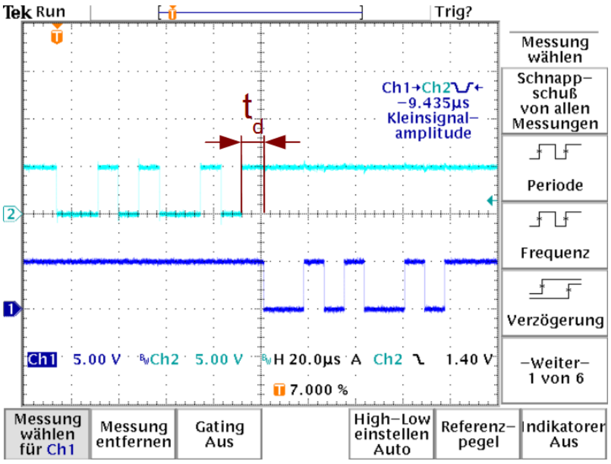

Figure 6.2: *Measurement of the response time between PC and haptic controller*

The outcome of this test is illustrated in figure 6.2. A response time of $t_d = 9.435\,\mu$s is measured for a communication between haptic controller and PC. The result of this measurement is sufficient for a communication with 115200 bps.

6.4. External Input PCB

Besides the communication PCB there is a second PCB, the *external input PCB*. First, it is used to connect the external single-throw switch (emergency button) to the development board. Secondly, it includes a debounce circuit in hardware. The functionality is explained in chapter 5.3.3. Figure 6.3(a) shows the bouncing behavior without the debouncing circuit. The signal is distorted with three peaks over the high level threshold voltage (V_{hlt}).[52] Therefore, three interrupts are fired during this measurement. Figure 6.3(b) shows an undistorted signal after the debouncing circuit where only one interrupt is fired. Figure 6.3 depicts different signals in both measurements. Without a debounce circuit the signal is low active. With a debounce circuit on the other hand it is high active. Concerning energy consumption the high active signal is the better solution and only has to be compensated in firmware.

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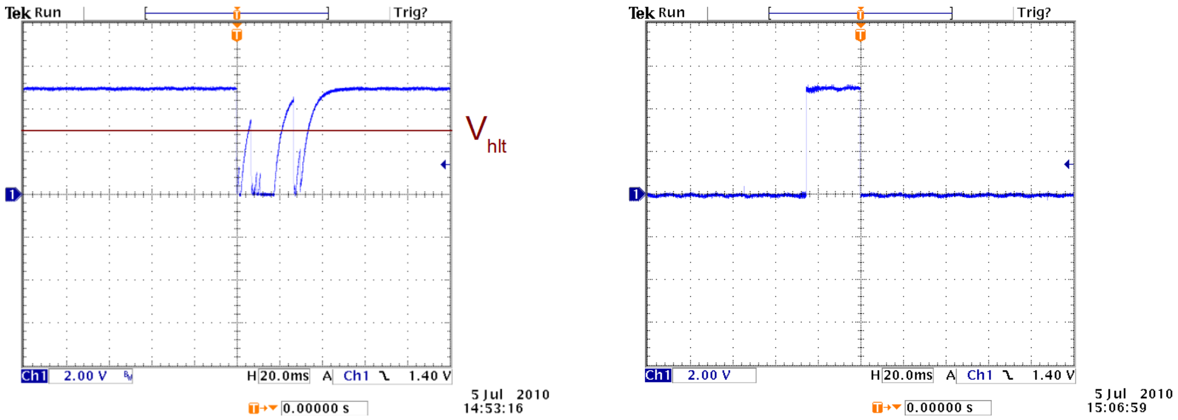
[52] The minimal high level threshold voltage is $V_{hlt} = 0.6 \cdot V_{CC}$ [6]



(a) Measurement without hardware debounce

(b) Measurement with hardware debounce

Figure 6.3: *Bouncing behavior of the emergency switch*

6.5. Communication Initialization

After testing the communication PCB, the communication between haptic controller, motor control unit (TMCM) and PC is initialized. Therefore, a test routine[53] is written. This firmware initializes the communication to the PC first. It uses the protocol standard developed by TRINAMIC for the TMCM modules. The PC responses with the version number of the PC software. Afterwards, the communication with the TMCM is initialized. Thereby the TMCM firmware version is requested and the module response with it's actual version number. This information is stored in the haptic controller. Further, two basic features[54] are implemented and executable by the button *2* and *3*. Button *1* in turn starts the initializing process again.

Besides the EIA RS-485 communication the USB communication with the PC is established. As mentioned before, the communication is for debugging purposes only. Thereby the haptic controller sends actual system information to the PC software. On PC side the information is received as text over a serial interface. Here, no communication protocol is used as it is a point to point serial connection.

6.6. Bus Performance

After measuring the response time and establishing a connection the bus performance is determined. The expressiveness of former tests is marginal because only one data byte is sent via the bus. The communication protocol used has a length of nine bytes. For this test the test routine of the former chapter is used again. Here, the delay (t_d) between the end of the initial message and the start of the response is measured. This data gives a first impression of the communication delay between the different modules. One result of each measurement is shown in figure 6.4.

The result of the whole series of measurements is summarized in table 6.4. The immense delay between haptic controller and haptic terminal is a matter of the operating system on the

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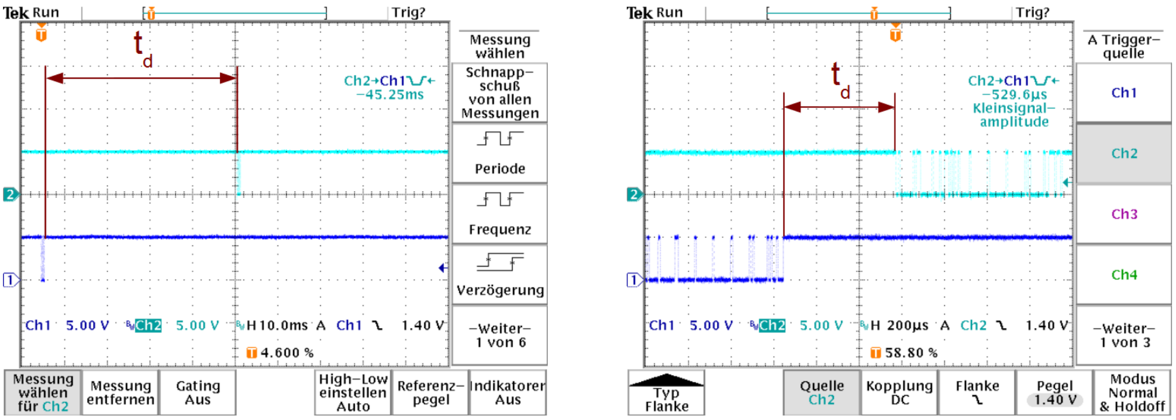
[53] This firmware can be found on the CD and is called HC_per0.1.

[54] Rotate Right (ROR) with a constant velocity of 300 rpm and an emergency stop



(a) Measurement between haptic controller and PC

(b) Measurement between haptic controller and motor controller

Figure 6.4: *Measurement of the bus performance*

PC. Windows XP is used which is no real time operating system. Even with the process priority *real time* a better result is not achieved. Therefore, the minimum delay between sending and receiving data to the haptic terminal is 67 ms. The minimum delay for the motor control unit is 710 μs.

Device	Minimal t_d	Average t_d	Maximal t_d
Motor controller	503.4 μs	559.38 μs	706.4 μs
Haptic Terminal	44.76 ms	53.384 ms	66.49 ms

Table 6.4: *Bus performance measurement*

Hence, the performance of the haptic terminal is insufficient for a high temporal resolution. Further developments may need another solution to achieve an adequate temporal resolution. For the prototype developed during this master thesis the maximal possible temporal resolution is sufficient.

6.7. Initial Operation

After passing each single test the fully assembled haptic device is tested. Therefore, the external PCBs are connected to the haptic controller PCB. In addition, the USB to serial converter is connected to the PC and the haptic terminal is started. In the end, motor control units are connected to the EIA RS-485 bus and the electrical motors. The fully assembled haptic device is shown in figure 6.5.

The firmware developed for the initial operation[55] differs slightly from the firmware used in the end. The sampling rate is decremented to 1 Hz and no force output except for the idle mode is set.

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[55] This firmware can be found on the CD and is called HC_iop_01

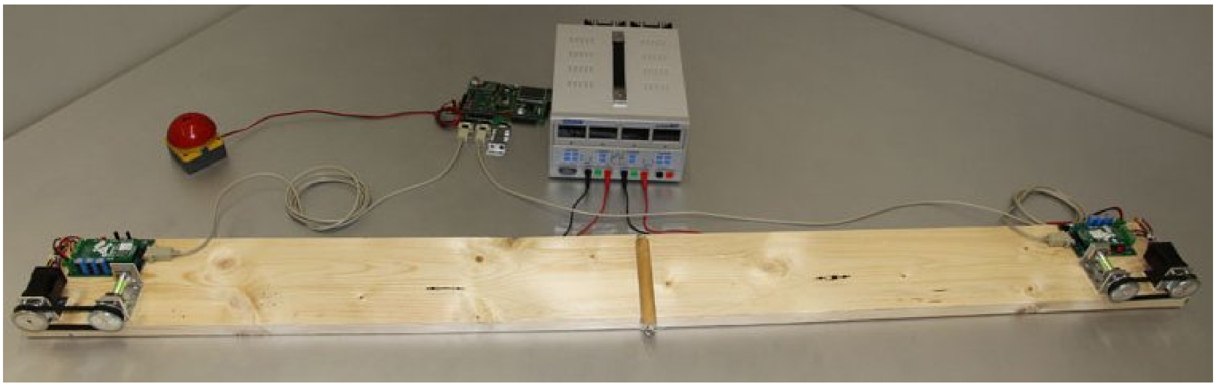

Figure 6.5: *Fully assembled haptic display*

This test will show whether all components work together to complete the haptic display. The data communication between haptic controller, motor control units and haptic terminal works correctly. The position data is received by the haptic terminal and displayed on the main screen. The reply from the haptic terminal is received by the haptic controller and processed correctly.

6.8. Working Point

The former step achieved an initial operation. Thereby the haptic display was fully assembled and tested. A defined force output was not part of that test. Hence, the next step is the calibration of the working point of the haptic system. Therefore, two actuating variables are determined and adjusted. The first is the rotary velocity of the electrical motor and the second is the output torque. Referring to the manual [21] a high output torque refers to a low rotary velocity. The mechanical impedance is calculated with equation (28). Following from this a high output torque and a low rotary velocity results in a high mechanical impedance of the system.

$$\underline{Z} = \frac{\underline{M}}{\underline{\Omega}} \tag{28}$$

The goal is to calibrate the system to a point where the mechanical impedance of the system approximately equals the user impedance to achieve a transparency as close as possible to one. This working point can be attained by measuring the user impedance and calculating the system impedance. Since no possibility to measure the user impedance is given at the HAW, it is done by trial and error.

First, the velocity is set to 2000 rpm and the current is incremented in 10 mA steps.[56] When the control element is lifted, the force is measured and the haptic feeling is tested. This procedure is repeated with different velocities. The values with the best result are chosen and set as default.

During this test a design error is detected. A gear ratio of 1:3 is too high for the haptic display. The resulting counteracting force is higher than the force the user is willing to spend. Therefore, the gear ratio is changed to 1:1. This affects the calculation of the force output and

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[56] Current and torque are related with a factor of 0.036 Nm/A.

the positioning resolution. The force output and the accuracy of the positioning resolution is now one third of the calculation.

The result of the trial and error method is a current of 0.3 A and a velocity of 1000 rpm.

6.9. Positioning Resolution

After establishing the working point the positioning resolution of the haptic display is determined. Therefore, the control element of the haptic display is set to the zero point.[57] From this point the control element is moved in one direction to different measuring points. Each measuring point has a defined distance to the zero point. With these measurements the actual positioning resolution is defined. The result is shown in table 6.5.

Distance	Integer value	Calculated step constant
2 cm	8	$2.500\,{}^{mm}\!/_{step}$
5 cm	22	$2.273\,{}^{mm}\!/_{step}$
10 cm	49	$2.040\,{}^{mm}\!/_{step}$
15 cm	76	$1.974\,{}^{mm}\!/_{step}$
20 cm	105	$1.905\,{}^{mm}\!/_{step}$
30 cm	160	$1.875\,{}^{mm}\!/_{step}$
40 cm	219	$1.826\,{}^{mm}\!/_{step}$

Table 6.5: *Positioning resolution measurement*

The theoretical length for one integer value is calculated with equation (22) on page 54 and the result is $1.571\,{}^{mm}\!/_{step}$. The results of the measurements are a maximum of $2.5\,{}^{mm}\!/_{step}$ and a minimum of $1.826\,{}^{mm}\!/_{step}$. Hence, an average value of $2.056\,{}^{mm}\!/_{step}$ is calculated. This deviation is caused by the wires which expand during application of a force. Further, a high distance compared to the low step distance results in a smaller error.

6.10. Force Output

The last step is the measurement and calibration of the force output. Therefore, the force meter is added to one wire and tightened to a basing point. The force output is measured and the haptic system is calibrated to the defined values.

6.11. Mechanical Network

After the calibration of the working point the simplified mechanical network from chapter 3.2.4 can be discussed now. To solve the mechanical network three parameters are required: motor output torque, haptic display and user impedance. First, the motor output torque is calculated with the formula from the manual [21].

Second, the haptic display impedance has to be measured. Therefore, one string is tightened to a force meter. The other end is tightened to the second actuator, which runs with a constant

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[57] The zero point is the point where the distance to each side equals.

velocity of 10 mm/s. Afterwards the force that is needed to wind up the string is measured. The actuators are changed and the measurement is repeated. The result is a force of 2 N at each side. Hence, the assembly of both actuators is correct.

The last unknown parameter is the user impedance. The possibility to measure the user impedance is not given at the HAW.[58] Therefore, this theoretical consideration is not a further subject of this master thesis and indicates the indispensable need of further research in this field. The result of the measurements is shown in table 6.6.

Parameter	Value
Output torque	Maximal 0.125 Nm
Haptic display impedance	$20\,\frac{N \cdot s}{m}$
User impedance	Incapable of measurement

Table 6.6: *Simplified mechanical network*

6.12. Basic Operation

The simulations are the final test for the haptic display. The quality of the haptic output is determined, which is done by using the haptic display and describing the haptic feeling it creates. Significant parameters are the temporal resolution, the positioning resolution and the force output. Three different simulations were defined in chapter 4.9.5. A button is placed on the lower right of the haptic terminal main screen to switch between these simulations.

6.12.1. Arithmetically Increasing Force Output

The simulation of the arithmetically increasing force output demonstrates the behavior of a common steel spring. At user defined positions[59] a force is applied to the user. At the beginning a low force is applied. With each position change in the direction the applied force is increased arithmetically.

The force output is tested on both sides. Therefore, a value of 20 cm is inserted into each input field for the counterforce position. The control element is moved into both directions to test the force output on the defined positions. Afterwards, on both sides the control element is moved further in the *force output region* to test the output behavior and the haptic feeling it creates.

The result of this test is a defined output on both sides at the defined position. The low temporal resolution of about 1 Hz is a problem. The resulting force output changes only once a second, therefore it creates a poor haptic feeling. The behavior of a spring (see red line figure 6.6) is achieved but the output behaviour is volatile (see blue line figure 6.6). By moving with the maximal constant velocity of 10 mm/s (difference between x_1 and x_2) the force raises 1 N (difference between F_1 and F_2). With the temporal resolution of 1 Hz the output force is raised

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[58] See [19] chapter 4, page 72-83 for an overview about methods to measure the user impedance.

[59] See chapter 5.4.2 on page 59.

stepwise with 1 N/s. This difference is noticed negative by the user. The haptic feeling is unresembling to a steel spring. Without increasing the temporal resolution this type of simulation is nonexecutable.

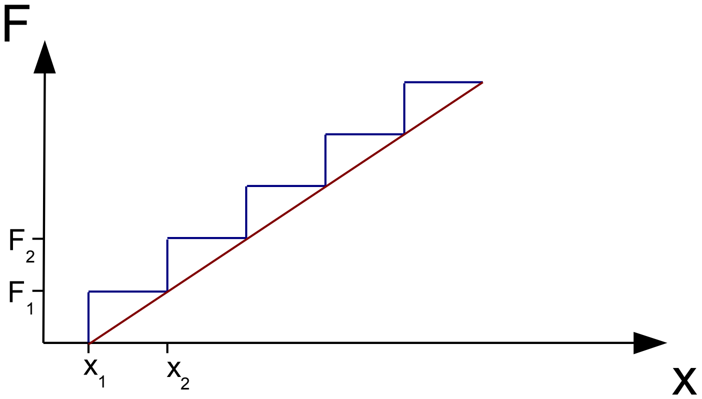

Figure 6.6: *Arithmetically increasing force output*

6.12.2. Abrupt Force Output

The abrupt force output simulation describes the impact on a compact object. On a user defined position an abrupt force output of 20 N is generated. The position can be adjusted with the input fields for the counterforce position.

Like the former simulation the force output is tested on both sides. Therefore, a value of 20 cm is inserted into each input field for the counterforce position. Then the control element is moved in both directions to test the force output on the defined positions.

The result of this simulation is a realistic haptic feeling. The abrupt force output is noticeable on both sides. Compared to the former simulation the force output is constant in this case. Therefore, a better haptic feeling is achieved. The precision of the force output position remains a problem. With the low temporal resolution the position is moving above 20 cm and the force is exceeded deeper in the *force output region*. Therefore, this simulation is usable with limitations to the force output position.

6.12.3. Time Dependent Abrupt Force Output

The simulation of the time dependent abrupt force output is similar to the former one with a time enhancement as a new variable. The time can be used to generate a virtual second axis. During this simulation every five seconds the position is changed between 10 cm and 20 cm.

The result is similar to the former one as the simulation is enhanced only with the time as variable. The haptic feeling is the same. Therefore, this simulation is also usable with limitations.

7. Requirements Verification

In this chapter the requirements developed in chapter 4.1 and shown in table 4.1 are compared to the result of the practical part. The verification is the final process of the master thesis and defines the quality of the developed haptic display.

7.1. Degree of freedom

One DOF is planned in the requirements developed for the haptic display. Force output is only required on the x-axis in the virtual environment. The developed haptic display provides one DOF. Its design allows a use for each axis of the 3D coordinate system. Therefore, this requirement is fulfilled completely.

7.2. Operating Space

The operating space is defined as ROM. A *wide* ROM is planned. This formulation allows a high flexibility in the execution. In this case a wide ROM is defined as the working area in the CAVE of the MMLab. The developed system design involves spindles where the strings are winded up. Depending on the required ROM the string length can be adjusted. Therefore, the ROM only limited by the space where the device is built up. Therefore, this requirement is fulfilled completely.

7.3. Temporal Resolution

The temporal resolution is about 1 Hz. This can be calculated by adding each delay of the main loop and the transmit and receive function of the haptic controller. The problem is the communication between motor control unit and haptic controller. For an unknown reason these controllers react only every 400 ms. During this time the communication is blocked. Different test routines are written[60] and executed with no acceptable result. At the time the master thesis has to be handed in this problem still remains. The producer of the motor control units is informed and further review is planned. Therefore, this requirement is not fulfilled.

7.4. Maximal Velocity

The maximal velocity is controlled by the haptic controller. The distance made during one sample period is calculated. With the known sampling rate every maximal velocity can be calculated and controlled. At the moment the maximal velocity is set as a constant in the firmware, but it can easily changed to an external adjustable system variable. Hence, the requirement is fulfilled.

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[60] This test routines for the PC and the haptic controller can be found on the CD.

7.5. Output Force Resolution

The output force resolution depends on electrical and mechanical parameters. The electrical parameter is the current output resolution of the motor control unit respective the torque output of the motor. In accordance with the programming manual [23] the output current resolution of the motor control unit (I_{outres}) is 0.036 A. With the torque constant of 0.036 Nm/A the torque resolution is calculated as followed

$$M_{res} = I_{outres} * M_{const} = 0.001296\,\mathrm{Nm} \tag{29}$$

The mechanical parameters are the radius of the spindle and the transmission ratio. In the beginning the specification was a transmission ratio from 1:3 in order to achieve an adequate output force and positioning resolution. The ratio has changed to 1:1 because the calibration to an adequate working point is not possible with such a high transmission ratio. Therefore, the output torque of the motor is equal to the effective torque of the spindle. Last parameter is the spindle radius with 6 mm which represents the lever arm. Hence, the output force resolution (F_{outres}) is calculated as followed

$$F_{outres} = \frac{M_{res}}{l_{rspindle}} = 0.216\,\mathrm{N} \tag{30}$$

With this value the requirement of the force output resolution is fulfilled. Further, the resolution is more than two times higher than prescribed.

7.6. Continuous Force Output

The continuous force output and the maximal force output are measured with the Kern force meter known from the initial tests in chapter 6.11 and chapter 6.10. One string from an actuator is tightened to the force meter. Then the continuous force output is calibrated to the required 15 N. In the haptic controller the possibility is given to change this value. This leads to the fulfillment of the requirement.

7.7. Maximal Force Output

The maximal force output is calibrated as the continuous force output is done. Thereby, the required value of 30 N is applied. The possibility to change the maximal value is also given in the haptic controller. Hence, the requirement is fulfilled.

7.8. Positioning Resolution

The positioning resolution was tested in chapter 6.9 and resulted in an average value of 2.056 $^{mm}/_{step}$. The requirement of 2 $^{mm}/_{step}$ under the restriction of the developed haptic display is fulfilled.

The reason why the result differs highly from the calculation in chapter 4.4.2 is the modified transmission. During the development process a transmission ratio from 1:3 was assumed. Afterwards, during the system integration process an adequate working point needed to be calibrated. Therefore, the transmission has changed to 1:1 to achieve a lower haptic display impedance. This was necessary to provide a better haptic feeling.

7.9. Recapitulation

The verification of the device is the final process. It gives an overview of fulfilled or unfulfilled specifications and defines the quality of the device. For this device ten major specifications are developed. Three of them, "number of DOF", "force reference" and "type of control element", are fulfilled by the design and do not need to be tested. Remaining specifications are tested and the result will be displayed within this chapter.

Two major problems are discovered, the temporal and the positioning resolution. The quality of the haptic feeling is defined by the temporal resolution. The requirement is 50 Hz at the minimum. With 1 Hz at the moment it is one fiftieth of the required temporal resolution hence not sufficient. Depending on the simulation the haptic display provides poor haptic feedback to the user.

Besides the quality the precision of the haptic feeling is further a major aspect. This parameter is defined through the force output, the temporal and the positioning resolution. As mentioned before the temporal and the positioning resolution are insufficient and therefore the precision is lower than expected.

Summarized, the quality of the developed haptic display is lower than expected. The actual design allows common simulations with a high force output but low positioning precision. Further, the low temporal resolution reduces the haptic feeling immensely. The conclusion is that the haptic display is usable to convey haptic feeling but it is not suitable for complex applications.

The outcome of the requirements verification is summarized in table 7.1.

Type	Description	Dimension	Comment
D	Number of DOF	one	Fulfilled
D	Force reference	Ground referenced	Fulfilled
D	Minimal operating space	$1.8\,\mathrm{m} \times 2.5\,\mathrm{m} \times 1\,\mathrm{m}$	Fulfilled
D	Temporal resolution	50 Hz	Not fulfilled
D	Maximal velocity of the control element	50 mm/s	Fulfilled
D	Maximal continuous force output	15 N	Fulfilled
R	Maximal continuous force output	20 N	Possible
D	Output force resolution	0.5 N	Fulfilled
D	Maximal force output	30 N	Fulfilled
D	Minimal positioning resolution	2 mm	Not fulfilled
D	Type of control element	Joystick	Fulfilled

Table 7.1: *Requirements specification verification*

8. Conclusion

8.1. Summary

This master thesis begins with the motivation chapter. The reasons are pointed out why haptics is more powerful than commonly expected and gets more in the point of interest . Further a short introduction of the current state is given.

The basics chapter starts with the physical conditions for haptics. Followed by an overview of human computer interaction and haptic displays, including their meaning in virtual environments. It ends with an overview of hardware components needed for the development of a haptic display.

In the specification analysis chapter the needs of a haptic display are analyzed and the requirements developed. Theoretical considerations are compared to actual devices. Hence, a theoretical concept is developed and a technical analysis followed, where the theoretical concept was applied and components are selected to fulfill each criteria of the concept. Weighing the pros and cons for each component is important for a successful design.

The practical part of this master thesis is the development of a working prototype. The gathered knowledge from the theoretical considerations is formed into a specified design concept and a prototype is built in hardware afterwards. This part starts with the system design and implementation chapter. Wherein a system diagram is developed and the implementation process is shown. Further, in the system integration chapter each component first and then the assembled haptic display are calibrated and tested. During this test phase first design errors are detected and afterwards corrected.

In the requirements verification chapter the actual results are compared to the requirements and problems are pointed out. Further, a table gives an overview on the fulfilled and unaccomplished requirements.

8.2. Discussion and Outlook

The goal of this master thesis is the construction of a 1D haptic device prototype with common hardware that provides a wide ROM. This part of the work is successful completed and the requirements are completely fulfilled.

The requirement on the developed haptic display is to provide the user with a good haptic feeling. The simulations show that this part could not be fulfilled because of the low temporal resolution. Unfortunately, this is the most important parameter for a haptic display. Good haptic feeling is provided with a temporal resolution above 50 Hz, as haptic displays with lower temporal resolutions provide a volatile force output behavior. In order to explain the volatile behavior, the temporal resolution is compared to the sampling rate for an audio signal: With a low sampling rate audio information is lost. By increasing the sampling rate additional audio information is collected up to the point where a sufficient signal quality[61] is available. For the haptic display the minimum signal quality respective the temporal resolution is 50 Hz. With a constant velocity of motion of 50 mm/s (maximal velocity of the haptic display) the force

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[61] Depending on the application the quality can be 8 kHz (Integrated Services Digital Network (ISDN) telephone standard), 44.1 kHz (Audio CD) or more.

output is calculated for every single millimeter. With the actual temporal resolution of 1 Hz the force output is calculated every 50 mm and therefore not sufficient. Modifications in order to achieve a higher temporal resolution are required, before other considerations will be able to be realized.

The reason of the low temporal resolution is the communication between haptic controller and motor control unit. Between two commands a delay of about 400 ms is necessary to achieve an answer from the motor control unit. Up to the time the master thesis is handed in the exact reason is not identified completely. One problem could be the firmware of the motor control units. This type of controller is never used in such a bus structure. Therefore, the producer of the motor control units is informed to review the firmware of the motor control units. An additional problem could be the transceiver used for the haptic controller. The switching between receive and transmit state takes some time. If a communication starts during this period an evaluable signal cannot be detected by the system, leading to the breakdown of the communication. These two problems are hardware problems. Moreover it is possible that the communication stack used in the firmware of the haptic controller or the PC software (haptic terminal) is faulty.

The first step to identify the problem is to test the haptic controller with an unmodified motor control unit. The modification is the change from an EIA RS-232 to an EIA RS-485 transceiver. With an EIA RS-232 transceiver and a direct connection the bus structure is discarded and the detected problems can be excluded. In case this leads to a better result the problem is caused by the bus system and its hardware components. If no improvement occurs the problem will be within the firmware of the motor control units, the haptic controller or the haptic terminal. The next step would be the firmware or software review of the haptic controller and the haptic terminal. If neither there a problem is found the problem is in the firmware of the motor control unit and the manufacturer has to be informed.

Despite the communication problems a very usable haptic display is developed in this master thesis. The haptic feedback of the *abrupt force output* simulation is acceptable and the haptic display is able to demonstrate haptic output. Knowledge about haptic and haptic displays is gathered and a complete development process is realized and illustrated during this master thesis.

The extension to two or three DOF should be the next step following to this master thesis. A device as developed here with only one DOF maybe practicable for simple simulations, however, for virtual environments as the CAVE it is of restricted use and requires specific scene setups. Common applications require at least three DOF (translational). The enhancement needs more specific and accurate calculations. Previous calculations were based on integer calculations which are acceptable for one DOF. Calculations of two or more DOF require floating point calculations which is the chokepoint. The microprocessor used for the haptic controller has no floating point engine. In order to compensate the missing engine a high processing speed is necessary. With a processing speed of 16 MHz the performance is not sufficient. Hence, a different microprocessor has to be used. The ATmega microcontroller family has no floating point engine at all. Therefore, a new design of the complete haptic controller is necessary because the pinout for the plug-on module is only for the ATmega family.

Furthermore, the need for a haptic controller as stand alone device is questionable. With the processing speed of common PCs the haptic controller logic can be integrated into the haptic terminal. In an alternative setup, a device to supply the user with relevant information and an emergency button only maybe required. The advantage of this is an easier and faster communication as the delay between haptic terminal and motor control unit will be much smaller. Figure 8.1 shows the actual communication path.

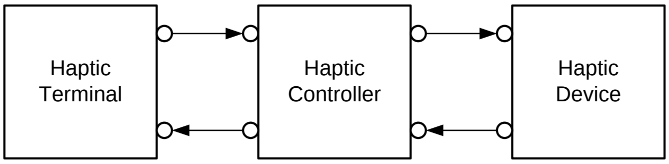

Figure 8.1: *Actual communication path*

Here the haptic controller operates as user interface and as the communication controller. In the beginning of the planning period it appeared as the best alternative. Afterwards the haptic controller emerged as bottleneck of the communication process. Figure 8.2 shows an approach without the haptic controller and with an external user interface. The communication is divided into a common bus communication for the motor control unit and a USB communication for the user interface. This strict separation gives the best performance for the more important bus communication. Further, faster communication standards can be used easily on a PC. The *IEEE 1394*[62] is a well established bus system and implemented on common PCs systems.

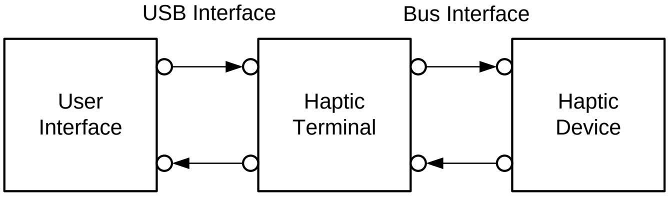

Figure 8.2: *Alternative communication path*

Besides the communication delay the response time of the PC system is a a problem of the developed solution. In addition, the delay between haptic controller and haptic terminal and especially between haptic controller and motor control unit exceeds the limit. Common systems run on a non-realtime system like Windows or Linux. Standard programming methods cannot operate in *realtime* mode on this systems. Therefore, the resulting communication delay is too high. This problem can be solved by construction of a system driver for Windows or Linux. These system drivers then react faster than the standard communication libraries. The work flow is as followed: Receive the information from the bus, compute and transmit the answer and creates the user output and/or input. This structure will lead to an enormous increasing of the reaction speed. Another approach is the usage of a realtime operating system like QNX, with which the delay can be reduced easily to 10 ms.

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[62] Also known as FireWire (Apple), i-Link (Sony) and Lynx (Texas Instruments).

As mentioned in chapter 3.1 one problem is the movement across the direction of the force. That means a movement not only on the x-axis but also on the y- and z-axis. However, the haptic system is not able to compensate this. To address this problem an optical tracking system can be used which works as follows: With at least three infrared cameras infrared light is emitted. A fixed arrangement of four or more infrared reflecting spheres, called target, on the tracked element reflect the infrared light and the cameras take pictures of the area with a frequency of 50 Hz. With these pictures the cameras calculate the position in space of the spheres. A defined point between the spheres is the origin of the device. With this position data the haptic system is able to calculate the correct position even when the user is moving along the y- or z-axis. This setup has one economic and one practical disadvantage. The economic disadvantage are the high costs of such systems the practical is the arrangement of infrared reflecting spheres on the control element. They could mechanically interfere the handle movement and may cause injury to the user or damage the device. A better way would be the enhancement of the system to more than one DOF.

A further problem is the positioning resolution. The internal positioning system with the hall sensors from the electrical motors is not sufficient. A resolution of 2 mm is desired for the haptic display. The system in this configuration has an average resolution of 2.056 mm over the entire range. Although this is acceptable but the working point needs to be calibrated more precise. Therefore, the gear ratio has to be changed from now 1:1 to a higher ratio. This leads to a reduction of the positioning resolution and this will then not be sufficient anymore. Therefore an external positioning system is required to compensate the transmission ratio reduction. Two methods are possible: on the first, an optical tracking system as described before and secondly an incremental encoder mounted on the electrical motor. Both methods are practicable, although only the costs are relevant.

Another step following to this master thesis is the integration in a 3D environment. The idea is a standalone device that can be connected to several visualization softwares. During this master thesis a simulator with common test scenarios is developed. The enhancement of the simulator should be the integration to each of the two visualization softwares that are used in the MMLab. The first one is the Visual Decision Platform (VDP), a commercial software from ICIDO. It allows easy plugin development by the usage of the given Application Programming Interface (API). The second one is COVISE, a commercial software from Visenso, where the connection to the haptic display is more difficult as no API is given.

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A. CD Contend

This Master report contains an appendix on a CD[63]. The following contend can be found on the CD:

- ♢ **Master Thesis**
  This thesis in PDF-format
- ♢ **Schematic and Layout**
  The schematics and the layouts of the external button and communication PCB (EAGLE projects)
- ♢ **CAD drawings**
  The CAD drawings from the mechanical components (AutoCAD projects)
- ♢ **Source Code - Haptic terminal**
  The source code of the haptic terminal (Visual Studio 2008 project)
- ♢ **Source Code - Haptic controller**
  The source code of the haptic controller (AVR Studio project)
- ♢ **Used publications**
  Free publications used for this master thesis

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[63] This CD is deposited at the supervising examiner's office and at the presence example in the library of the HAW.

Declaration of Authorship

This work was done within the meaning of section 25(4) of the Examination and Study Regulation of the International Degree Course Information Engineering in partial fulfillment for the degree of Master of Engineering (MEng) at the Faculty of Information and Electrical Engineering of the University of Applied Sciences Hamburg.

I, Stephan Plaschke, certify that the work presented here is, to the best of my knowledge and belief, original and the result of my own research, except as acknowledged, and has not been submitted, either in whole or in part, for a degree at this or any other University.

Stephan Plaschke Hamburg, 25^{th} August