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Adaptive Control of a Tactile Surgical Navigation System

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von

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Chapter 1

Introduction

The surgical room has seen a complete revolution in the last 20 years. The introduction of computer aided systems like robots and navigation systems have made the entities involved in a surgical operation more complex. Performing a surgical task involves three primary entities. The surgeon, the medium, and the patient. The surgeon uses the medium to interact and communicate with the patient. It may be a standard surgical instrument, an endoscopic camera, a robotic surgery system or other technologies. The medium also uses auditory (A), visual (V), or haptic (H) channels to link the surgeon to the patient. During conventional open surgery, the surgeon communicates and interacts with the patient's internal tissues through a large open incision with the help of his hand or surgical instruments. The surgeon directly communicates with the patient without a mediator in any of the communication channels. Advancements in computer aided surgery have progressively moved the surgeon farther away from the patient, creating man-machine interfaces and making the surgeon's communication medium with the patient more complex. The introduction of these complex man-machine interfaces may introduce valuable information in the form of force-feedback, vision enhancement, tactile feedback or by even enhancing the surgeon's kinematic capabilities by scaling down motion and filtering out hand tremor [1]. Despite these advantages, the increase in communication channels introduces a greater cognitive burden on the surgeon which can increase the risk of injury. One of the biggest flaws of computer aided surgical systems is that they have no built in components to compensate or counter the effects of the high cognitive burden on the surgeon.

This thesis concentrates on a computer aided system which supplements the surgeon's visual feedback with tactile feedback provided by vibroactuators on the back of his/her hand. The concept was developed (by Hein et al., in [7]) in the form of a multimodal surgical navigation system which combines tactile and visual signals as feedback information to the surgeon. The tactile signals provide information critical for three dimensional positioning of the surgeon's hand.

Results presented in [7], [15] and [16] show that tactile signals alone can assist a human in performing surgically related tasks, and that a combination of tactile and visual signals provide a tangible performance improvement over visual signals alone. However, large performance differences manifest themselves between different users and different times. In order to obtain more consistent and reproducible motor reactions from the human in response to tactile signals, the system must be designed to adapt to the human.

This Thesis presents an adaptive controller which will serve as a fast tracker for the time variances and inter-individual differences in the multimodal surgical navigation system. The perspective taken in this thesis is to consider the surgical procedure as a control problem with the surgeon as the "plant". An adaptive control algorithms is developed, studied and applied to the system and experiments to compare the accuracy of the system with and without adaptation are designed and conducted. The results obtained were also compared with those obtained with other surgical support systems in literature.

1.1 Structure of Thesis

Chapter 2, *Motivation and Statement of Problem*, presents an overview of the motivation of this thesis. It also outlines the statement of problem.

Chapter 3, *State of the Art*, reviews related work on computer aided surgical systems. It also reviews related work on adaptive controllers in surgery. In addition, it reviews related work on the transmission of information through vibrations. This chapter places the work of this thesis in context by summarising related work and identifying an area which has received little attention. In addition, the findings from this related work are considered in terms of how they could be used to inform the design of an adaptive controller for a tactile surgical navigation system.

Chapter 4, *Adaptive controller for a tactile surgical navigation system*, discusses the approach used to design the adaptive controller. This approach is based on the design principles of considering the human as the "plant", and adapting to him when he is either in a disturbed or an undisturbed state. Therefore, this chapter provides an overview of the principle of the "predictive mode" and the "adaptive mode" and discusses how these principles can be applied to the design of the adaptive controller. This chapter also discusses the different components of the tactile surgical navigation used in this work.

Chapter 5, *Realization*, extends the work presented in chapter 4 by presenting in detail the methods used to design the adaptive controller. Two experiments related to surgical procedures are reported. The experiments evaluate the effectiveness of the control algorithms used in the predictive mode of the adaptive controller. The experiments also investigates the effects of adaptation on the accuracy and duration of task performed with the tactile surgical navigation. In addition, these findings lead to a decision about which control algorithm will be used in the predictive mode in the rest of the research.

Chapter 6, *Experiment and Evaluation*, reports an experiment which evaluates the effectiveness of the whole system during an experiment related to cochlear implant. The results of the experiment are also compared with those obtained with other support systems in literature.

Chapter 7, *Conclusions and Outlook*, summarises the work presented in this thesis, and relates the findings back to the statement of problem outlined in Chapter 2. The limitations of this research are identified, and suggestions for future work based on the issues raised by the thesis are proposed.

Chapter 2

Motivation and Statement of Problem

Otological milling is a fundamental procedure in ear surgery. It serves to either delineate vital structures as an integral part of the process of removing disease tissues (e.g stapespedomy) or enable access for further intervention (e.g cochlear implantation). During milling the high speed rotating drill bit may penetrate the thin ear bone wall and significantly damage the patient's tissues (e.g the facial nerve or the dura) without the knowledge of the surgeon.

Figure 2.1: Milling process in Neurotologic surgery, [14]

Although milling bone during otoneurosugery is accomplished by the surgeon in free hand, it is difficult to do so without damaging critical structures. The accuracy of the milling is therefore very dependent on the surgeon's experience and knowledge of the anatomy. Thus so far, some navigational, robotic, navigated control and automatic identification concepts for guiding the drill have been developed to assist the surgeon in performing this complicated task. Nevertheless the key problems have not yet been resolved.

Imaged-based navigation systems in particular have been proven to improve the accuracy of milling the shape of implant beds for cochlear implants [17]. The fact that image-based navigation systems force the surgeon to always look at a remote monitor to gather information about the position of the tool with respect to anatomical structures motivates this work. Thus a new multimodal surgical navigation system with tactile feedback is presented.

This chapter presents both the advantages and disadvantages of the multimodal navigation system in otological milling and elucidates upon the need for the design of an adaptive control system.

2.1 Milling in cochlear implantation

There are a number of implants in neurotologic surgery (e.g., implantable hearing devices and cochlear implants). Cochlear implantation surgery involves inserting an electrode into the cochlea and connecting it to a receiver implanted under the skin. The challenges faced during the process include accessing the cochlea, which is embedded at a depth of approximately $35mm$ in the temporal bone. In order to access the cochlea the surgeon is required to pass between two bone-embedded nerves- the facial nerve, which if violated will cause paralysis to the ipsilateral side of the pateint's face, and the chorda tympani, which if violated will result in less sensitivity to the ipsilateral tongue tip. The space between these nerves is approximately $2mm$. Also, these implants require a "bed" in the calvarial bone where the implanted module (receiver/simulator) will sit.

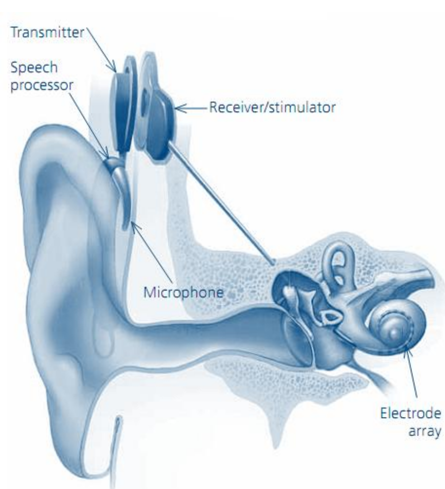


Figure 2.2: Ear with cochlear implant showing different components : source, NH Medical Arts

Thus, the surgeon uses a standard procedure called mastoidectomy, where the bone of the skull behind the ear is gradually shaved down a drill to permit access to the cochlea between the nerves. During the mastoidectomy, the surgeon must expose other important anatomical structures embedded in the temporal bone, including the sigmoid sinus, carrotid artery, and the labyrinth. It is thus highly desirable to include support systems to compliment the human hand-eye coordination in this procedure. There is a huge need for navigation systems with high accuracy in neurotologic surgery. A navigation system which uses tactile signals in conjunction with visual signals may increase the accuracy of already available image guided navigation systems (IGS) by reducing the surgeon's need to avert his gaze from the field of operation. Adaptability is critical in tactile surgical navigation because slight variations in the initial conditions or external perturbations can lead to unpredictable, reproducible and inconsistent execution of motor tasks. The adaptive controller designed in this work will help to decrease the variability in consecutive performances of the same action, i.e. motor output due to tactile input.

2.2 Surgeon's challenges in the use of the multimodal navigation system

2.2.1 Planning of the surgical operation

Despite the advances in cochlear implant surgery, success is still largely determined by the surgeon's skill in optimizing the insertion and positioning of the electrode array in the cochlear, namely achieving proximity to the modiolus. The limiting factor in optimizing the integration of an electronic device into a biological system is surgical experience. It has been shown that the location and orientation of the cochleostomy determines the subsequent position of the electrode array, which in turn largely determines post-operative hearing ability especially in the case of cochlear malfunctioning [17]. These requirements of the cochlear implant surgery place a high demand on the surgeon's experience and a method of assistance would thus be welcome in a surgical operation with low tolerances such as cochlear implant. In this regard, the multimodal navigation system which is planned based, can enable the surgeon to evaluate pre-operatively the optimal location and size of the receiver-stimulator's seat and the cochleostomy, and plan the possible anomalous course of the facial nerve. The surgeon can also outline the contours of typical surgical landmarks like the sigmoid sinus, jugular bulb in its intratemporal course, facial nerve in all its segments from the internal auditory meatus down to the stylomastoid foramen. This pre-planning is possible thanks to pre-operative image data provided by medical image technologies like computer tomography.

2.2.2 Accuracy

The main goal of using navigation systems in surgery is to increase the accuracy of the procedure. The idea is to improve the accuracy in positioning and orientation during the operation. Ontoneurosurgery may greatly benefit from the multimodal surgical navigation system as it may improve the quality of the surgical procedure by improving the accuracy of the implant bed. With the multimodal surgical navigation assistance, the continual feedback provided by the combination of visual and tactile signals helps in the control of the surgical instrument during the milling of the implant bed. Also, assisting the surgeon in milling tasks leaves him/her concentrated and fresh for further task like posterior tympanotomy and cochleostomy.

2.2.3 Reproducibility

In order to achieve consistent accuracy of the surgical procedure, performance differences between different users and different times need to be eliminated. The multimodal navigation system is supposed to adapt to the surgeon.

2.2.4 Security

Milling to create the cavity for an implant is a fundamental process in ontologic surgery. This process is controlled by the surgeon and requires a high degree of hand and feet coordination to remove bone in a precise manner. Also, the operating areas often have limited access, and the surgeon requires high skill and concentration to avoid touching healthy structures and causing collateral damage. Thus the multimodal navigation system has to be able to guide the surgeon during the milling process. Using both tactile and visual signals as feedback to the surgeon should improve the security of the surgical procedure while the adaptive controller of the navigation system should be able to cope with loss of concentration of the surgeon.

2.3 Technical Challenges in the use of the multimodal navigation system

2.3.1 Accuracy

Different sources of errors are inherent with the use of the tactile navigation system. The first is the so called fiducial localization error (FLE), which is the error in identifying the position of the markers attached on the patient (FLE_rad) and in the operation room (FLE_OP). (FLE_rad) errors come from the resolution of the CT or MRI scan, noise in the scan and image distortion of the scan. Contributions of (FLE_OP) include human error in identifying the fiducial markers and errors from the position tracking system. The second problem is loss of line of sight between the tracking system and the markers. The third is the loss of accuracy due to the human inconsistently perceiving/reacting to tactile signals. In the design of the navigation system it was assumed that most of these errors will be absorbed by the controller component. The adaptive controller designed in this thesis is suppose to identify and quantify these errors in order to compensate for them.

2.3.2 Insufficiency of classical feedback control theory

Harold Stephen Black's invention of the feedback amplifier in 1972 revolutionised the telecommunication industry and paved the way for the development of key aspects of control theory. Black solved the problem of variations in supply voltage and amplifier gain by feeding back the output, creating a device which preserved its transmission characteristics even in the presence of disturbances in the supply voltage and uncertainty of the open-loop gain. Black's invention generated great stimulus for the development of classical feedback control theory.

Mathematically a feedback control system can be considered as the interconnection between a physical process called the plant, P, where $P : u_1 \mapsto y_1$ and a controller C, $C : y_2 \mapsto u_2$ where $(u_1, y_1)^T$ represents the plant signals, $(u_2, y_2)^T$ the controller signals, and $(u_0, y_0)^T$ the external disturbances acting on the system. P and C are operators which are typically modelled by differential or difference equations. P is denoted the plant 'model' because the equations describing P are a simplified representation of the true physical plant, P_1.

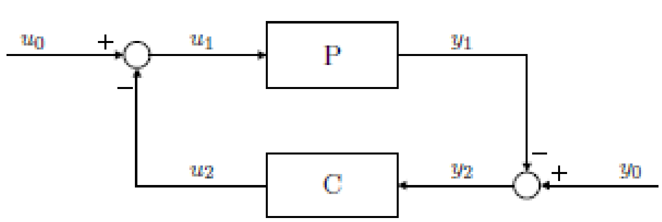


Figure 2.3: Feedback closed loop system

In control theory, the equations representing P are usually obtained by analytical or empirical methods. This process is called identification.

The effective control of real life processes in the industry requires a model, P that is able to accurately predict the behaviour of the process over the complete operating range of the plant, P_1. One method of identification is by considering the laws of physics in the interaction of different components and materials during the process. The other method is the so called empirical method which uses a plant's measured inputs and outputs to construct mathematical models in the absence of prior knowledge of the plant's underlying structure.

Both methods have their flaws. The former is usually difficult to apply especially with non-linear plants and usually ends up producing a large number of complex equations that may or may not characterize the plant's behaviour completely. The latter is usually limited to situations where the key goal is the output prediction for control purposes. Both methods have a common disadvantage in that they produce fixed models which do not react to disturbances in time and many real life plants have time variant disturbance properties. Classical feedback control theory does not present a solution to plants with time variant disturbances.

This limitation motivates the field of adaptive control. The basic concept behind adaptive control is that a learning component in the controller gathers information from the on-line observation of the closed loop signals of an uncertain physical system P in order to learn about the uncertainty. The information gathered is utilised to generate control signals yielding better performance than a fixed, non-learning classical controller. For instance, performing a surgical task can be considered as a feedback control loop with the surgeon as the 'system'. Disturbance sources like the many communication channels imposed by the computer aided system renders the system uncertain. Including an adaptive controller into computer aided surgical systems will make them to react better to the performance differences between different users and different times.

2.4 Statement of problem and contributions of this thesis

Commercially available surgical navigation systems provide a remote monitor from which the surgeon receives spatial information about the surgical tool and surrounding tissues. The remote monitor forces the surgeon to look away from the area of interest on the patient, which may increase the risk of injury. Thus non-optical man machine interfaces in surgical navigation have garnered much interest. A solution proposed by Kneissler et al. in [12] attempts to solve this problem by automatically switching the surgical tool on when it is within the working area and off when it is outside of the working area. Although this provides for redundancy of the surgeon while easing their cognitive burden, it is limited in its uses because it can only be applied to powered instruments. Thus Hein et al. in [7] proposed a new multimodal surgical navigation system where tactile signals in conjunction with an optical display provide feedback to the surgeon. The tactile signals, which indicate spatial information critical for navigation, are provided through vibroactuators attached to the back of the surgeons hand. The advantages that come with this new concept include:

- The display is brought right where the surgeon needs it,
- There is minimal gazing away from field of operation,
- Tactile signals can be perceived simultaneously with visual, auditory and other signals,
- Tactile signals can substitute for an overused, impaired, or unavailable sensory channel,
- Using vibration would allow information to be communicated discreetly without disturbing others, and could be used to alert surgeons in noisy environment
- There is a low risk of the saturation of optical canal and hence
- Low risk of injury.

Results presented in [7], [15] and [16] show that tactile signals alone can assist a human in performing surgically related tasks, and that a combination of tactile and visual signals provide a tangible performance improvement over visual signals alone. However, large performance differences manifest themselves between different users and different times. These flaws can be partly accounted for by the following:

- *Attentional tunnelling/narrowing:* In highly demanding situations, the surgeon may focus on a small group of sensory inputs and not feel stimulus,
- An intuitive tactile language, one that requires very little cognitive processing to interpret, may be very difficult to design or require extensive training,
- May be difficult to detect a stimulation if the hand of the surgeon is in motion, whether the motion is self propelled or environmentally caused,
- The increase of cognitive burden and
- the saturation of users to tactile signals

In order to obtain more consistent and reproducible motor reactions from the human in response to tactile signals, the system must be designed to adapt to the human. Thus, this thesis presents an adaptive controller for the multimodal navigation system. The concept is to consider the surgical procedure as a control problem with the human as the plant. An adaptive control algorithm is developed, studied and applied to the system and experiments to compare the accuracy of the system with and without adaptation are designed and conducted. As a matter of fact this thesis sets out to achieve the following goals:

- Increase consistency and reproducibility of response to tactile signals,
- Reduce the effect of saturation to tactile signals,
- Reduce the time taken to finish surgical task,
- More precise control of instrument position.

Chapter 3

State of the Art

This chapter presents existing concepts which have been developed to solve the problems presented in the chapter above. Various support systems have been developed for various types of surgical procedures. These support systems can be classified into either navigation and robotics systems or intelligent tools.

3.1 Navigation systems

Although computer navigation systems have been applied in many open and minimally invasive surgical procedures, the basic principle on which they operate is similar. Prior to image acquisition, either bone- or skin-applied navigation markers

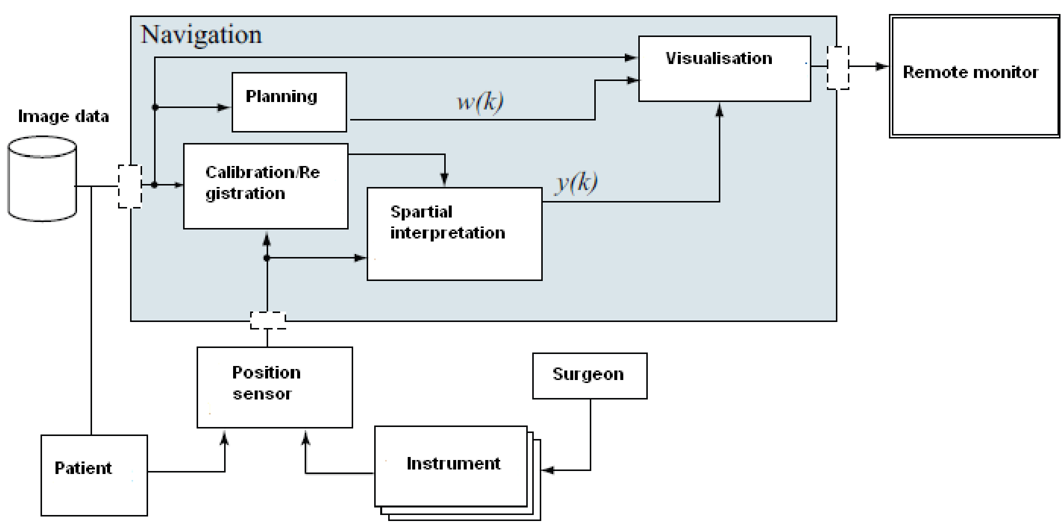


Figure 3.1: Components and information flow in surgical navigation systems [7].

are attached near anatomical regions of interest. A surgical planning step localizes these navigation markers in the image data set after CT and/or MRI acquisition and optionally performs post processing, which may include the definition of anatomical structures of interest and additional information; for instance a surgical trajectory, safety margins, and no-go regions. Immediately prior to surgery, the navigation system is set up in the operating room. During an intraoperatively performed patient-to-image registration, the navigation aids are localized by a tracking device and the mathematical transformation mapping objects from the image space to the tracking device space is calculated. After checking the system accuracy, the navigation itself starts and arbitrary structures in the image data set are visualized in relation to surgical instruments through a remote display.

Currently available commercial surgical navigation systems can be classified in two ways :

1) *Support provided to the surgeon* [9]. Navigation systems based on this classification support the surgeon by providing the relative position of the surgical instrument with respect to the patient. In order to display the position of the instrument relative to the patient, image guided navigation systems use preoperative image data sets of the patient. Navigated imaging systems provide intraoperative image data during the operation. Plan based navigation systems enable the surgeon to plan the surgical procedure and in addition to instrument and patient data, provide planned data like trajectories, a working area, or no-go areas with sensitive structures. Plan based navigation systems give way to a different way of classifying navigation systems.

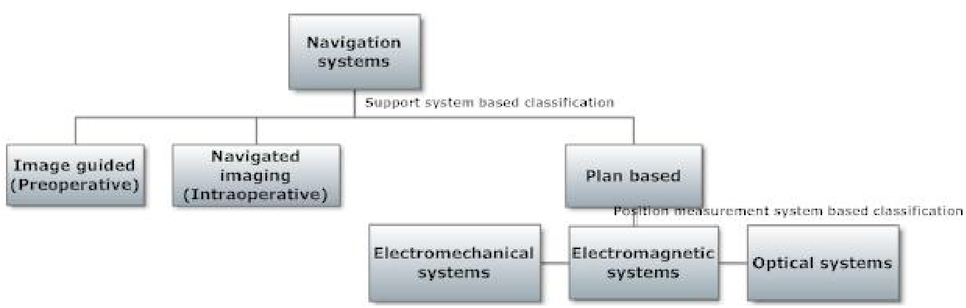


Figure 3.2: Classification of surgical navigation systems

2) *Technology of the integrated position measurement system* [8]. Technologies used for the integrated measuring systems include electromechanical, electromagnetic, or even optical. Electromechanical systems like Leksell Stereotaxie-System (Elekta Inc., Stockholm, Sweden) measure the position through mechanical contraptions. Electromagnetic systems are based on measurements on magnetic fields which can measure the position and orientation of particular coils. An example of such a navigation system is the ARION system [10] . Optical position measurement systems use stereo cameras (CCD, infrared, and so on) and use the principle of triangulation

Figure 3.3: Example of navigation system: Mechnical system stereotaxie-System (Elekta Inc.) and Radionics (Integra Radionics), optical system VerctorVision (BrainLab)

of active or passive markers. Optical systems are most preferred by developers because they do not disturb the movement of the surgeon.

3.1.1 Advantages of navigation systems in surgery

The advantages of navigation systems reside mainly in the detailed pre-operative planning. For instance, in cochlear implant surgery, the advantages reside in the pre-operative planning by simulation, precise controlled drilling, and accurate fixation of the implant. As a matter of fact, the surgeon can evaluate pre-operatively the optimal location and size of the receiver's-stimulator's seat and the cochleostomy and anticipate the possible anomalous course of the facial nerve. Also the continual visual feedback provided to the surgeon helps him/her identify targets and avoid no-go areas. The surgical procedure will therefore be less dependent on the surgeon's experience and knowledge of anatomy.

3.1.2 Disadvantages of navigation systems in surgery

In spite of the advantages surgical navigation systems bring in the surgical rooms, the concept on which they operate also brings along sources of error during the surgical task, as the remote display forces the surgeon to gaze away from the patient and field of operation.

This constant gaze away from the field of operation can lead to the saturation of the optical canal and increase risk of injury. Vickers [11] observed through his ergonomic study that visual monitoring of anything other than the monitor requires a change of visual focus. The monitor provides only a two dimensional mapping of events. Surgeons have to therefore carry out a space reconstruction of the data which is a possible source of error.

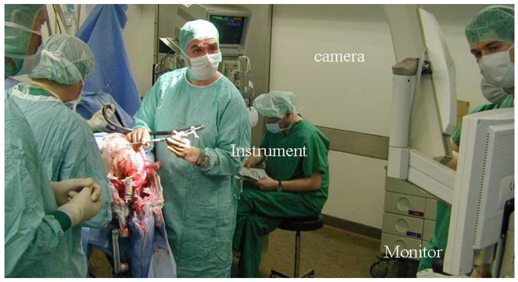


Figure 3.4: Conventional set-up of navigation system with surgeon gazing away from the patient (Charité Berlin (2001))

The above identified problem increases the psychological and physical strain on the surgeon. Mindful of the fact that many surgical tasks already require the analysis of medical images like CT or MRI, it will be interesting to explore other non-optical communication channels. This will leave the visual channel concentrated on the surgical scene.

3.2 Surgical robots

Presented in this section are some surgical robots. Surgical robots can be classified into three main types according to their control principle:

- Automatic systems,
- Tele-manipulation systems and
- Interactive systems

The following sections elucidate on each type of surgical robot.

3.2.1 Automatic systems

Automatic robots used in surgery are very similar to industrial robots. The required path to be taken by the surgical tool is predefined with the help of visual representation of the anatomy acquired by an imaging device (e.g; CT, MRI) and preoperative planning. After the path planning phase, the relative locations of the anatomical structure are registered. The robot can then execute the surgical task using position or velocity commands without further intervention from the surgeon.

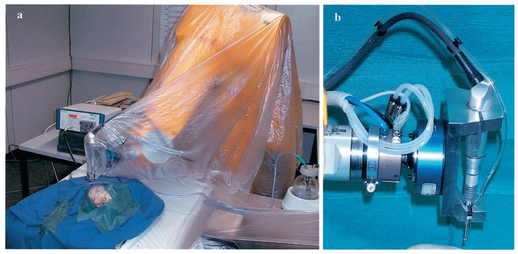


Figure 3.5: Force controlled automatic robot for Otoneurosurgery: a) Experimental setup with transparent sheet for protection, temporal bone spacimen, b)End of robot arm shown the milling burr [13]

To alter the path, replanning is required but the surgeon can stop the action for safety reasons. Automatic robotic systems are suitable for orthopedic or neurological surgical procedures with well-constrained anatomical structures such as hard tissues and bones or with soft tissue such as brain, confined by the skull [1]. Philipp A. Federspil et al. in [13] recently reported the developement of a force -controlled robot for otoneurosurgery. This robot is thesame type as CASPAR. Danilchenko et al. in [19] recently proposed an automatic robot for mastoidectomy.

3.2.2 Tele-manipulation systems

During tele-manipulation surgery, the surgeon sits at a console where they can view the procedure through remote monitors which provide them with a three dimensional image of the operating site. A pair of master manipulators is mounted within the console, one for each hand, controlling a pair of slave manipulators at the operating site.

There is a separate slave arm which holds an endoscopic camera through which the image of the operating site is transmitted to the surgeon. Two tele-manipulation systems in surgery are commercially available. The da Vinci surgical system (Intuitive Surgical Inc.) and recently the ZEUS system [2]. The ZEUS system has been used to demonstrate transatlantic teleoperated surgery [2] [3], while the da Vinci system has been used to validate difficult minimally invasive coronary surgical procedure [4] [5] [6].

3.2.3 Interactive systems

Interactive robots can be considered as guided systems in surgical cases requiring high precision, such as microsurgery, microvascular reconstruction, oththalmology,

Figure 3.6: The ZEUS tele-manipulation system: ©2012 Intuitive Surgical, Inc.

Figure 3.7: The da Vinci tele-manipulation system: ©2012 Intuitive Surgical, Inc.

or urology. In contrast to the automatic systems, the surgeon interacts directly with the robot with the robotic arm and moves the tool in space. Forces and torques applied on the system by the surgeon's hand are sensed and translated into a velocity comand to the robot. Existing interactive systems on the market include: MKM of Carl Zeiss Inc., SurgiScope of Elekta AB Coparate.

Hein et al. in [20] proposed an interactive system, IIH for application in head and spinal surgery. The system allows for complete interactive control by the surgeon. This system has already been applied clinically in maxillofacial surgery for the exact placement of implants.

Figure 3.8: IIH interactive system [20]

3.2.4 Advantages of surgical robots

Advantages of surgical robotic systems include their high accuracy in the performance of surgical tasks as they are designed to exceed human capability. Surgical robots also need a shorter time to perform task when compared to the human operator. They will most likely be able to perform tasks that are otherwise impossible, for instance new microsurgery procedures which require high dexterity access to small anatomical structures. The performance of a robot also degrades slower with time as compared to that of a human.

3.2.5 Disadvantages of surgical robots

There is still a long way before robots are commonplace in a surgical room. The biggest problem with these systems is that of acceptance. This concerns mostly automatic systems as they have to undergo very strict procedures before being permitted in the operation room. Robots force the surgeon to change his workflow as he has to spend more time planning the operation and fixing the patient and sensors. Another disadvantage of robotic systems is that of the sterilization of the complex force sensors and other mechatronical devices attached to the surgical instruments. The robotic systems also demands a technically trained surgeon in order to recognize critical situations for the machine. This calls for security and flexibility concerns. Robotic systems are also very expensive.

3.3 Intelligent tools

In this work intelligent tools are considered to be systems which provide support to the surgeon by affecting the functionality of the surgical instrument. The surgeon concentrates on the surgical procedure while mechatronical sensors attached to the tools provide feedback to a control system which in turn acts on the instrument depending on the situation at hand.

3.3.1 Navigated control

The concept of navigated control proposed by Kneissler et al. in [12] can be classified as an intelligent tool as it reacts to surgical errors commited by the surgeon by regulating the on/off status of a surgical tool depending on the current position of its tip. ON: when the tool is within the working area and OFF: when the tool is out of the desired working area. The setup of the navigated control system is like that of the navigation system already described above with a modification in the control component which is left to the surgical instrument. After a planning phase, the surgeon performs the operation freehand and the surgical instrument reacts to errors made by the surgeon without his notice.

Advantages of navigated control

The concept of navigated control was meant to solve the problem of the surgeon gazing away from the field of operation to a remote monitor. In so doing the surgeon's cognitive burden can be reduced while increasing his redundancy. Navigated control also presents the surgeon with most of the pre-operative and intra-operative information in a very effective with a high degree of safety.

Disadvantages of navigated control

Even though this approach provides for the redundancy of the surgeon while easing their cognitive burden, it can only be applied to powered instruments and hence is limited in application

3.3.2 Smart drill

Shen et al. in [14] proposed a "smart" otologic drill, which can predict and react to a drilling fault and bring the instrument to a rapid and safe halt. The identification of the drilling faults is done using a multisensor information fusion system and a neural network. The drill is still operated in the traditional fashion by the surgeon. The

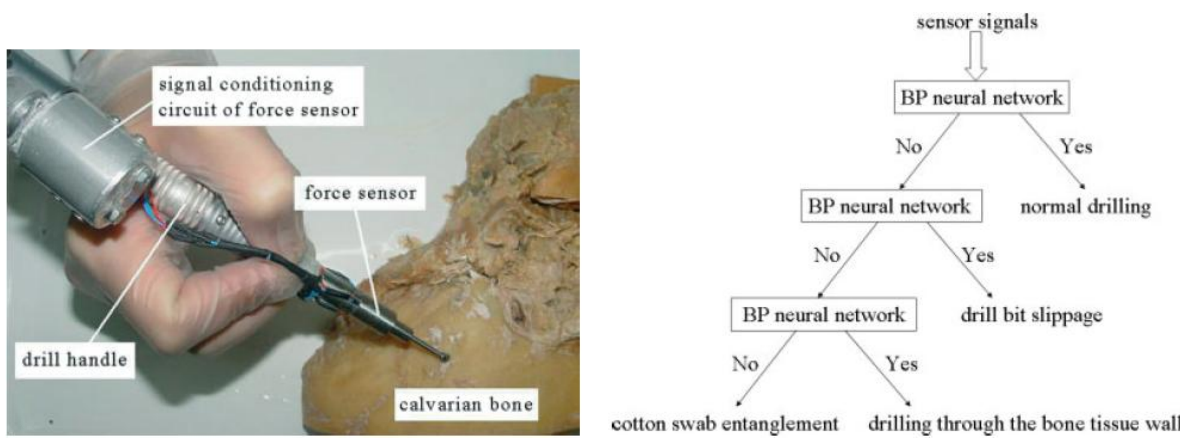


Figure 3.9: Left: Proposed smart drill with sensors. Right: Neural network to identify drilling faults

advantage of the smart drill is the fact that it will be less expensive than navigation and robotics systems.

The inventors of this system are however planning to also provide feedback using a loud speaker, which might increase the cognitive burden of the surgeon.

3.4 Adaptive control systems in surgery

Despite the fact that advanced robust and adaptive control methodologies have been (and are being) extensively developed for highly complex engineering systems, modern adaptive control technology has received far less consideration in surgical support systems. However, this is slowly changing and there is no doubt that adaptive control-system technology has a great deal to offer in computer aided surgical systems. For example, in surgical robotics, haptics dramatically improve the quality of the teleoperation. However, time delays can accumulate in the closed loop when haptic hand controllers are located in a different room (or even a different city) than the robot. When puncturing through tissue or hitting a solid surface, the commanded movement or force will be too large during the time delay, until the surgeon feels the effect and can pull back on the control. Time lag in the loop reduces the performance, resulting in increased overshoot at a puncture and increased collision force at a solid surface. In the face of such high levels of system uncertainty, robust controllers may unnecessarily sacrifice system performance whereas adaptive controllers can tolerate far greater system uncertainty levels to improve system performance. In contrast to fixed-gain robust controllers, which maintain specified constants within the feedback control law to sustain robust performance, adaptive controllers directly or indirectly adjust feedback gains to maintain closed-loop stability and improve performance in the face of system uncertainties.

An adaptive controller is made up of a combination of an on-line parameter estimator which generates estimates of unknown parameters with respect to time, and a control law that is motivated from a known parameter case. Two main types of adaptive controllers can be distinguished by the way the parameter estimator (adaptive law) combines with the control law. Indirect adaptive controllers estimate the plant parameters online and use them to calculate the controller parameters. This approach is therefore based on an explicit plant model.

Direct adaptive controllers parameterize the plant in terms of the controller parameters that are generated directly without intermediate calculations involving plant parameter estimates. This approach is rather based on an implicit plant model. For instance as shown in [21] , for a linear time invariant (LTI) single-input single-output (SISO) plant model, θ^* may represent the unknown coeficients of the numerator and denominator of the plant model transfer function. An on-line parameter estimator generates an estimate $\theta(t)$ of θ^* at each time t by processing the plant input u and output y. The parameter estimate $\theta(t)$ specifies an estimated plant model characterized by $\hat{P}(\theta(t))$ that for control design purposes is treated as the "true" plant model and is used to calculate the controller parameter or gain vector $\theta_c(t)$ by solving a certain algebraic equation $\theta_c(t) = F(\theta(t))$ at each time t. The form of the control law $C(\theta_c)$ and algebraic equation $\theta_c = F(\theta)$ is chosen to be the same as that of the control law $C(\theta_c^*)$ and equation $\theta_c^* = F(\theta^*)$ that could be used to meet the performance requirements for the plant model $P(\theta^*)$ if θ^* was known. It is, therefore, clear that with this approach, $C(\theta_c(t))$ is designed at each time t to satisfy the performance requirements for the estimated plant model $\hat{P}(\theta(t))$, which may be different from the unknown plant model $P(\theta^*)$. Therefore, the principal problem in indirect adaptive control is to choose the class of control laws $C(\theta_c)$ and the class of parameter estimators that generate $\theta(t)$ as well as the algebraic equation $\theta_c(t) = F(\theta t))$ so that $C(\theta_c(t))$ meets the performance requirements for the plant model $P(\theta^*)$ with unknown θ^*. Figure 3.10 shows the block diagram of an indirect adaptive control.

In direct adaptive control, the plant model $P(\theta^*)$ is parametrized in terms of the unknown controller parameter vector θ_c^*, for which $C(\theta_c^*)$ meets the performance

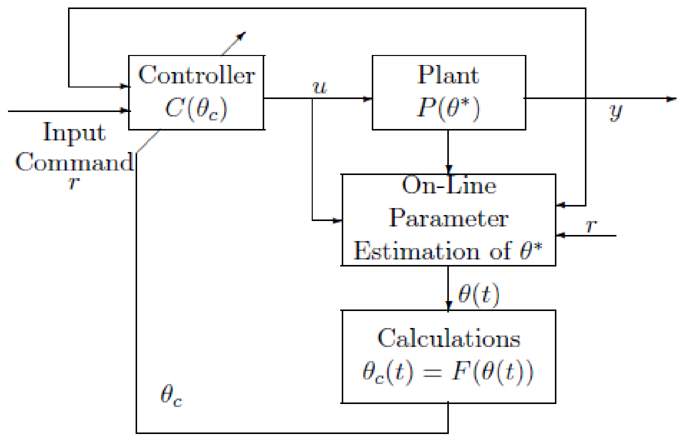


Figure 3.10: Block diagram of indirect adaptive control [21]

requirements, to obtain the plant model $P_c(\theta_c^*)$ with exactly the same input/output characteristics as $P(\theta_c^*)$.

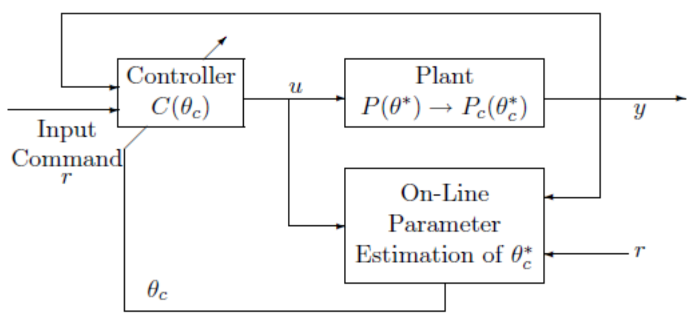


Figure 3.11: Block diagram of direct adaptive control [21]

The on-line parameter estimator is designed based on $P_c(\theta_c^*)$ instead of $P(\theta^*)$ to provide direct estimates $\theta c(t)$ of θ_c^* at each time t by processing the plant input u and output y. The estimate $\theta_c(t)$ is then used to update the controller parameter vector θ_c without intermediate calculations. The choice of the class of control laws $C(\theta_c)$ and parameter estimators generating $\theta_c(t)$ for which $C(\theta_c(t))$ meets the performance requirements for the plant model $P(\theta^*)$ is the fundamental problem in direct adaptive control. The properties of the plant model $P(\theta^*)$ are crucial in obtaining the parametrized plant model $P_c(\theta_c^*)$ that is convenient for on-line estimation. As a result, direct adaptive control is restricted to a certain class of plant models. Figure 3.11 shows the block diagram of the direct adaptive controller.

As already mentioned above, adaptive controllers have not been extensively applied in computer aided surgery. A few examples can however be spotted in literature; for instance, Cornellà et al. (2008) in [22] developed an adaptive control scheme for improving the performance of a surgical robot when it executes tasks autonomously.

A commercial tracking system is used to correlate the robot with the preoperative plan as well as to correct the position of the robot when errors between the real and

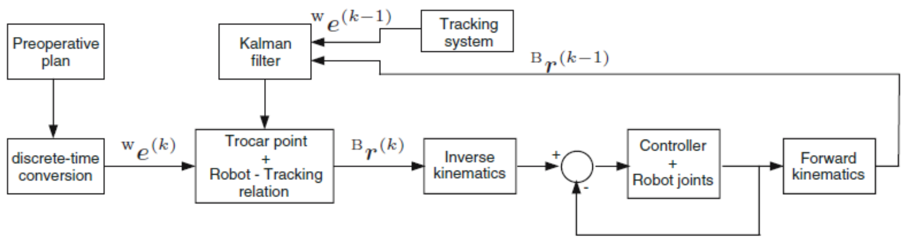


Figure 3.12: Block diagram of adaptive control algorithm by Cornellà et al. [22]

planned positions are detected. Due to the noisy signals provided by the tracking system, a Kalman filter is proposed to smooth the variations and to increase the stability of the system. Using this algorithm, Cornellà validated the efficiency of the approach using rigid and flexible endoscopic tools, obtaining in both cases that the target points can be reached with an error less than 1mm.

As already mentioned above, time delays can cause difficulties in master/slave haptic devices. When puncturing through tissue or colliding with a solid object, the operator does not feel the change for some time. During this period of time delay, the device applies a larger-than-desired force before the operator has a chance to pull back on the controller. This will lead to more overshoot in a puncture situation and a harder collision with a solid object. The amount of impact force in collisions is especially important since expensive force sensors are easily damaged. Thus D. Richert et al. in [23] an adaptive backstepping design provides a closed loop haptic control. Richart examined the case of endoscopic surgery, which constitutes a one degree-of-freedom (DOF) force or velocity tracking problem. Time lag in the loop reduces the performance, resulting in increased overshoot at a puncture and increased collision force at a solid surface. The goal was to design a computer control that can run on the robot (micro)controller, which is not subject to significant time lag (as shown in figure 3.12). Ideally, the control design tracks a desired force when contacting tissue or surfaces and track velocity when moving in free space.The pro-

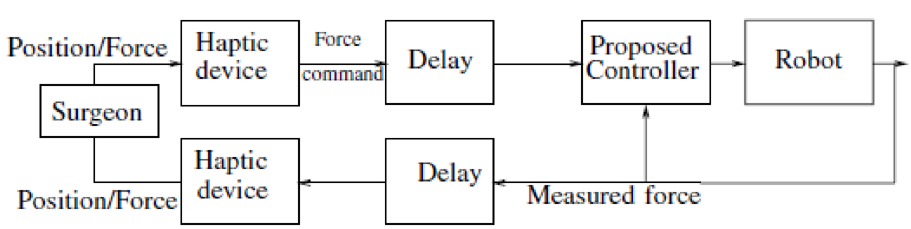


Figure 3.13: Model of proposed inner-loop force-feedback system by Richart et al. [23]

posed control achieves adaptation by utilizing neural networks in the control design to achieve stability in the presence of unknown or unmodeled dynamics terms. The advantages of the adaptive controller include:

- adapt to unknown nonlinear environments,
- adapt to uncertain robot dynamics,
- reduce the amount of overshoot during puncture,
- reduce the force of collision with a solid object,
- produce smooth applied control forces.

It is interesting to note that this approach is an example of a direct control algorithm.

Another direct control algorithm applied to a computer aided surgical system is the adaptive PI (proportional integral) Cartesian controller used to compensate for the laparoscopic orientation errors when a fulcrum position uncertainty exists, proposed by V. F. Muñoz et al. in [24]. The proposed adaptive control algorithm is applied to a robotic assistant ERM (Endoscopic Robotic Manipulator) designed by the authors. Since the robot has a passive wrist and it is not fixed to the operating table, the relative position between the robot camera holder and the insertion point is unknown. In this way, the proposed approach keeps the camera orientation according to the motion references in spite of this uncertainty and compensates for other unexpected disturbances about the relative robot-patient position.

3.5 Vibrotactile display and applications

The aim of this work is to design an adaptive controller for a vibrotactile surgical navigation system. The purpose of this section is to provide an overview of research in the field of vibrotactile display, thereby, placing the work of this thesis in context. The term "vibrotactile display" refers to the use of vibrations to present information to a user. This could be as simple as a single vibration from a mobile phone to indicate that a call has been received, or as complex as an entire vibrotactile language, with each character encoded in a different combination of vibrotactile parameters [33]. This is not intended to be an exhaustive review of all research in the field, but rather to provide an overview of the different applications in which vibrotactile feedback has been used. The review is limited to applications of vibrotactile display for alert and navigation.

3.5.1 Vibrotactile display

Most computer based support systems have relied on visual display to present information to users. However, there are situations in which vision is unavailable or inappropriate, and other modalities could be considered. For example, when interacting with mobile devices, such as mobile phones and personal digital assistants (PDAs), the visual display is often insufficient due to the limited screen space, or inappropriate, such as when the device is in a pocket but requires the user's attention. Or in the case of this research, when interacting with a surgical instrument and a patient, the visual display provided by the remote monitor often forces the surgeon to gaze away from the patient. Therefore it is important to consider using alternative modalities through which information can be presented. Another situation in which non-visual communication is critical is for people with visual impairment. On the other hand, sighted people who are engaged in a visually intensive task could benefit from receiving information non-visually. For example, pilots or car drivers are focused on the view in front of them and on visual information from the dashboard, but might also require navigation information. Providing this through visual displays could overload this sense and therefore presenting information to other senses, such as hearing or touch, might be beneficial. This dissertation focuses on the use of vibrotactile display, to present information to a surgeon during an operation. In the following sections existing applications of vibrotactile display for alert are discussed.

3.5.2 Vibrotactile display for alert and navigation

Geldard [34] identified two very important advantages of vibrotactile display are that it is attention grabbing and is not blocked by environmental noise. Geldard noted that these factors make vibrotactile display an ideal choice for presenting emergency warnings and alerts.

Mobile devices

One of the most common uses of vibrotactile display is for alerting users to incoming calls on a mobile phone or upcoming appointments in a personal digital assistant (PDA). These alerts are generally simple vibration to grab the user's attention, but no further information is encoded in the vibration. Recent developments have lead to more complex vibration alerts in commercially available mobile devices. The simplest of these is in some Nokia phone models which enhance the rhythm of ringtones with matching vibration patterns, but it is not possible to use these vibration patterns alone without the audio, and they have not been specially designed to be distinguishable by the vibration alone. The Motorola E398 phone features a multi-function transducer which produces both audio and tactile feedback, with the tactile feedback occurring when frequencies are in the range of 100-300 Hz In this phone, the vibration is used to enhance ringtones with haptic effects [35], [36].

Immersion developed what can be considered as the most extensive addition of vibration feedback to phones. He developed the "VibeTonz" system (http://www.vibetonz.com), which enables the implementation of more complex vibration effects. This system allows phone manufacturers to create their own tactile effects and add these to phone alerts, user interface elements and messaging applications. In terms of alerts, they suggest that vibration effects could be added to enhance audio ring tones, or could be used independently to allow people to know who is calling them from the vibration alone. However, there has been no research into how to design the most distinguishable messages. As discussed in Section 2.4, using vibration alone would allow information to be communicated discreetly without disturbing others, and could be used to alert users in noisy environments, therefore this could be beneficial for mobile phone alerts.

In-car alert and warning systems

Applications for vibrotactile feedback can also be found in alert systems in cars. One commercial application of this is the Citroen Lane Departure Warning System. In this system the driver's seat is vibrated if the system senses that the car is about to cross white lines without the driver indicating beforehand (http://www.citroen.com/).

Ho et al. [40] [41] made and extensive research into the use of vibrotactile alerts for car drivers. The investigation involved the use of vibrotactile cues to alert drivers to potentially dangerous events on the road. Their results showed that drivers responded significantly faster to alerts provided via vibrotactile stimuli than those presented by either audio or visual stimuli[40] and that more rapid responses were facilitated by presenting the vibrotactile stimulus to the side of the body (front or back of torso) that corresponded to the location of the event [41]. These results indicate that vibrotactile messages can be attention grabbing, and that people are able to accurately localise vibrations presented to the front or back of the torso. However, the vibration stimuli are quite simple and only encode one dimension of information (front/back) and, therefore, they are less complex than the type of messages investigated in this thesis.

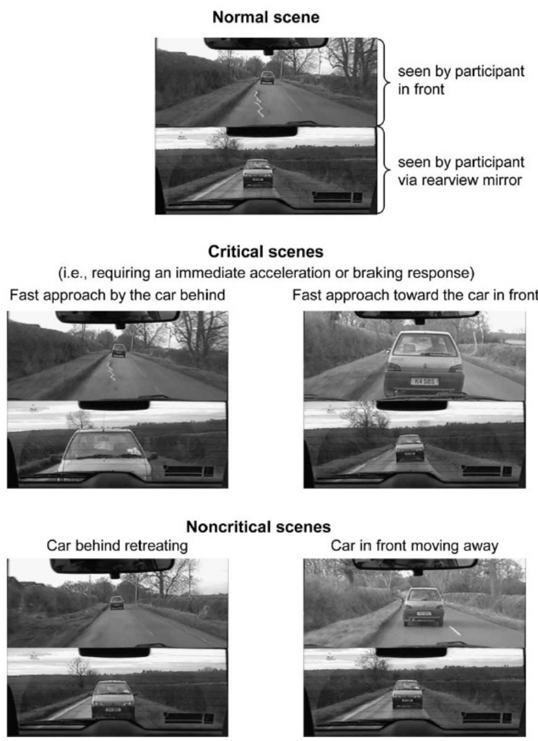


Figure 3.14: Sample video taken from one experiment by Ho et al. [41]

In-car navigation systems

Van Erp and van Veen [37] designed "Vibrocons" (vibrotactile icons) for an in-car navigation system, using vibrotactile devices mounted in a car seat. The Vibrocons encoded the direction the driver should turn using spatial location, with a vibration on the left leg indicating a left turn, and a vibration on the right indicating that the driver should turn right. The distance to the turning was encoded in the temporal pattern, with the direction information presented more frequently as the turning point approached. This vibrotactile navigation system was compared with a visual display where the information was presented using alphanumeric characters, and in a third condition participants used both visual and tactile feedback [38]. The results showed that the tactile feedback resulted in faster reaction times, lower mental effort and lower workload than the visual display. When tactile and visual cues were both available, response times were slower than in the tactile-only condition. This seems to have occurred because, when the visual cues were available, the drivers would check them as well after feeling the tactile feedback, to confirm that they had understood the Vibrocon. This indicates that while users are able to interpret vibrotactile messages, they lack confidence in their interpretation of them. The results of this study indicate that vibrotactile feedback can be effective in improving response times when people are under workload, and that more than one dimension of information can be interpreted from vibrotactile stimuli (in this case, direction and distance were both encoded).

In another study Asif et al. [43], exploited different methods of encoding multiple directions information with a tactile belt in the car. Asif compared the vibrotactile presentation of spatial turn-by-turn information with a conventional car navigation system to measure cognitive workload, performance and distraction of the driver. Their results showed that drivers showed better orientation performance on the tactile display than with the conventional car navigation system. At the same time there was no difference in cognitive workload, performance, and distraction.

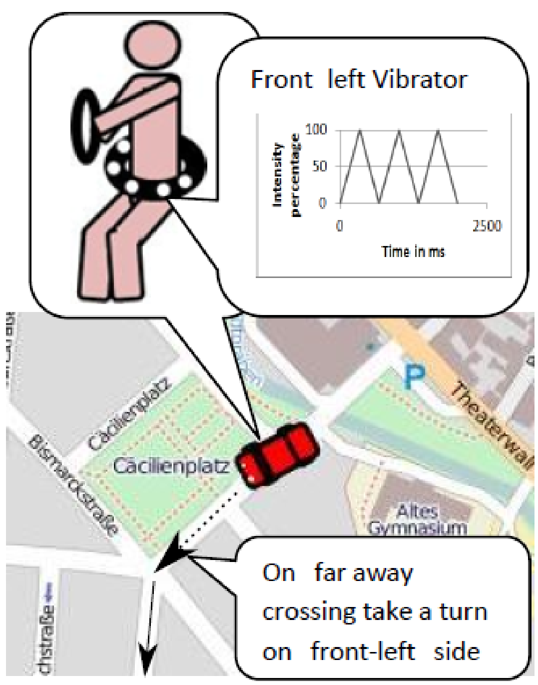


Figure 3.15: Three pulses of the vibrotactile signal on "front-left" side of the tactile belt indicate that the car is approaching the calculated crossing after covering the "far" distance. Asif et al. [43]

Asif went ahead to conclude that, a tactile interface can be useful to present more information than simple left or right directions in high load driving conditions in which drivers are required to observe the traffic situation with their visual and auditory senses.

Navigation systems for pilots

Another interesting application of vibrotactile display can be found in navigation systems for pilots. In a related work, Van Veen and van Erp [39] investigated the use of a vibrotactile vest to present information, including navigation information, to fighter jet pilots. Tactile display would be particularly useful in this setting as vision can be affected when pilots are in g-load conditions, and tactile information might be more readily received. The tactile vest consists of 128 tactile actuators distributed across the torso. In this display the spatial location of the activated tactile actuators can be used to present a variety of information. For example, activating a single point could indicate the direction of a target or destination. In addition, a line of actuators could be activated to indicate an artificial horizon. The tactile display could also be used to present coded information such as fuel supply, speed, altitude or time, or to enable discreet communication between pilots or crew members. These examples would use a more coded approach.

Navigation systems for blind people

Vibrotactile feedback has also been used to help blind or visually impaired people to navigate. For example, Ross and Blasch [42] designed a wearable tactile display, which indicated whether the user was walking in the right direction or if a change of direction was needed. Three vibrotactile actuators were located on the user's upper back. If the user was on target, the centre actuator was activated every two second to indicate this. The left and right actuators were activated to indicate that the user was off target in that direction. When compared with a speech interface and a non-speech audio interface, the results showed that the tactile display resulted in better performance and was preferred by users.

3.6 Discussions

This chapter has reviewed the state of the art of different computer aided systems in surgery, outlining their advantages and flaws, provided a review of vibrotactile displays, and has shown that vibrotactile feedback is applicable to a wide range of different purposes, especially in alert and navigation systems.

Three main computer aided surgical systems have been identified:

- Navigation systems
- Surgical robots
- Intelligent tools

One goal of this review was to cross check the multimodal (tactile and visual) modes of feedback used in this work with man-machine interfaces used in other fields, most commonly visuals provided by a remote monitor. Navigated control, one of the most promising technologies, solves the problem outlined in this work by eliminating the surgeon's gaze away to a remote monitor by directly switching the surgical instrument off when it is in a no-go region. It can however be applied only to active instruments.

Five main applications of vibrotactile display have been identified:

- Mobile devices
- In-car alert and warning systems
- In-car navigation systems
- Navigation systems for pilots
- Navigation systems for blind people

It could be concluded from the review that tactile signals can be used as a medium of feedback to users even though the users were not very confident of the information received. This lack of confidence, coupled with the fact that extensive exposure to tactile signals can lead to fatigue and hence a loss of concentration, indicates that the usefulness of tactile signals as a feedback to surgeons during operations is still in its infancy. Adaptive control algorithms could solve this challenge as they may reduce or eliminate time variant effects during tactile signal perception. At the start of this research, there has been very little formal research in this area. Furthermore, there has been no research into adaptive control algorithms for vibrotactile surgical navigation systems. A new approach to the design of such an adaptive controller is presented in the following chapter.

Chapter 4

Adaptive controller for a tactile surgical navigation system

The novelty of this thesis is the development of a new technology for the adaptive control of a tactile surgical navigation. In addition to the conventional remote display present in commercial navigation systems, this thesis presents an adaptive controller for a new navigation system with tactile feedback information to the surgeon. The concept considers the surgical procedure as a control system with the surgeon (human) as a "plant". The adaptive controller operates in two modes, the "predictive mode" and the "adaptive mode." The predictive mode uses a direct adaptive control algorithm to provide tactile feedback information critical for navigation to the surgeon. In the adaptive mode, the system monitors and characterizes the human operator reaction to disturbances. The characterization of the disturbance depends on the surgical application in question. The characterized information is then used in a "reactive" manner to correct errors which the predictive mode could not account for.

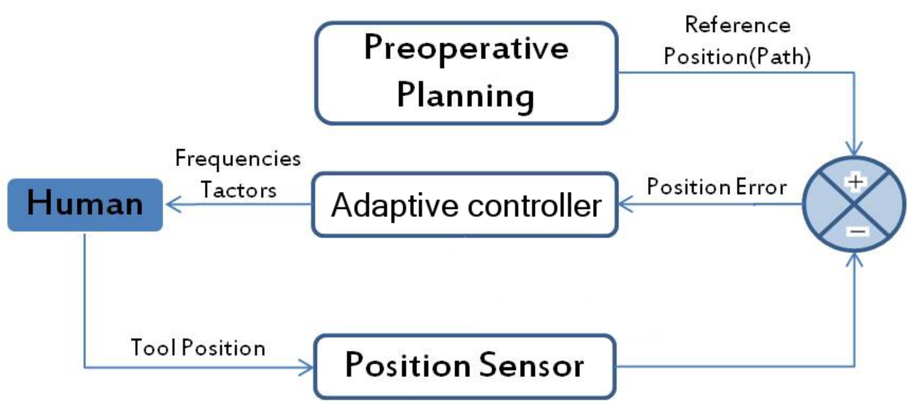


Figure 4.1: The concept considers the human as the plant

4.1 Tactile Navigation system

This section describes the main characteristics of the surgical navigation system used in this work. Presented in this work is a new navigation system, ConTACT (cooperative navigation system with tactile signal transmission) which in addition to providing information to the surgeon by a monitor also transmits information directly to the surgeon through vibrotactile signals. After a registration and calibration step, the actual positions of the patient and instrument are interpreted as spatial data in relation to plan data. Results of the analysis are then sent to an

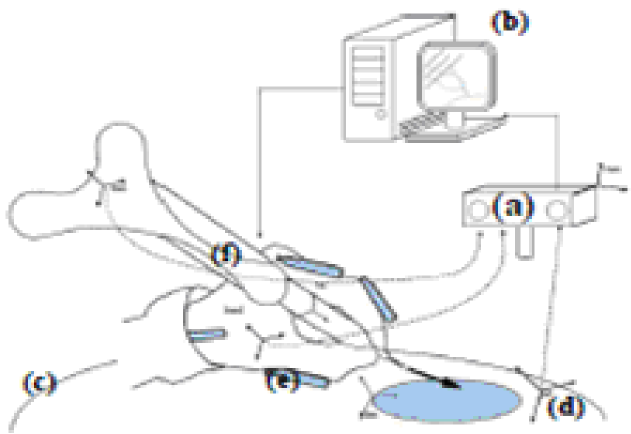


Figure 4.2: conTACT-System-Setup: a) Position measurement system, b) Control-Computer, c) Surgeon, d) Working area, e) vibrotactors, f) surgical Instrument. From [7].

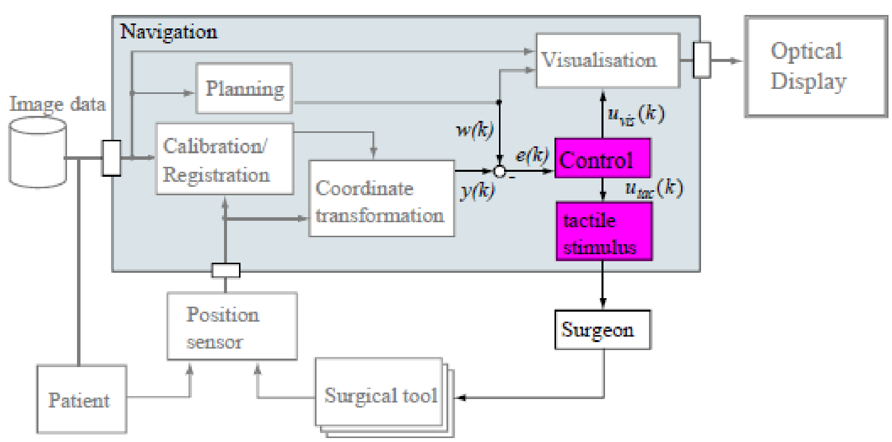


Figure 4.3: Block diagram showing components of tactile navigation system. From [7]

embedded controller part which sends control values to the human through vibrotactors which are arranged on the back of his hand as shown in figure 4.2. The control information is also sent to a remote optical display. It is assumed that the surgeon‘s motor reaction is affected by tactile signals in a way that is suitable for navigation. Figure 5.1 shows the components of the tactile navigation system with the components in pink showing the novelty of ths approach. This thesis concentrates on the control of the human using tactile signals.

4.1.1 Preoperative image data

In the first step, image data from the patient is obtained. Computer tomography (CT) and magnetic resonance tomography (MRT) images provide a great possibility in this case. This step is a prelude to the registration process which is facilitated by attaching markers on or in the patient. These markers are in the form of fiducial which are implanted in the bones in order to be visible in the CT images. The fiducial remain in the patient during the operation process since they are required during the intraoperative registration process. The image data is then stored in the form of DICOM 3.0 standard and imported into the navigation system.

4.1.2 Preoperative planning

The obtained preoperative images provides the opportunity to plan the surgical operation. The planning of the process involves the definition of trajectories as well as go and no-go areas and volumes for the surgical instrument. Planning highly depends on the type of surgical procedure in question.

4.1.3 Registration and calibration

The image data uploaded to the navigation system are correlated to the anatomy of the real patient in a registration phase. This is facilitated by a localizator of the pose measurement system. It is therefore possible to measure the position of the patient.

Chapter 5

Realization

This chapter explains the steps taken to realize the adaptive controller. They include:

- Mathematical derivation of direct adaptive control algorithms
- Simulation studies, as a proof of applicability and stability of algorithms
- Implementation of the adaptive control algorithm into the tactile surgical navigation system
- Application of the tactile display and the adaptive controller to a procedure related to neurotologic surgery

5.1 Concept of an Adaptive controller for the tactile navigation system

Figure 5.1 shows the block diagram of the realization of the adaptive controller. Before the surgical procedure begins, a preoperative planning phase is done where reference positions, paths or working areas are defined and uploaded to the control block as input. During the surgical procedure, the position of the surgical instrument is sensed and provided by the pose measurement system. This information is then combined with the preoperative information and a behavioural state to evaluate the motor reaction model and hence the control parameters. Two models user are evaluated.

1) ***The disturbance model***

Creating an adaptive control system for a man-machine system requires that we determine the human operator's reaction to disturbances in the system. In our case, such disturbances include the saturation of the human skin to tactile vibrations, the loss of concentration, and inconsistencies from the position sensor. The human response to these disturbances can be characterized either by predicting the response based on a model, quantifying the response based on statistics or merely measurements which can be employed by an artificial intelligence system. The first approach cannot be directly applied in our case since there is no model of human reaction to disturbances during tactile navigation. The only hope in the application of this approach is to quantify the disturbances based on predefined rules. For instance even though one cannot say exactly when the user losses concentration, one can predict this when the user no longer takes the warnings provided by the tactile signals serious. This can be done by measuring the deviation from the planned trajectory.

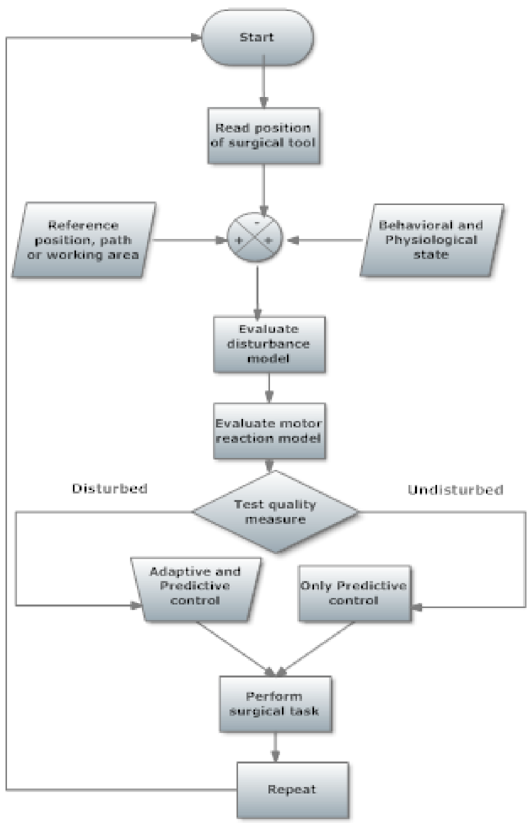


Figure 5.1: Block diagram of the adaptive controller

2) ***The motor reaction model***

The human motor response to tactile vibrations of various frequencies can be modelled using either indirect or direct identification techniques. While the former provides for an explicit mathematical model, it is very difficult to achieve due to the time variant nature of the human response to tactile signal. The later is suitable and easy to apply in our case since the model of the human can be expressed by the control law in use. The direct identification technique compares the actual sensed response to the predicted response and adjusts the control output signal to the human accordingly.

Depending on the response of the human to the disturbances or to the tactile vibrations, the adaptive control system automatically determines if the user is in a disturbed or undisturbed state and automatically switches control to either of the control modes: Predictive and adaptive when the user is disturbed and only predictive when the user is undisturbed.

5.2 The Predictive mode: Methods of direct Adaptive Control

As already mentioned above, the predictive mode of the adaptive controller proposed in this work is characterized by a direct adaptive control algorithm. The choice of the control algorithm is very important in the performance of the adaptive controller. The algorithms used in this work had to satisfy the following conditions:

- It can be applied without a reference model
- The algorithm should be able to adapt and control different types of systems, from stable, unstable, linear to nonlinear and time variant systems
- It should be easy to derive and implement

Based on the criteria presented above three algorithms were selected: an adaptive PID based on the theory of adaptive interaction, an Adaptive neural network based on the theory of adaptive interaction and a fuzzy logic controller.

The PID algorithm

This section presents the summary of the key features of the PID controller. The textbook version of the PID algorithm is described by:

$$u(t) = K_p(e(t) + \frac{1}{K_i}\int_0^t e(\tau)\,\mathrm{d}\tau) + K_d\frac{de(t)}{dt}) \tag{5.1}$$

where y is the measured process variable, r the reference variable, u is the control signal and e is the control error. The control signal is a sum of the three terms: the P-term which is proportional to the error, the I-term which is proportional to the integral of the error, and the D-term which is proportional to the derivative of the error. The controller parameters are proportional gain K_P, integral time K_i, and derivative time K_d. The integral, proportional and derivative part can be interpreted as control actions based on the past, the present and the future. In order to apply the PID control algorithm to the tactile surgical navigation system the parameters, K_p, K_i and K_d are calculated. This can either be done off-line with a method like Ziegler's or online with a parameter estimation algorithm like the adaptive interaction. The advantage of an online tuning algorithm is the fact that the objectives and hence the requirements of a PID controller often change during different stages of control. Also the system to be controlled might change its response to the input with time. In the case of this thesis where we considered the surgeon (human) as the plant, it is clear that the human's motor reaction to tactile signals varies with time and even with different individuals. The offline tuning methods are therefore non-adaptive and cannot account for errors due to variations in the behaviour of the plant. The theory of adaptive interaction was therefore applied to the PID control law in order to create the adaptive controller for the tactile surgical navigation system.

5.2.1 Adaptive PID based on the theory of adaptive Interaction

Theory of adaptive controller

The approach used in this work to tune the parameters for the PID controllers is the so called adaptive interaction developed by Brandt et al. in [27]. The concept behind the theory is to decompose the controlled system into subsystems. In the case of the PID control system, the subsystems include the plant, the proportional, integral and derivative control. The control parameters K_p, K_i and K_d represent the interactions between the subsystems.

When the algorithm is applied to a PID controller it can be viewed as a non-linear controller because the parameters K_p, K_i and K_d are changing continuously according to the adaptation dynamics. The idea is not for the parameters to converge to some constants, but allow them vary as the inputs or disturbances vary with time. Explained below is the derivation of the theory of adaptive interaction and its application to the PID controller.

Consider a complex system consisting of N subsystems which are called devices, with each device $n \in N := \{1, 2, ..., N\}$ having an integrable input and output signal x_n and y_n respectively. The dynamics of each device is described by a generally nonlinear causal functional:

$F_n : X_n \to Y_n, n \in N$, where X_n and Y_n represent the input and output spaces respectively. i.e the output, $y_n(t)$ of the nth device relates to its input, $x_n(t)$ by:

$$y_n(t) = (F_n o x_n)(t) = F_n[x_n(t)], n \in N \tag{5.2}$$

where o denotes composition.

Interaction between devices

The devices interact in a non exclusive dependent fashion, through a connection (labelled for reference as) c. Let the set of all connections be denoted by C. Let pre_c denote a device whose output is conveyed by connection c and $post_c$ be the device whose input depends on the signal conveyed by connection c. Also let the set of input interactions for the nth device be $I_n = \{c : pre_c = n\}$ while the set of output interactions be $O_n = \{c : post_c = n\}$. For instance, if we consider device 3

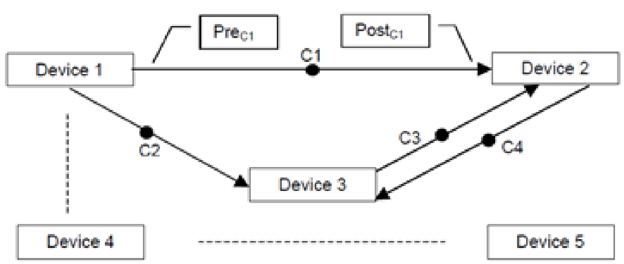


Figure 5.2: Interaction between devices and connections

in Figure 5.2., $I_3 = \{c_2, c_4\}$ and $O_3 = \{c_3\}$. Also since c_2 connects device 1 to 3, it implies $pre_{c2} = 1$ and $post_{c2} = 3$. All interactions are assumed to be linear, i.e the input to a device is a linear combination of the output of the other devices via connections in I_n and possibly an external input signal $u_n(t)$:

$$x_n(t) = u_n(t) + \sum_{c \in I_n} \alpha_c y_{pre_c}(t), n \in N \tag{5.3}$$

where α_c represents connection weights(parameters). An analogy of these connection weights in PID controllers are the control parameters as will be shown in below. It is important to note that we assume that each device is a single-input single-output(SISO) system. This assumption is far from restrictive since the partition of the system into devices is arbitrary and up to the designer; meaning that one can can partition a multi-input, multi-output system into several SISO systems.

The goal of the adaptation algorithm

The direct adaptive control algorithm combines parameter estimates with a control law in order to control classes of plants whose parameters are completely unknown and/or could change with time in an unpredictable manner. The choice of the parameter estimator, the choice of the control law and their manner of combination defines different types of adaptive control algorithms. The goal of the adaptive interaction algorithm is to adapt the connection parameters α_c so that some performance index, $E\left(y_1, ..., y_n, u_1, ...u_n\right)$ (choosen by the designer) as a function of the external inputs and outputs will be minimized. The parameter estimator used in this work is given as follows: For a given system with dynamics given by:

$$y_n\left(t\right) = F_n\left[u_n\left(t\right) + \sum_{c \in I_n} \alpha_c y_{pre_c}\left(t\right)\right], n \in N, \tag{5.4}$$

If $F_n^{'}\left(x\right)$ is the Fréchet derivative[25] of $F_n\left(x\right)$ given by the functional such that: $\lim_{||h|| \to 0} \frac{||F_n[x+h] - F_n[x] - F_n[x] - F_n^{'}[x] o h||}{||h||} = 0$ If the connection parameters α_c are adapted according to:

$$\dot{\alpha} = \left(\sum_{s \in O_{post_c}} \alpha_s \dot{\alpha}_s \frac{\frac{dE}{dy_{post_s}} o F_{post_s}^{'}\left[x_{post_s}\right]}{\frac{dE}{dy_{post_s}} o F_{post_s}^{'}\left[x_{post_s}\right] o y_{post_c}} - \gamma \frac{\partial E}{\partial y_{post_c}}\right) o F_{post_c}^{'}\left[x_{post_c}\right] o y_{pre_c}, c \in C \tag{5.5}$$

and equation 5.4 has a unique solution, then the performance index E will decrease monotonically with time. So the following is always satisfied.

$$\dot{\alpha} = -\gamma \frac{dE}{d\alpha_c}, c \in C \tag{5.6}$$

where $\gamma > 0$ is an adaptive constant and for simplicity's sake, the explicit reference to time has been removed. Combining Equation 5.4 and 5.5 with a control law like the PID control forms the adaptation algorithm which is applied to the vibrotactile surgical navigation system proposed in this work.

Tuning the PID gains

As already mentioned above, an adaptive controller is a combination of the choice of an online parameter estimator, and the choice of a control law in a particular manner to control a time varying system. In this work the parameter estimator used is condensed in equation 5.4 and 5.5, while one of the control laws used is the PID control. In this section we derive the tuning algorithm for a PID controller. This derivation is basically applying the theory of adaptive interaction on a PID controller. Lets consider a PID control system decomposed into four subsystems (devices) as displayed in figure 5.3. Device 1 is the proportional part, with a transfer function 1; Device 2 is the integral part with transfer function s^{-1}, Device 3 is the derivative part with transfer function s; and Device 4 is the human (plant). The

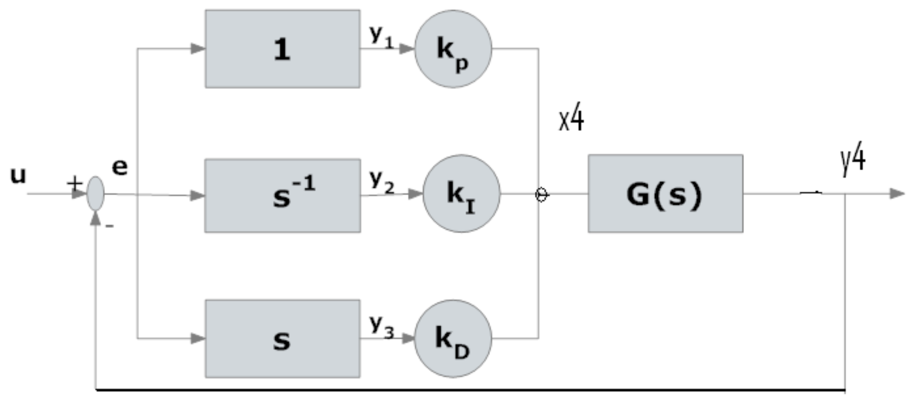


Figure 5.3: PID control system decomposed into subsystems (devices)

adaptive connections are: $\alpha_c := \{K_p, K_I, K_D\}$. The next step is to calculate O_{post_c} for all these connections and then to replace them in equation 5.4. It can be seen from equation 5.5 that, $O_{post_c} = O_4 = \emptyset$ (There is no output interaction from y_4 back to any other device) and therefore equation 4 reduces to:

$$\dot{\alpha} = -\gamma \frac{\partial E}{\partial y_{post_c}} o F'_{post_c}\left[x_{post_c}\right] o y_{pre_c} \tag{5.7}$$

We proceed by choosing a performance index with the goal to minimize the error from figure 5.3 as follows:

$$E = e^2 = (u - y_4)^2 . \tag{5.8}$$

Since F_n and E are instantaneous functions, the functional composition o can be replaced by multiplication. Replacing E into equation 5.6 we obtain for the various control parameters:

$$\dot{K_p} = -2\gamma\,(y_4 - u)\,F'_4\,[x_4]\,y_1 = -2\gamma e F'_4\,[x_4]\,y_1 \tag{5.9}$$

$$\dot{K_I} = -2\gamma e F'_4\,[x_4]\,y_2 \tag{5.10}$$

$$\dot{K_D} = -2\gamma e F'_4\,[x_4]\,y_3 \tag{5.11}$$

Hence to apply the algorithm to a control system, the only information needed about the plant is its Fréchet derivative. Feng Lin *et. al* in [26] found out by simulation that the Fréchet derivative can be approximated by a constant β. Therefore replacing this approximation into equation 5.8, 5.9 and 5.10 and absorbing 2β into the adaptive constant γ, we obtain the following modified online tuning algorithm.

$$\dot{K_P} = -\gamma e y_1 \tag{5.12}$$

$$\dot{K_I} = -\gamma e y_2 \tag{5.13}$$

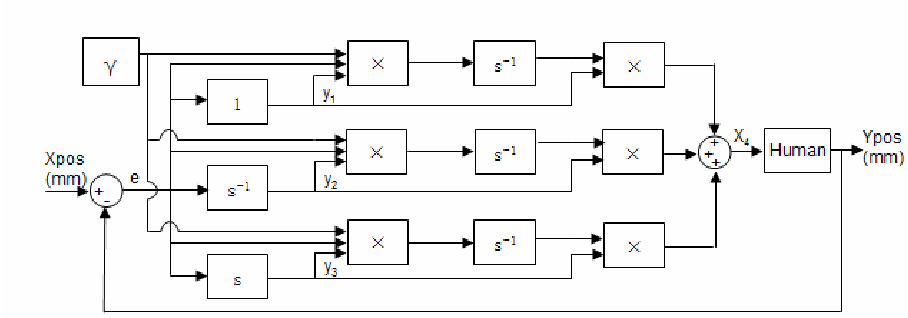


Figure 5.4: PID adaptive algorithm applied to the human (plant)

$$\dot{K_D} = -\gamma e y_3 \tag{5.14}$$

Figure 5.4 shows the block diagram of the adaptive control algorithm applied to the tactile navigation system. The external input to the system $xpos$ is the desired position of the surgical instrument while the $ypos$ is the actual position measured by the pose measurement system (MicronTracker). The numerical solutions of the differential equations described by equation 5.11 to 5.13 give the parameters of the adaptive controller online at every time t. The only parameter which is tuned offline is the adaptive coefficient γ. This was tuned to a value of 0.03.

Simulation studies

This section presents results of simulation experiments performed to demonstrate the adaptation properties of the adaptive control PID algorithm. This can also serve as a prove of the stability of the algorithm. In order to achieve this goal, various types of plants were simulated and controlled using SIMULINK. The Simulink model performed is shown in figure 5.4.

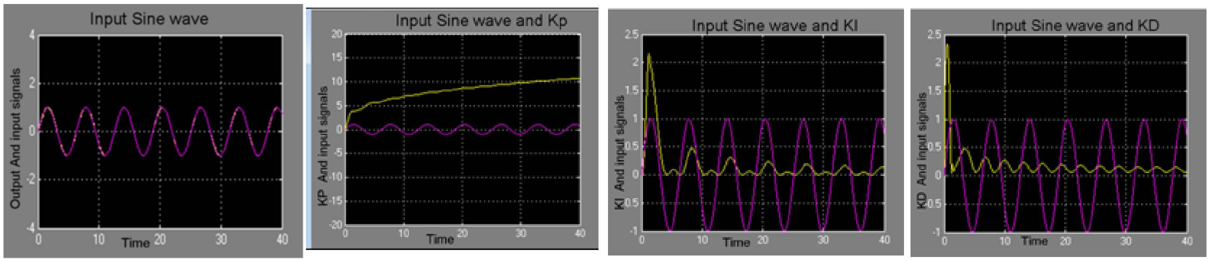
Stable plant

Simulation was started by considering a linear stable plant with the following transfer function.

$$G(s) = \frac{5000}{(s+1)(s+5)(s+100)} \tag{5.15}$$

The value of γ was tuned to a value of 0.03. Figure 5.7 shows the results of a simulation with the input u being a sinosodal with a frequency of $\omega = 0.1Hz$ and a magnitude of 1. After tuning, the rise time and overshoot are excellent as shown in figure 5.7.

Unstable plant

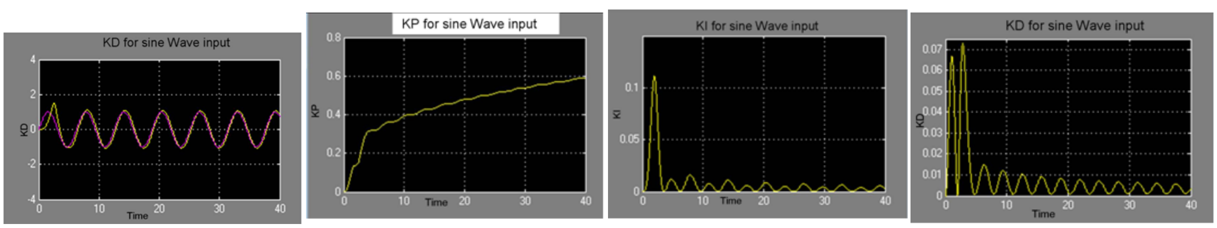


(a) (b) (c) (d)

Figure 5.5: Stable plant

Also simulated was an unstable plant because of the pole at the origin. Figure 5.6 shows excellent adaptation results.

$$G(s) = \frac{5000}{s(s+1)(s+5)(s+100)} \tag{5.16}$$



(a) (b) (c) (d)

Figure 5.6: Unstable plant

The adaptive PID control algorithm based on the theory of adaptive interaction has many advantages including its simplicity and its independence to a plant model. Simulations results above show that it performs well under different conditions, stable or unstable plants. These results motivates the application of the algorithm to the tactile surgical navigation system.

5.2.2 Neural network based on the theory of adaptive interaction

In this section we apply the direct adaptive control algorithm based on the theory of adaptive interaction to the neural networks. Therefore we take the devices in the system as neurons as shown in figure 5.7. The following notations will be used:

- n represents a particular neuron;
- s represents a particular synapse;

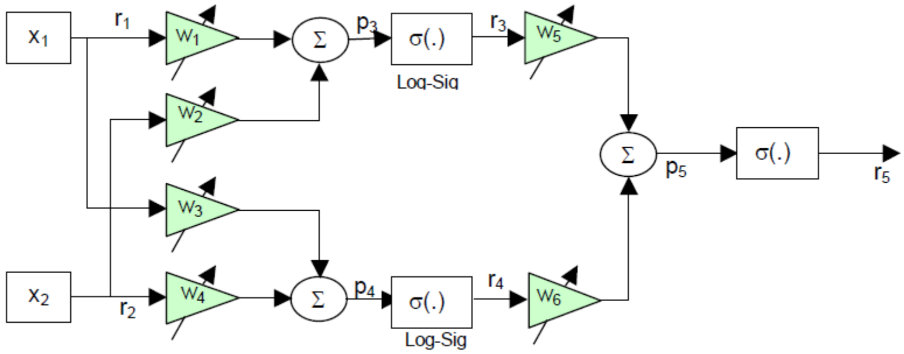


Figure 5.7: Block diagram of a simple neural network

- D_n is the set of dendritic(input) synapses of the neuron, n;
- A_n is the set of axonic(output) synapses of the neuron, n;
- pre_s is the presynaptic neuron corresponding to synapse, s;
- $post_s$ is the postsynaptic neuron corresponding to the neuron, s;
- w_s is the strength (weight) of the synapse, s;
- p_n is the membrane potential of the neuron, n;
- r_n is the firing rate of the neuron, n;
- γ is the direct feedback coefficient for all neurons;
- f_n is the direct feedback signal; and
- σ is the sigmodal function; $\sigma(x) = \frac{1}{1+e^{-x}}$

The neural network and adaptation algorithm can be described as follows:

$$p_n = \sum_{s \in D_n} w_s r_{pre_s} \tag{5.17}$$

$$r_n = \sigma(p_n) \tag{5.18}$$

If we denote

$$\phi_n = \frac{1}{2}\frac{d}{dt}\sum_{s \in A_n} w_s^2 \tag{5.19}$$

which gives us the result:

$$\phi_n = \sum_{s \in A_n} w_s \dot{w}_s \tag{5.20}$$

then by applying the adaptation law in equation 5.4, the weight adaptation becomes:

$$\dot{w}_s = r_{pre_s}(\phi_{post_n}\sigma(-P_{post_s}) + \gamma f_{post_s} \tag{5.21}$$

Equation 5.17 and 5.18 represents the adaptation algorithm for neural networks.

The next step is to apply the adaptive algorithm in equation 5.17 and 5.18 to a direct adaptive controller. The close loop configuration of the adaptive control system is shown in figure 5.8.

As a matter of fact, the direct adaptive neural network controller used in this work has two inputs, e_1 and e_2. e_1 is the error between the set point and the plant output and e_2 is a delayed signal based on e_1.

The introduction of e_2 has a reason as follows. Since the adaptive neural network controller is a memory-less device, in order for the control output to depend not only on the current input (error in this case), but also on past inputs, it is important to introduce some delayed signal. The configuration of the adaptive neural network controller is therefore as shown in figure 5.9.

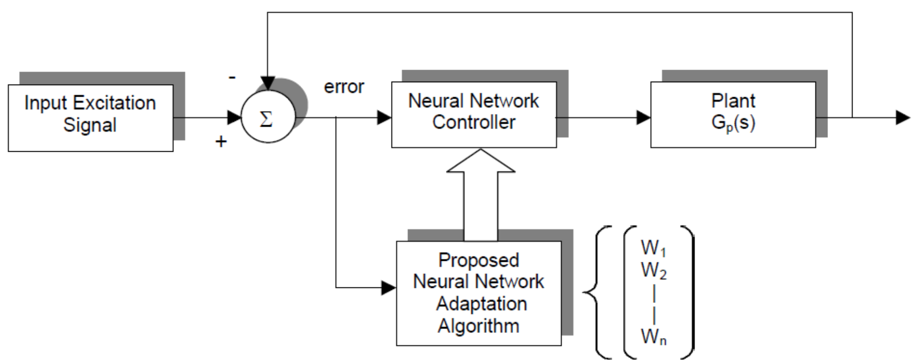


Figure 5.8: Configuration of neural network based adaptive control system

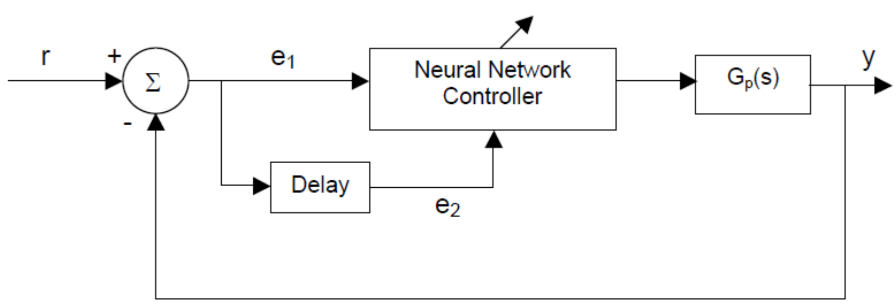


Figure 5.9: Neural network based adaptive control system

The configuration of the output stage the controller was done either with a tangent sigmoid at the output or with a constant gain at the output. The advantage of the tangent sigmoid is the ability to provide a dual polarity signal to the output. Simulation results however show that the constant gain output also works and provides better results.

The input-output relations of the neuraons from figure 5.7 can therefore be described mathematically as follows: $r_1 = e_1$ and $r_2 = e_2$. $p_3 = w_1 r_1 + w_2 r_2$ and $p_4 = w_3 r_1 + w_4 r_2$. $r_3 = \sigma(p_3)$ and $r_4 = \sigma(p_3)$. $p_5 = w_5 r_3 + w_6 r_4$.

Considering $E = e_1^2 = (r-y)^2 = r^2 - 2yr + y^2$ then, $\frac{\partial E}{\partial y} = -2r + 2y = -2(r-y) = -2e_1$.

The adaptive control algorithm presented in equation 5.4 and 5.5 can now be applied to the neural network as follows:

$$\dot{w}_1 = e_1 \phi_3 \sigma(-p_3) \tag{5.22}$$

$$\dot{w}_2 = e_2 \phi_3 \sigma(-p_3) \tag{5.23}$$

$$\dot{w}_3 = e_1 \phi_4 \sigma(-p_4) \tag{5.24}$$

$$\dot{w}_4 = e_2 \phi_4 \sigma(-p_4) \tag{5.25}$$

where $\phi_3 = w_5 \dot{w}_5$ and $\phi_4 = w_6 \dot{w}_6$. It is more complicated to derive the adaptive law for w_5 and w_6 as they are linked to the plant to be controlled. From equation 5.5, O_{post_c} is empty, If the Fr$\acute{e}$chet derivative is approximated by a constant which is absorbed in γ then

$$\dot{w}_5 = -\gamma r_3 e_1 \tag{5.26}$$

and for a similar reason

$$\dot{w}_6 = -\gamma r_4 e_1 \tag{5.27}$$

γ is considered as the adaptation rate or the learning rate. It was varied to analyze the rate of adaptation of the adaptive controller.

Simulation studies

In order to study the effectiveness of the adaptive control algorithm, simulations studies were done on different type of plants. The simulink model is shown in figure 5.10

Effects of different plants

The plants investigated are shown below:

$$G_1(s) = \frac{1000}{(s+1)(s+12)(s+6)} \tag{5.28}$$

$$G_2(s) = \frac{88.76}{s(s+21.5)(s+2.47)} \tag{5.29}$$

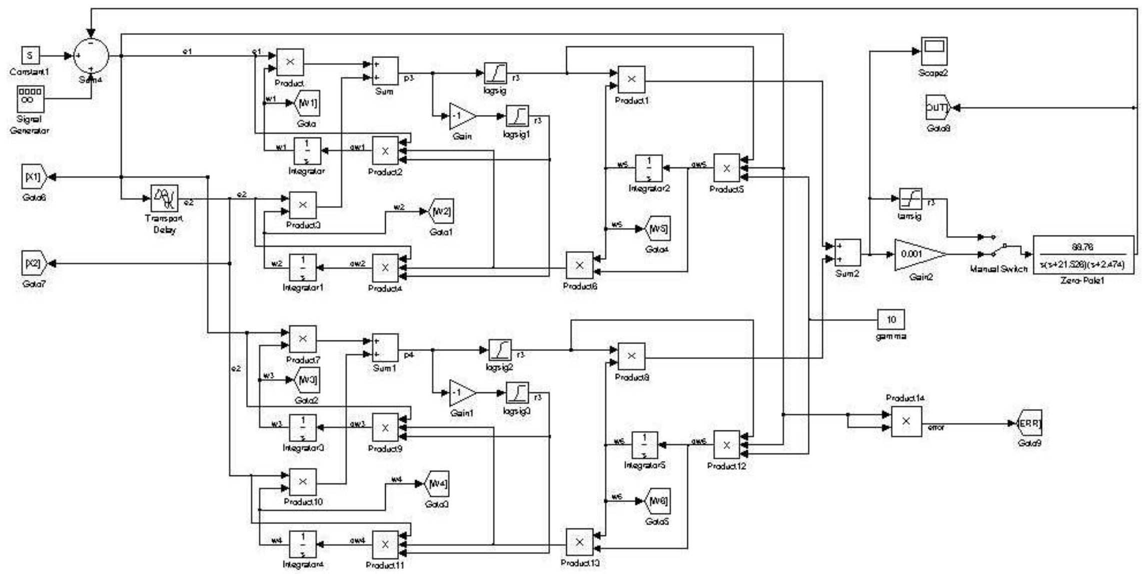


Figure 5.10: Block diagram of simulink model of the adaptive neural network controller

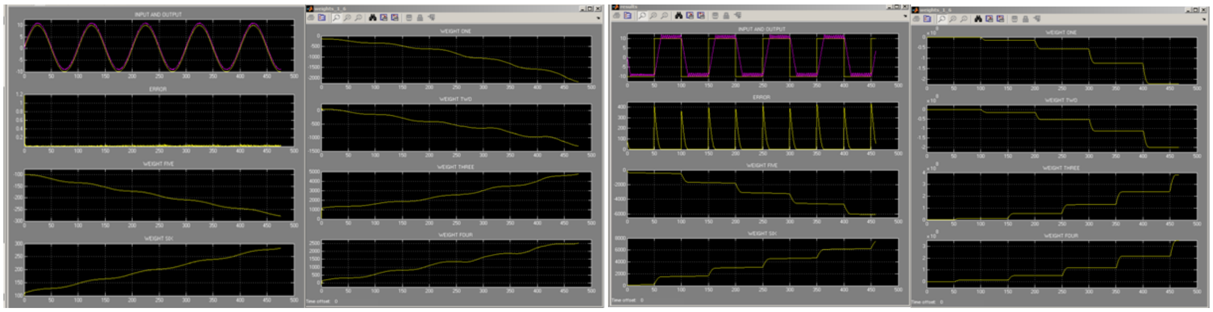
$$G_3(s) = \frac{500}{(s-1)(s+5)} \tag{5.30}$$

The input signals and conditions were:

- Sine wave with frequency, $\omega = 0.001Hz$
- Square wave with frequency, $\omega = 0.01Hz$
- Sawtooth wave with frequency, $\omega = 0.01Hz$
- Amplitude: 10
- Output gain 0.01
- initial weights: $w_1 = -100, w_2 = 100, w_3 = 100, w_4 = -100, w_5 = -100, w_6 = 100$

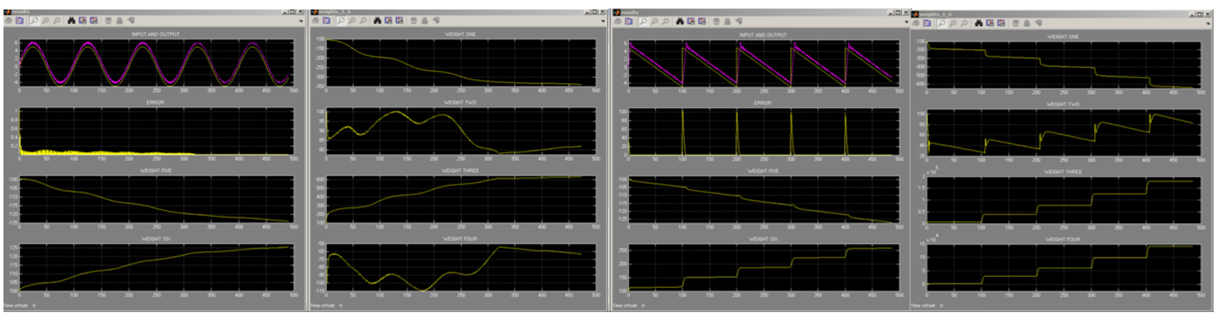
The only parameter that was tuned offline was the adaptive constant, and it was tuned until the algorithm adapted for various plants. It is important to note that plant $G_2(s)$ is open loop unstable because of the pole at the point $s = 0$, while $G_3(s)$ is the so called non-minimum phase systen which is very open loop unstable due to the pole at the point $s = 1$.

The results of some simulations are shown in figures 5.11, 5.12 and 5.13. From the simulation results, it can be concluded that the application of the theory of adaptive interaction to adaptive neural network control results in a direct control algorithm that works very well. The learning works well with different types of second and third order plants. The direct adaptive controller could control plants which are open loop stable or unstable. Finally adaptation was achieved in both minimum phase and non-minimum phase plants. This results provided the motivation to apply this direct adaptive controller to the tactile surgical navigation system.



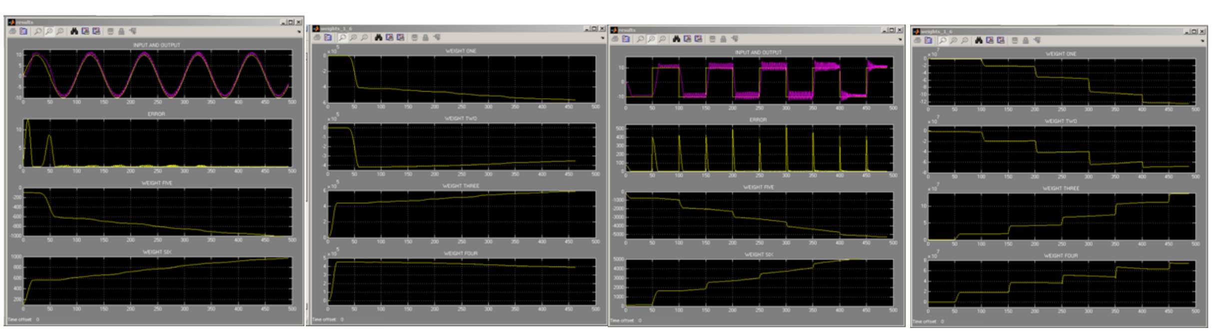
(a) (b) (c) (d)

Figure 5.11: Simulation of a stable plant, $G_1(s)$



(a) (b) (c) (d)

Figure 5.12: Simulation of an unstable plant, $G_2(s)$



(a) (b) (c) (d)

Figure 5.13: Simulation of a non-minimum phase plant, $G_3(s)$

5.2.3 Fuzzy Logic controller

Fuzzy Logic was initiated in 1965 [31], by Lotfi A. Zadeh , professor for computer science at the University of California in Berkeley. In fact, Fuzzy Logic (FL) is a multivalued logic, that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low, etc. Notions like rather tall or very fast can be formulated mathematically and processed by computers, in order to apply a more human-like way of thinking in the programming of computers [32].

Fuzzy controllers are very simple and are based on the concept of fuzzy logic. They consist of an input stage, a processing stage, and an output stage. The input stage maps sensor or other inputs, such as switches, thumb wheels, cameras and so on, to the appropriate membership functions and truth values. The processing stage invokes each appropriate rule and generates a result for each, then combines the results of the rules. Finally, the output stage converts the combined result back into a specific control output value. The method of fuzzy control was one of the direct adaptive control algorithms used in this work.

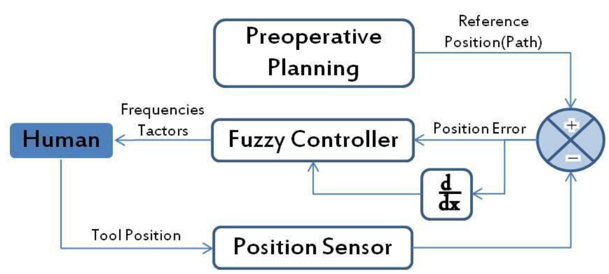


Figure 5.14: Control cycle of the tactile navigation system

In this thesis, the position error and its rate of change are fed into the fuzzy controller, which then determines with what frequency the tactor should vibrate at. Applying a fuzzy controller for positioning control calls for the need to define membership functions for each input and output. Human experience, logic and problem constraints helped in the definition of the ranges of the membership functions. For example the range of the error (5.15) is based on the fact that the user is 100mm away from the target at the beginning and also from the range of errors from previous experiments using the PID controller. Triangular membership functions were used. Figure 5.15 and 5.16 display the membership functions defined for the inputs. NL = Negative large, NM =Negative medium, NS = Negative small, PL = positive large, PM = Positive medium, PS = Positve small, VS = Very small, S = Small, M = medium, L = Large, VL = Very large.

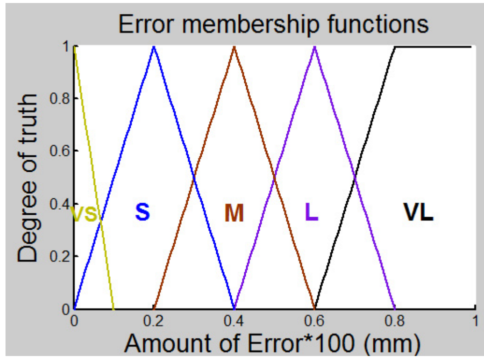


Figure 5.15: Position error (input)

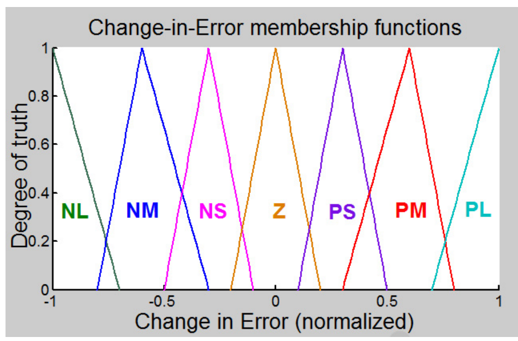


Figure 5.16: Position change in error (input)

Fuzzy rules

The human experience gained during previous experiments coupled with logic provided information for the building of the fuzzy rules. For instance, previous experiments on the system have demonstrated that the velocity of the operator increases with increasing frequency of the vibrating tactors[29]. 35 fuzzy rules were designed for the control of the human as shown in table I. The following notations are used in table I: e_{pos} = position error, $\dot{e}_{pos}$ = change in position error, ω = frequency of vibration.

Rule 35 is therefore implemented as follows: *IF the human is very far from target (position error is very large **(VL)**) AND the change in position error is very large **(PL)**, the vibration frequency is increased to large (L).* The increase in frequency will increase the velocity of the operator towards the target. Defuzzification was based on the mean of the center of gravity. The fuzzy controller thus controls the human via tactor frequency variation to position the surgical instrument.

	Inputs		Output
Rule	e_{pos}	$\dot{e}_{pos}$	ω
1	VS	NL	L
2	VS	NM	M
3	VS	NS	S
4	VS	Z	Z
5	VS	PS	S
6	VS	PM	M
7	VS	PL	L
8	S	NL	Z
9	S	NM	S
10	S	NS	S
11	S	Z	S
12	S	PS	S
13	S	PM	M
14	S	PL	L
15	M	NL	Z
16	M	NM	S
17	M	NS	S
18	M	Z	S
19	M	PS	M
20	M	PM	L
21	M	PL	L
22	L	NL	S
23	L	NM	M
24	L	NS	M
25	L	Z	M
26	L	PS	L
27	L	PM	L
28	L	PL	L
29	VL	NL	M
30	VL	NM	M
31	VL	NS	L
32	VL	Z	L
33	VL	PS	L
34	VL	PM	L
35	VL	PL	L

Figure 5.17: Fuzzy rules

5.2.4 2D Positioning Experiment

The effectiveness of the predictive mode of the adaptive controller proposed in this work was put to the test using a 2D positioning experiment. Each of the three direct control algorithms (adaptive PID, adaptive neural network and the fuzzy controllers) used were tested in the positioning of a surgical instrument. The concept of tactile signal perception has already been proven in [7]. The main aim of this experiment therefore is to verify the improvement in the response of the user to tactile signals when an adaptive controller in predictive mode is added in the control loop.

Set up and Procedure

Nonexpert subjects were to position a surgical instrument held in the hand in an x-y-plane from a start position to an unknown/unseen target position(10 cm away from the start position) generated randomly by the computer. The direction towards the target was indicated by an active tactor. The closer the subject was towards the target position, the smaller the duty factor of vibration. The vibration signal was stopped after the target was reached with a precision of 1mm. During the experiment, the position of the surgical instrument is followed by the pose measurement system and the displacement vector $d(k)$ between the actual and target position is calculated online as follows:

(5.31)

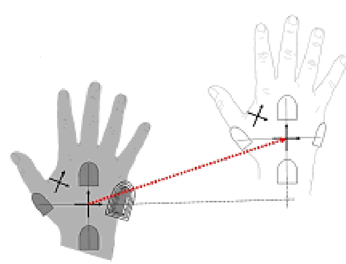


Figure 5.18: Illustration of positioning experiment: Right vibrating tactor indicating directing [7]

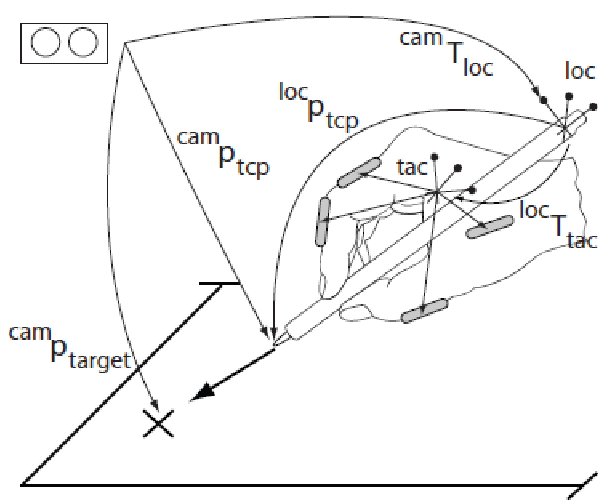


Figure 5.19: 2D positioning [7]

$$^{cam}d(k) =^{cam} P_{target} -^{cam} P_{tcp}(k) \tag{5.32}$$

The displacement vector $d(k)$ between the actual and target position is the input to the adaptive PID, neural network PID and the fuzzy controllers. Four tactors are placed on the back of the user's hand. Each tactor represents the a displacement direction in the plane. In order to use the tactors as direction indicators, the position of the tactors should be provided. Therefore a coordinate system is superimposed on the tactors which is relative to the localizator of the pose measurment system. The transformation between the virtual tactor coordinate system and the localizator is calculated by a transformation matrix $^{loc}T_{tac}$ and stored. The tactor position can therefore be expressed in the tactor coordinate system. The displacement vector between the actual and target positions are derived by a calibration matrix.

$$^{tac}d(k) = (^{loc}T_{tac})^{-1}.(^{cam}T_{loc})^{-1}.^{cam}d(k) \tag{5.33}$$

All subjects were right handed students between the ages of 21 and 38. None of the subjects reported any sensory difficulty. 5 subjects repeated the experiment 5 times each for each controller.

Results of 2D positioning experiment

The two criterion used to evaluate each control algorithm are the time taken to perform the task and the shape of the area curves. The area of the error curve was also considered in the comparison between the fuzzy controller and the non-adaptive PID controller. It is assumed that the faster the user reaches the target, the better the user understood the tactile feedback by the controller. The shape of the error curve provides information of how well the control errors progressed with time. A steeply falling error curve shows that the user was rather confident as to where the destination point lay. A smaller area under the error curve also indicates that the overall time taken to reach the destination was low. The area under the curve was calculated using the following formula [29].

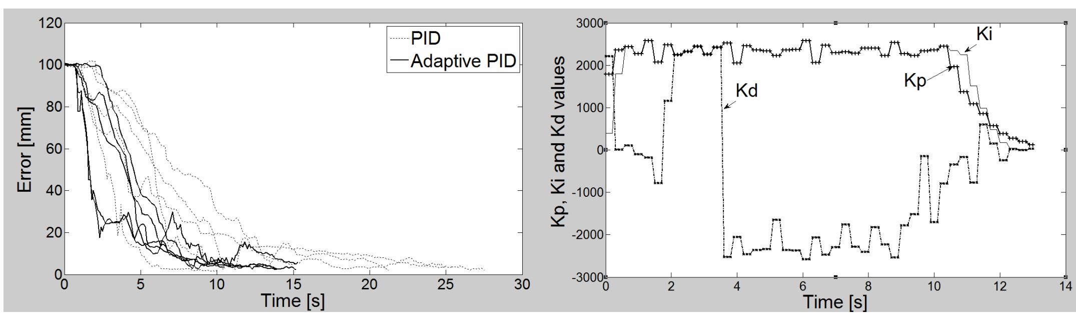
$$A = \sum_{i=1}^{k_{max}} \frac{|e(k_1)| + |e(k_0)|}{2}.\,(k_i - k_{i-1}) \tag{5.34}$$

Where $e\,(k)$ is the error at time k and the area between two data points is approximated to a trapezium.

Results show that all the direct adaptive control algorithms used could help navigate a user with tactile signals to the target position. Each controller was compared with the non-adaptive PID controller in order to select the representative algorithm to be presented in this thesis.

Table 5.1: Summary of performance of each controller

Controller	time (s)		Area
	Mean (s)	SD (s)	Mean
non-adaptive PID	29.44	13.48	841.03
Adaptive PID	17.28	5.11	397.12
Adaptive neural network	24.41	8.02	610.41
Fuzzy controller	19.07	8.52	531.45



(a) (b)

Figure 5.20: (a)Decreasing error curves for adaptive PID controller compared with those of the non-adaptive PID controller, (b)Varying adaptive controller parameters

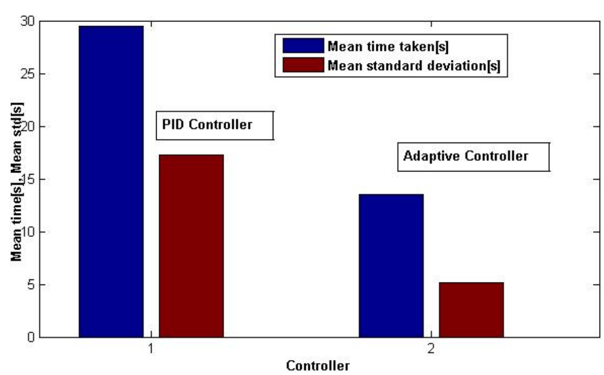


Figure 5.21: Mean, standard deviation of duration for positioning task by five subjects during five runs each for both the adaptive and PID controllers

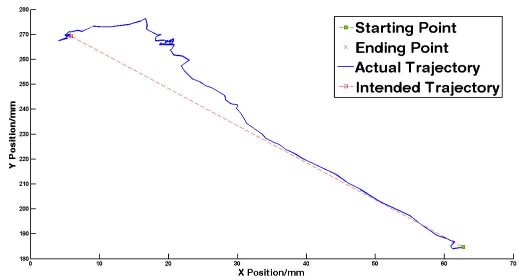


Figure 5.22: Movement in the x-y plane for one run of the fuzzy controller

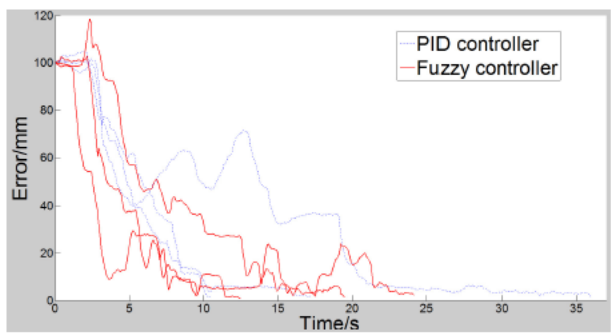


Figure 5.23: Error curves of one subject showing three runs for each controllerr

Table 5.1 shows the summary of the performance of each controller. These results show that the duration of the positioning task could be reduced by up to 12.16 seconds on applying adaptation. As a matter of fact the adaptive PID controller enables the user to perform the positioning task in the shortest period of time. Individual differences were neglected when deriving the parameters of the non-adaptive PID controller. This is also reflected in the results as not only better results are obtained during adaptation, but the standard deviation of the non-adaptive PID controller is the highest. The more erratic nature of the error curve from the non-adaptive PID controller betrays the time variant nature of the positioning task.

User feedback indicated that higher vibration frequencies were interpreted as a warning signal. Higher frequencies were thus used to indicate that the user was close to the destination. This conclusion was already arrived at in a related study in [29]. The fact that a higher vibration frequency acts like a brake for the user when he or she is approaching a target can be very useful in surgical navigation. In the case of neurotologic surgery, tactile signals can be used to provide information about safety areas, volumes, margin and trajectories. The next experiment presented is a milling experiment which takes advantage of this motor reaction of humans to tactile signals. During the milling experiment an inverse version of the adaptive PID controller will be used, whereby the frequencies will be increased with decreasing distance between actual and target position.

5.2.5 Milling Experiment

Milling is one of the many surgical techniques which can be enhanced by the use of computer aided surgical systems. There are a number of different implantable hearing aid devices which provide hearing aid for patients on the market. These devices are implanted during a surgical procedure called cochlear implant. After a general anaesthetic is given a "bed" is usually milled in the mastoid bone behind the ear. The implant (receiver or stimulator) will then be placed in this bed. The milling is done with a small cutting burr around an outline marked by placing a template of the hearing device on the mastoid bone. Another application of the milling exercise is in microsurgery in the middle ear. More than 20 million people suffer from eardrum infections which require surgical intervention[30]. In middle ear surgery the surgeon is faced with very small structures like ossicles and sensitive structures such as nerves and blood vessels. However in order for the surgeon to get access to the operating field, he has to mill with extensive force. Both applications of the milling exercise presented above require a degree of accuracy by the surgeon during the tasks to avoid pain and damage of sensitive structures during surgery. We foresee the use/practicality of tactile navigation systems in milling tasks in the future and therefore studied a milling task.

The human intuitive understanding of tactile signals is explored in a milling experiment by comparing human feedback and response to the system's multimodal navigation processes. Multimodal signals have been shown in [7] to be more intuitive and thus provide better results as opposed to purely visual signals. The aim of the milling experiment in the present work is to analyse the improvements in accuracy and duration when an adaptive controller is added in the control loop. Multimodal navigation has been proven to be better and therefore this work concentrates on improving the human response to multimodal signals, reason why the experiment was done only in the multimodal mode.

Setup and Procedure

The experimental setup is shown in figure 5.24. The subjects were to mill a plastic skull specifically on an integrated plaster model which represented the ear channel. The plastic skull together with the plaster model represented the patient in the experiment. During the experiment, position information about the patient and surgical instrument were measured by an integrated optical pose measurement system

(MicronTracker). The preplanning of the milling area was done before the experiment and this was a circle of diameter 2.0 cm in the ear channel. This was defined as the working/go area and the subject was to mill within this area without exceeding the borders. Since the milling of bone in cochlear implant is done in a 2D plane and then repeated with a new depth, the experiment was done only in a 2D plane. In order to avoid errors that occur with the resolution of CT (computer tomography) images the planning phase of this simplified experiment was done by analytically defining the working area. The experiment was performed in multimodal mode, meaning that in addition to a tactile support on the back of the hands, the circle was also displayed on a monitor and the subject could visualize the actual position of the milling tool which was indicated in the enabled working area. The accuracy

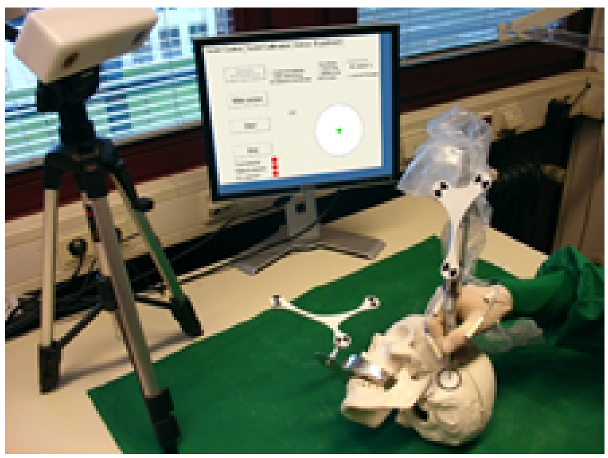


Figure 5.24: Experimental setup of milling experiment

evaluation was based on how well the subject milled within the working area and without exceeding the border. The distance of the last 5mm to the border was indicated by an increasing frequency of 1 Hz to 5 Hz of tactile vibrations. The task duration was analysed and the difference between the border circle's geometry and the actually milled region on 36 equidistant points (figure 5.25) were calculated. Five non-expert subjects between the ages of 22 and 38 performed the experiment five times each per controller. All subjects had previous experience with the positioning experiment described above.

In order to calculate the relative relationship between the surgical instrument and the patient, localizators are attached on the patient as shown in figure 5.24. Also shown in figure 5.25 is the coordinate system and the transformation of the coordinates. The surgical instrument is calibrated before the start of the experiment. In this case the transformation ${}^{tool}T_{tcp}$ between the instrument localizator *tool* and the instrument tip *tcp* is known. The following transformation can be calculated

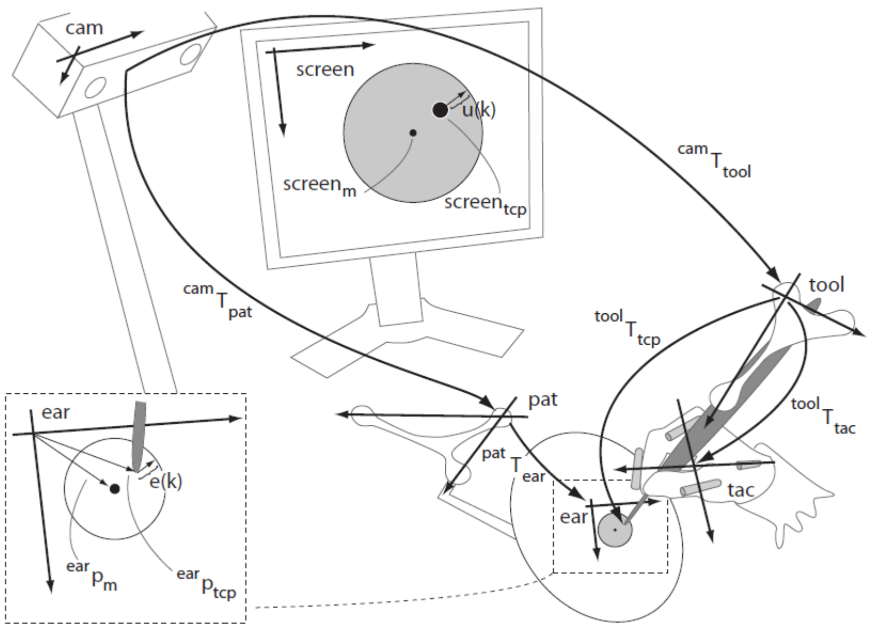


Figure 5.25: Coordinate system and coordinate transformation of the experimental environtment [29]

between the *pat* localizator and the *ear* localizator.

$$^{pat}T_{ear} = (^{cam}T_{pat})^{-1}.^{cam}T_{ear} \tag{5.35}$$

The area to be milled by the user is determined by the calibrated instrument. Before the start of each experiment, the midpoint of the area $^{ear}P_m$ is registered by pointing the instrument tip.

Results of the Milling experiment

The results show how the adaptive controller was an improvement over the non-adaptive PID. The accuracy of the experiment was measured in terms of the precision in mm and the duration to complete the task. The mean and standard deviation shown in table 5.3. shows an improvement in the mean error of about 70 microns with the addition of the adaptive controller in the control loop while the standard deviation improved by 60 microns. The duration of the milling task has seen an improvement of 17s.

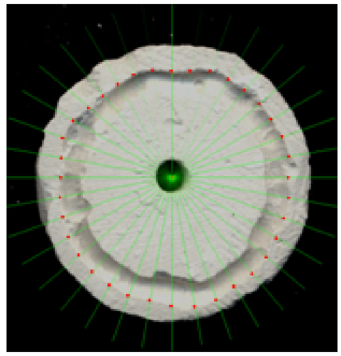


Figure 5.26: One run milling result of one subject showing 36 equidistant points

Table 5.2: Comparing accuracy of milling task with the non-adaptive PID and adaptive PID controllers

	non-adaptive PID	Adaptive PID
Mean error(mm)	-0.34	-0.27
Standard deviation(mm)	0.45	0.39
Duration (mins)	1:31	1:14

5.3 Adaptive mode

The adaptive mode monitors, characterizes and controls the surgeon's reaction to disturbances . it adapts to errors not detected by predictive mode. The control values depend on the demands of the surgical task in question. Mastoidectomy in cochlear implant was chosen a case study not only because it is a common procedure as well as stand alone task, but also because the entrance to the lateral skull base has many applications.

5.3.1 Adaptive mode during milling of beds for cochlear implant

The milling experiment described in section 5.2.5 already accomplishes the first step of mastoidectomy as shown in the results in figure 5.26. This experiment however helps the user to mill only the boarders of the required bed. In order to mill the complete cavity where the receiver will seat, the adaptive mode of the adaptive controller is applied in conjunction with the predictive mode of the adaptive controller. This section describes the design of the predictive mode. Two strategies were used for the adaptive mode during the milling of beds for cochlear implant.

1) ***Variation of the milling mode***

The milling mode describes the method used to plan the trajectory of the milling instrument. However the human is not a machine, so free hand milling is done intuitively and can vary between individuals and geometry. The idea behind the variation of the milling mode is to restrict the user to mill in a particular direction in order to remove leftover bone material which prevents the receiver from fitting in the milled bed.

In order to achieve this goal, the milling process was divided into two main stages.

- Milling of the non critical area (stage 1)
- Milling of the critical area (stage 2)

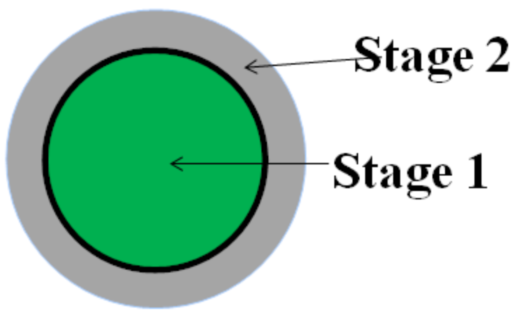


Figure 5.27: View of milling stages

Stage 1 serves to remove a maximum of bone material in a predefined working area considered not to be critical. During this stage, tactile feedback is provided to the user as described in section 5.2.5. That is to say the user is to mill within a predefined working area without exceeding the boarder. If he/she does, he receives a vibration depending on the position of the milling instrument. The radius of the working area is smaller than the radius of the required bed.

The remaining portion of the working area is considered close to critical anatomic structures like nerves and is supposed to be milled even more carefully. This is done in stage 2 as mentioned above. During this stage, the adaptive mode of the controller is switched on and the user is directed by tactile signals in a predefined mode. The following modes of moving the milling instrument were designed and experimented.

- Vertical milling mode
- Horizontal milling mode

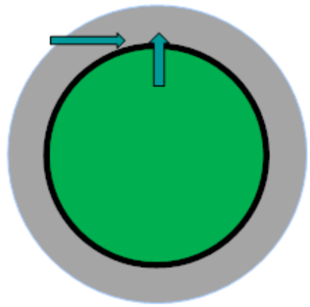


Figure 5.28: Vertical and horizontal milling modes

Adaptation is provided to the user by switching the milling procedure from one mode to the other. From a control system point of view, the control signal provided to the user in stage 1 is opposite to that provided in stage 2. In stage 1, the control signals are tactile vibrations serving as an alert signal for the user, indicating his nearness to the predefined boarder, while in stage 2, the tactile signals provided to the user directs him to move towards the direction of vibration.

2) ***Vibration of all tactors in critical situations***

During, the positioning experiment described above in section 5.2.4, the user was prompted by vibration of all tactors to indicate the end of the experiment. This idea can be used in the adaptive mode of the controller whereby, all tactors are vibrated when the user approaches critical structures or boarders. This is intended to make the user come to a halt and reconsider the trajectory of his or her instrument. This method of adaptation is applied to both stage 1 and 2 of the milling procedure as described above.

Chapter 6

Experiment and Evaluation

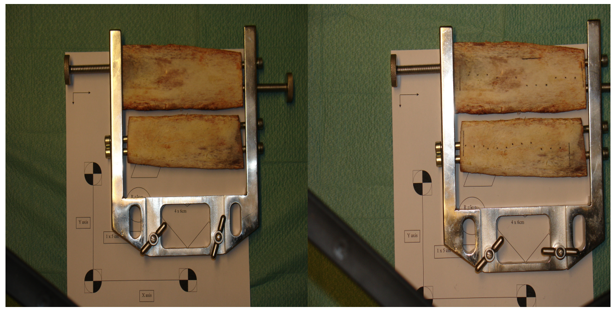
Presented in this chapter are the experiments to investigate how adaptation can affect the use of vibrotactile display during a surgical procedure. The surgical procedure chosen for this purpose is milling in cochlear implant surgery as described below. The results were compared with those obtained with other support systems in literature.

6.1 Milling of beds for cochlear implant

The effectiveness of the adaptive controller developed in this work is verified. This experiment is carried out both in the predictive and adaptive mode of the controller. The user is expected to mill an implant bed for the receiver of a cochlear implant device.

6.1.1 Setup and procedure

The experimental setup is shown in figure 6.2. The subjects were to mill bone material from a cow. During the experiment, position information about the patient and surgical instrument were measured by an integrated optical pose measurement system (MicronTracker). The preplanning of the milling area was done before the experiment and this was a circle of diameter 2.0 cm in the ear channel. This was defined as the working/go area and the subject was to mill within this area without exceeding the borders. Prior to the experiment three small holes are made on the bone to represent the center and two points on the circumference of the circle to be milled. The image of the bone is taken and uploaded to the computer. The image is then loaded to the monitor. A calibration between the real bone and the image on the monitor is done by pointing the surgical instrument on three corresponding points on the bone clicking with the mouse. A small white dot hovers the image to indicate the position of the instrument on the monitor.



(a) (b)

Figure 6.1: a) Bone material mounted for milling before preplanning b)Bone material after preplanning with holes representing center and circumference of circles to be milled.

The working area was divided into two stages as described in section 5.3.1 above with both stages having a border. During stage 1 (1 mm of diameter) of the milling procedure, the distance of the last 5mm to the border was indicated by an increasing frequency of 1 Hz to 5 Hz of tactile vibrations. During stage 2, the tactile signals were provided to the user through one of the two different forms as described below. The user indicated when he was finished with stage 1 and then stage 2 was initiated. Through the remote monitor, the user had a visual feedback of the system output. The outline of the area to be milled was not drawn on the bone material, but could be seen on the remote monitor.

Due to the fact that during a real cochlear implant operation, the preparation of a groove for the electrode is done after the package bed is milled, this task was not performed in this experiment. Hence the milling area was disc-shaped. The milling task was performed in two variants:

a) *Variation of milling mode*

During this variant of the experiment, the user is directed by tactile signals in either a horizontal or vertical direction as shown in figure 5.28. In order to do this the distance between the instrument and the border of the milling area of stage 2 was calculated. If the current position is within the planned milling area (less than 5mm from the border) the system does not do anything and the user is allowed to manually mill the bone without any tactile feedback. Near the borders and outside the predefined area, the adaptive controller activates one tactor which indicates either vertical or horizontal milling. Since this proved to be confusing for nearly every user during pre-experimentation, the tactile signals were provided, but the user was still in charge of the control of the milling system. The variation of the milling mode by various tactors therefore served as a warning signal, indicating that the user should reconsider the path of his surgical instrument or concentrate if he is in a disturbed state.

b) *Vibration of all tactors during critical situations*

As already indicated in section 5.2.4, the end of the positioning experiment could be communicated to the user by vibrating all tactors. The fact that the user actually stops when all tactors vibrate is applied to the adaptive mode of the controller. During stage 1 of the experiment, the distance of the last 5mm to the border was indicated by an increasing frequency of 1 Hz to 5 Hz of tactile vibrations. However if the user is in such a disturbed state that the instrument is sensed to be out of this working area, all tactors immediately vibrate. The user indicates when he is finished with stage 1 and stage 2 is activated. If the user is within the planned area, the system does nothing and allows the user to manually mill. If the user is 5mm away from the planned border, all tactors vibrate until the user moves the instrument back into the planned area.

Since the milling of bone in cochlear implant is done in a 2D plane and then repeated with a new depth, the experiment was done only in a 2D plane. In order to avoid errors that occur with the resolution of CT images the planning phase of this simplified experiment was done by analytically defining the working area. The experiment ended when the user indicated that he is through milling the predefined area. The accuracy evaluation was based on how well the subject milled within the

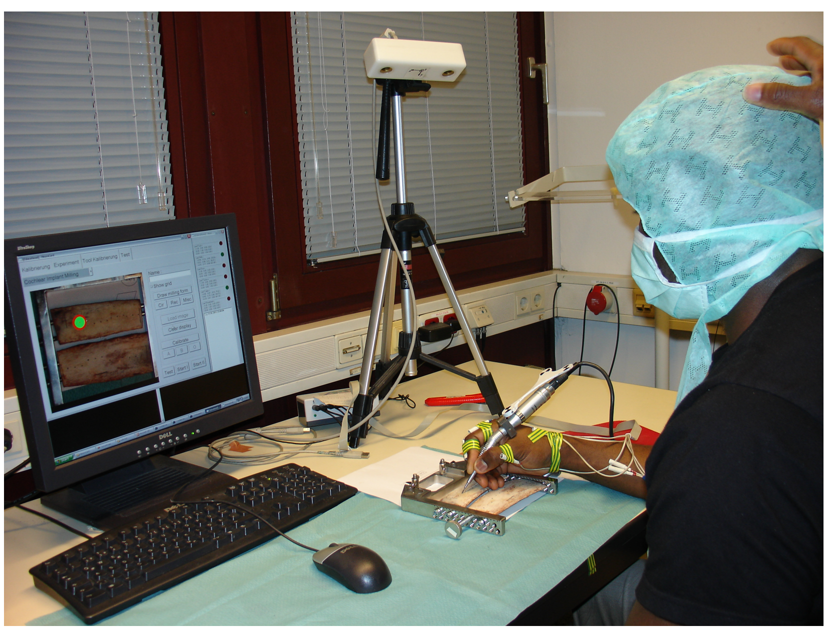


Figure 6.2: Experimental setup of experiment: Green and red circles on the monitor shown indicating stage 1 and stage 2 respectively. The small white dot indicates the present position of the instrument

working area and without exceeding the borders in stage 1 and 2. This was done by calculating the difference between the border circle's geometry and the actually milled region on 36 equidistant points. The task duration was also analysed.

6.1.2 Subjects

Six subjects (one expert and five non-experts) between the ages of 22 and 43 performed the experiment three times each per variant of the experiment. The variants were either *adaptation by variation of milling mode* or *adaptation by vibration of all tactors* as described above. All subjects had previous experience with the positioning experiment described above. As a matter of fact, 6 persons, 3 runs each per variant, with 36 measuring points, implying $N = 648$ per variant.

6.1.3 Results and evaluation

The aim of this experiment was to investigate the performance of the adaptive controller in a scenario closely related to a surgical application (cochlear implant). The results are also compared with those obtained in similar experiments with different support systems for the surgeon.

The measured size of the milled cavities was compared to the desired package bed size. The following precision could be achieved for the milling task performed by two approaches and taking the recorded time (see table 6.1 and 6.2). Table 6.3 shows the comparison of results obtained with conventional freehand milling and other support systems in literature.

The assisted milling based on different approaches of presentation of the tactile feedback was successful. The results also show that a better accuracy could be obtained when the method of adaptation was based on vibration of all tactors. When the subjects were questioned on which approach of adaptation they found more effective, most of them indicated that the concept of vibrating all tactors was a better means of alerting them causing them to a kind of reset of the procedure and hence reminding them to concentrate. The variation of the milling mode was described by subjects to be rather confusing for two reasons: Firstly presenting tactile signals to indicate direction when the subject was 5mm away from the boarder was too ambitious as he cannot directly interpret the direction to follow. This is in agreement with results obtained with the positioning experiment in Chapter 6. This is also as a result of the fact that as stated in section 2.4, an intuitive tactile language, one that requires very little cognitive processing to interpret, may be very difficult to design or require extensive training.

Secondly during stage 1 of the experiment, tactile feedback was provided to the subject in the form of an alert. That is to say the tactile signal was like a ”break” for the subject to stop him from crossing the predefined boarder. However, in stage 2, the mode of presentation of the tactile feedback was inverted. The subject therefore needed a lot of cognitive activity to switch from one method to control to another. The subjects actually confessed that they actually only considered the tactile feedback in this case as alert and did not care or follow the coded direction.

Another interesting finding revealed by the result is the discrepancy between the accuracy obtained in the milling experiment in section 5.2.5 and stage 1 of this experiment. Both experiments are similar in design but the difference of 0.93mm between the mean errors is rather alarming and deserves an explanation. This may be as a result of the fact that the material milled in the former experiment was a plaster model as compared to real cow bone in the later experiment. The hardness of the cow bone caused an increase in the vibration of the surgical instrument and hence served as attenuation for the perception of tactile vibrations.

The expert subject was an ear, nose and throat(ENT) surgeon with 5 years of working experience. The results show that the accuracy of the expert subject during the variation of the milling mode was better in stage 1 by 0.3mm and in stage 2 by 0.7mm. When adaptation was provided by the vibration of all tactors, the accuracy of the expert subject during stage 2 increased by 0.2mm. The expert subject required about half the time used by the non-expert subjects during all experiment. The accuracy of the expert subject is comparable to the accuracy of the conventional freehand milling and is higher than the accuracy using an image-based navigation system in milling task.

Comparing the results in table 6.1 and 6.2 with results in the state of the art (table 6.3) it can be noticed that milling with navigated control leads to the highest accuracy.

Table 6.1: Accuracy of milled cavities compared to desired cavities for 5 non-expert subjects

	Variation of milling mode		Vibration of all tactors	
	Stage 1	Stage 2	Stage 1	Stage 2
Mean(mm)	-1.1	-1.6	-1.2	-1.3
SD(mm)	0.48	0.46	0.49	0.42
Mean Duration (s)	253	193	230	197
SD of Duration (s)	32	29	34	27

Table 6.2: Accuracy of milled cavities compared to desired cavities for 1 expert subject

	Variation of milling mode		Vibration of all tactors	
	Stage 1	Stage 2	Stage 1	Stage 2
Mean(mm)	-0.8	-0.9	-0.9	-0.7
SD(mm)	0.32	0.35	0.35	0.32
Mean Duration (s)	121	87	116	85
SD of Duration (s)	25	27	24	28

Table 6.3: Accuracy of milled cavities compared to desired cavities from literature

	Accuracy(mm)		Duration(s)	
	Mean	SD	Mean	SD
Freehand milling[44]	0.8	0.2	178	28
Image based navigation system[17]	0.3	–	900	–
Navigated control[44]	0.2	0.2	244	35
Surgical robot[13]	0.3	0.1	540	–

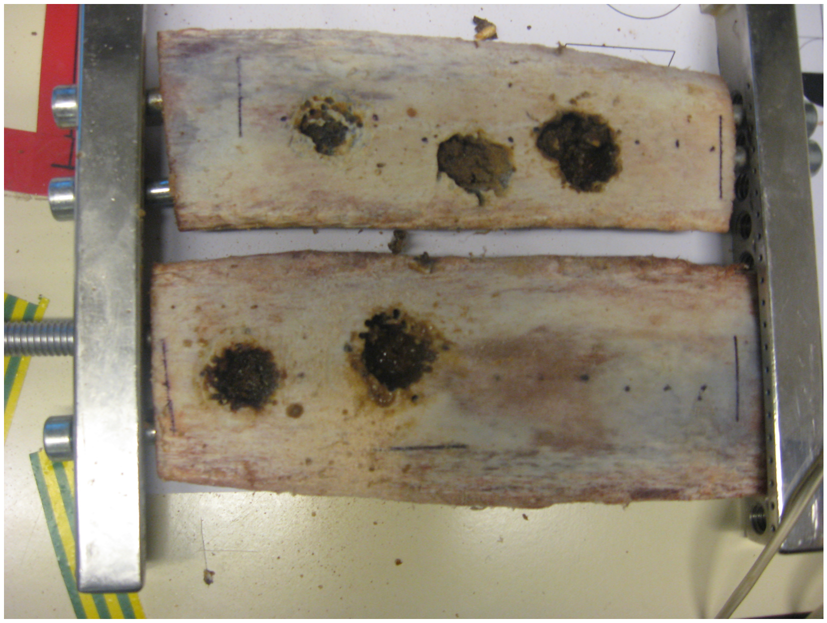


Figure 6.3: Cavities milled by one non-expert subject during five runs

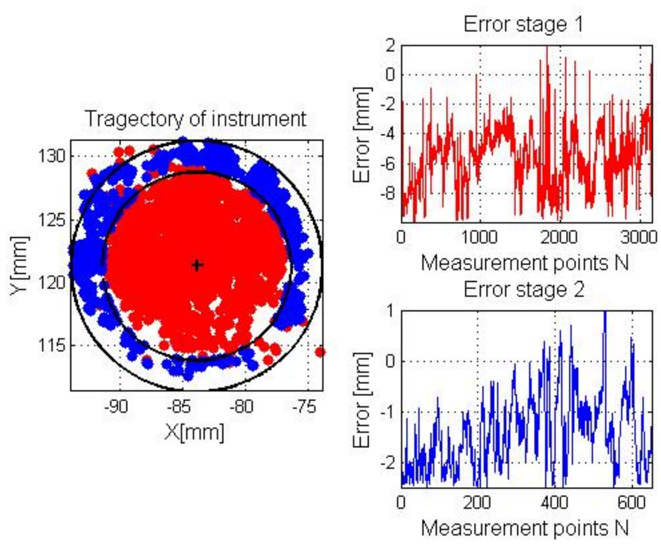


Figure 6.4: Plot of desired values(solid line) and measured values for one run: Red represents stage 1 and blue represents stage 2

6.1.4 Discussions and limitations

Herein, described is a first step along what will likely be a lengthy road toward clinical testing and implementation of mastoidectomy via an adaptive controller in tactile surgical navigation. This first step involved the modification of the control component of the tactile navigation system to adapt to the user while he is performing complex milling on a bony specimen. In the testing with 5 non-expert subjects and

1 expert subject, it was found that the surgeon's preoperative plan was successfully executed by the subjects with the expert subject obtaining an accuracy comparable with that obtained in freehand milling and higher than that obtained with an image based navigation system. Excitement at this success is tempered, however, by the realization that a great deal of work remains before this concept can be tested in the operating room. Although the fundamental engineering concepts behind the control technique are well developed, less well studied is the translation of such concepts to clinical applications. This was a rather simplified experiment which neglected issues such as maintenance of sterility and possible floor of blood which can cover the area of intervention.

It is important to acknowledge the limitations of this study. Firstly during the experiment,there was the lack of soft tissue work, which comprises at least a substantial portion of any ear surgery. Secondly the users were not always very confident with their interpretation of the tactile signals provided to them. For this study to attain its full potential, more work has to be done on the factors affecting the human perception of tactile signals.

The pose measurement system was another potential source of error as the accuracy of the experiments also depends on its tracking accuracy. Being an optical measurement system, it brings along the disadvantage of line of sight. When an object or human is between the line of sight of the pose measurement system and the markers on the specimen, the system cannot measure the position. This usually lead to confusion especially for the non-expert subjects

Chapter 7

Conclusions and Outlook

This thesis has investigated the design of an adaptive controller for a tactile surgical navigation system. While applications of vibrotactile signals have been proposed, or studied by other researchers [39, 40, 41], there has been no formal studies of how best to design a method of adaptation the user. This research is the first formal investigation into the design of an adaptive controller for a tactile surgical navigation system.

The aim of this research was to investigate how to design an adaptive controller to adapt to inconsistencies in the system caused by disturbances due to inter-individual differences, time variation of behaviour, loss of concentration among others. In Chapter 2, the thesis statement was as follows:

"In order to obtain more consistent and reproducible motor reactions from the human in response to tactile signals, the system must be designed to adapt to the human. Thus, this thesis presents an adaptive controller for the multimodal navigation system. The concept is to consider the surgical procedure as a control problem with the human as the plant. An adaptive control algorithm is developed, studied and applied to the system and experiments to compare the accuracy of the system with and without adaptation are designed and conducted."

This statement has been defended by answering the following questions:

Q1: What method of adaptation can be applied to the user when he is in an undisturbed state?

Q2: What method of adaptation can be applied to the user when he is in a disturbed state?

These two questions have been addressed through a review of the state of the arts on adaptive control algorithms and by a series of experiments related to surgical procedures. This chapter summarises the work reported in this thesis and discusses how the findings answer the two questions above.

Results obtained have shown one hand that adaptation leads to better accuracy and lower time to complete tactile navigation task and on the other hand that performing surgical task with the tactile surgical navigation system is comparable in accuracy to conventional freehand milling. The accuracy of other support systems in literature like navigated control and surgical robots is higher than obtained with the tactile surgical navigation. To conclude, one can say that there is a great potential for the application of tactile feedback in surgery, but more work has to be done to take these studies from the laboratory to the surgical room.

7.1 Summary

Chapter 3 provided a review of support systems in surgery, adaptive control systems in surgery and the applications of tactile display. This chapter identified a number advantages and disadvantages of different support systems in surgery. It also identified various control algorithms which might be useful in the design of the adaptive controller presented in this work. In addition, this chapter discussed various applications of tactile feedback, thereby putting the work presented in this thesis in context.

Chapter 4 discussed the strategy for the design of an adaptive controller for a tactile surgical navigation system. This approach was to consider the human as the "plant" and to control the human both when he is either in a disturbed or an undisturbed state. In addition, this chapter also presented the various components of the tactile navigation system.

Chapter 5 Highlighted the realization of the approach used in this thesis. It also reported two experiments investigating the accuracy of the various adaptive control algorithm used for the undisturbed mode of the adaptive controller presented in this work. The results of the positioning experiment showed that the adaptive PID control algorithm based on the theory of adaptive interaction was the best of the three algorithms chosen. In the milling experiment, it was shown that the introduction of adaptation increased the accuracy and reduced the duration of a procedure related to milling in middle ear surgery.

In Chapter 6, An experiment related to milling in middle ear surgery was presented and the results were discussed and compared with those obtained in literature.

7.1.1 Outlook

The work in this thesis is the first formal investigation into the design of an adaptive controller for a tactile surgical navigation system. It has, therefore, opened up many more questions and research ideas which have been outside the scope of this thesis. These ideas are summarised in this section.

Evaluation of tactile navigation system in real world situations

As identified in Chapter 6, one limitation of this work is that the tactile navigation experiments have only been carried out in a lab setting, with the user's full attention is on the task. To establish whether tactile feedback could be effective in real world surgical applications, it will be necessary to carry out navigation experiments in different contexts and under different degrees of workload. Therefore, experiments should be carried out to investigate how navigation is affected by other tasks, such as walking and talking with staff.

Assessing the impact of training

The experiments in this thesis tested tactile navigation after a very short training period of around 5 minutes. It would be interesting to see how performance is affected by different types of training. In particular, no feedback was provided to users during the training for these experiments. It is possible that providing feedback during the training session might give users more confidence in their responses, and could also correct any miss-mappings they may have made. Another possibility is to investigate how performance changes after people have been exposed to them regularly over an extended period of time. This could be achieved by keeping a data bank of subjects and conducting a longitudinal study with the same subjects over a period of time.

Modelling the motor reaction of humans to tactile vibration

This thesis presented an adaptive controller for a tactile surgical navigation system. The system allowed the characterization of the human control behaviour in real time. However, this characterization was done using the so called direct identification where the plant model is parametrized in terms of an unknown control parameter vector. There was therefore no explicit model mapping tactile input to motor output.

Another interesting future work for this thesis will be to apply the method of indirect adaptive controllers. Indirect adaptive control algorithms estimate the plant parameters online and use them to calculate the controller parameters. This approach is therefore based on an explicit plant model. The task could then be to verify if using an explicit model in the control loop will lead to better results in tactile navigation.

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