Haptic feedback

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Haptic Feedback

A literature study on the present-day use of haptic feedback in medical robotics

A.F. Rovers

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DCT Report nr. 2002.57

TU/e – Practical Traineeship Report

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Dynamics and Control Technology Group

...However, after nearly 15 years of development, we are now witnessing the evolution of the truly intuitive interface. Interestingly, it is not the visual modality per se that won the race to deliver this interface, but the combined senses of vision, force and touch...

(Prof. Robert J. Stone)

Contents

Preface

This report is written as a preparation for my final project in the Control Systems Technology group at the Eindhoven University of Technology. The main goal of this report was to provide insight into recent developments on the field on the use of tactile feedback in medical robotics to perform remote Minimally Invasive Surgery.

Chapter 1

Introduction

The first chapter gives an introduction to the MIS-surgery techniques and medical robots that are currently available. Also the limitations of the human operator are studied. With this knowledge it is possible to study the system requirements in the second chapter. The third chapter finally provides an overview of the control and modelling techniques that are found during the literature study.

1.1 Minimally invasive surgery

Traditional surgical approaches have utilized incisions intended to provide the maximum exposure of the operative site. On the contrary minimally invasive surgical approaches (MIS) employ small incisions through which cameras and instruments are passed to accomplish the operation from within a body cavity (fig. 1.1, [24]):

- **Camera:** A laparoscope is inserted trough one of the incisions. The laparoscope is composed of a chain of lens optics to transmit the image of the operation site to the CCD camera connected to its outer end, and optical fibers to carry light to illuminate inside.
- **Instruments:** The instruments used for the operation are specially designed long and thin instruments with trigger-like handles. They are inserted through trocars placed at the incisions to air seal the body cavity.

The MIS technique with its small incisions brings along some advantages for both the patient and hospital [36],[11],[8]: reduced trauma and post-operative pain resulting in shorter hospital stays and faster rehabilitation times for the patient, smaller risk of infections because of the limited incision in the body and better cosmetic results.

Unfortunately the MIS technique also has some disadvantages. Due to the nature of endoscopic surgery, the surgeon has no direct view on the surgical scene and has lost the ability to palpate tissues and organs. The corresponding diagnostic information is lost[1]. Furthermore, motion is usually restricted to 4 degrees of freedom and on top of this, the motions are in reversed directions resulting in more difficult instrument handling (fig. 1.2).

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[1] Palpation is critical to identifying otherwise obscure tissue planes, arterial pulsations, and regions of tissue thickening that may signify pathology such as infection or cancer.

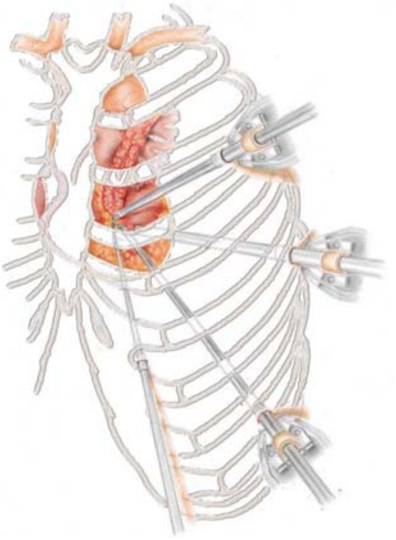

Figure 1.1: MIS operation (through thorax)

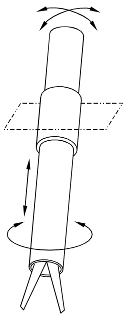

Figure 1.2: The 4-dof's of a laparoscopic intrument

Depending on the body part under treatment, MIS can be subdivided in: thorascopy (chest cavity), arthosocopy (joints), pelviscopy (pelvis), angioscopy (bloodvessels) and laparoscopy (abdominal cavity).

1.2 Medical robotics

A classification of medical robotics is provided in Appendix B.1. This section focusses on master-slave systems in which direct contact between the surgeon and patient is uncoupled by using a remote system that tracks the motion of the surgeon. Interference between the two systems is possible. Therefore medical robotics might be used to overcome some of the disadvantages of MIS technique [36],[1],[33],[11]:

- Motion and force scaling can be used to obtain an increased precision.
- A master-slave setup can result in a more ergonomic operating environment. This results in less fatigue and hand-tremor. Remaining tremor can be filtered away by software filters.
- New procedures that would otherwise be impossible to perform due to human limitations are now among the possibilities.

Some articles [22],[29] claim that the efficiency of certain MIS procedures can be increased by using robotic techniques, while other [24],[4] state that the efficiency decreases because of the complex handling of the robotic instruments and the time that is required to set-up the system.

When studying master-slave systems one could ask if it would be a good idea to go one step further and introduce completely autonomous robots. In [1] Wall gives some arguments why autonomous robots are not welcome yet:

- Computing power is still several decades away from the cognitive insight a robot requires to deal with the delicate human body.
- The operation room (OR) environment is complex to implement these systems.
- Surgeons distrust and fear machines that completely take over their practices.

At the moment two master-slave systems are commercially available: the ZEUS robot from Computer Motion Inc. and the Da Vinci from Intuitive Surgical Inc. Both systems are based on conventional MIS techniques: two robot arms control the endoscopic instruments and a third arm to guide the laparoscopic camera. The surgeon operates the robot from the surgeon console in which a (possible 3D) view of the remote site is displayed. Force feedback is not available. A more detailed discussion can be found in Appendix B.2.

1.3 Human Operator

The medical robotic systems that are used nowadays provide no force feedback, so valuable information is lost. Furthermore the human sense forms a sort of independent channel to the brain whose information is assimilated quite subconsciously. By adding an independent input channel, the amount of information that is processed by the brain is increased. The increase in information reduces the error and time taken to complete a task. It also reduces the energy consumption and the magnitudes of contact forces used in a teleoperation situation [31].

Before starting to design a robotic system that provides haptic ("touch") feedback, it is important to understand the working of the human operator: sensing and precision of movements. Human sensing is subdivided as follows ([31],[32] and references therein):

- **Kinesthetic sensing:** this form of sensing uses proprioceptive feedback from the muscular and skeletal system. Kinesthetic sensing encompasses larger scale details, such as basic object shape and mechanical properties, for example, compliance.

- **Cutaneous sensing:** uses information that is provided via the mechanoreceptive nerve endings in the glabrous skin of the human hand. It is primarily a means of relaying information regarding small-scale details in the form of skin stretch, compression and vibration.
  The receptors can be classified as rapid adapting (these provide little to none static response and allow perception of higher spatial frequencies) and slowly adapting (primary concerned with sensation of cutaneous pressure). Table A.1 in Appendix A.1 shows a detailed overview of the mechanoreceptors and their properties.

Kinesthetic sensing detects frequencies up to 10 Hz while cutaneous sensing is able to detect much higher frequencies. However the ability to discriminate between mechanical vibration sensations decreases above 320 Hz.

The human response to different actions can vary from 1-2 Hz for unexpected signals, to 10 Hz for reflex actions [28]. Jones not only mentions similar bandwidths in [15] but also specifies the resolution and thresholds for the kinesthetic system (Table A.2 in Section A.1). When the motions are performed in a fixed and awkward position this results in a tremor of the hand: a noise signal with an amplitude of 0.003 mm and a frequency between 8 and 12 Hz [8].

Chapter 2

System Design

The second chapter focusses on several aspects of the system design. First the system requirements are studied. These are the minimal requirements that are needed to make a robot useful for surgery. Next, the modules for hard- and software design are studied. Finally the non-technical demands for a sucesful surgery system are described.

2.1 Specifications

2.1.1 Qualitative specifications

When designing the PHANToM haptic interface[1] Salisbury did the following observations with respect to haptics [20]:

- Force and motion are the most important haptic cues.
- Many meaningful haptic interactions involve little or no torque.
- A small wrist-centered workspace is sufficient.

An ideal haptic interface should therefore meet the following criteria [20],[7]:

- Free space must feel free. This means that the natural dynamics of the system should not distract the user from the system: low friction and apparent mass, no backlash.
- Solid virtual objects must feel stiff. According to Salisbury users can be convinced that a virtual surface with a stiffness of at least 20 N/cm represents a solid, immovable wall.
- Virtual constraints must not be easily saturated. The force that can be generated should be sufficiently high to represent most haptic interaction.

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[1] See also Appendix Section B.3.

2.1.2 Quantitative specifications

Summarizing Section 1.3 and Appendix A.1 one can draw the following conclusion with respect to the general useful bandwidths and force level:

- Bandwidth kinesthetic sensing: up to 10 Hz.
- Bandwidth cutaneous sensing: up to 320 Hz.
- Bandwidth of human motion: up to 10 Hz with a tremor signal between 8 and 12 Hz.
- Comfortable force level for one finger: up to 7 N.

In [18] Kilchenman and Goldfarb investigate the effect of the control bandwidth and force saturation level of a haptic controller. Test-persons were asked to perform tasks with regard to size identification. Information above a bandwidth of 40 Hz and a force level of 3 N did not significantly improve the performance of the subjects, although adding higher levels of force feedback or system bandwidth, the designer might be improving the realism of the simulation as compared to touch interactions with non-synthetic objects.

The precise features of the device under design strongly depend on the operations for which it will be used. In [8] Kwon and Song analyzed different microsurgical environments (fig A.3) with respect to tool motions and accuracy. By using the tool models (fig A.1) and accessory force-ranges (fig. A.2) one can estimate the design specifications for a particular task.

When designing a robot for a particular task one can also obtain the specs from measurements on instruments during a real operation. Table A.3 shows for example the design specifications or suturing a knot as presented by Çavuşoğlu et al. [17].

2.2 Hardware design

The design of the haptic interface has a big influence on the perceived haptic information. Inherent mechanical impedance of a haptic display may determine the impedance range which can be produced while the friction degrades the force resolution and increases force thresholds for the haptic device. Although a controller might cancel out these effects one should carefully design the hardware. Appendix Section B.3 provides a list of (highly accurate) master and slave components and their characteristics that are commercially available: Sensable PHANToM, Immersion Laparoscopic Impulse Engine, Immersion Impulse Engine, Force Dimension DELTA and Z-KAT WAM.

In order to use these devices successfully one must consider the following points:

- Adding an extra 2-dof EndroWrist to the interface makes performing some tasks more easy (especially when suturing knots [17]).
- The set-up of the device must provide an ergonomic workspace.
- The bandwidth of the controllers and dynamics of the interface should be high enough to permit natural movements and enable sufficiently accurate

force-feedback. Further more natural dynamics of the device should not distract the user from the scene (apparent mass and friction low).

Commercially available devices allow rapid set-ups of new experiments, but are often expensive and sometimes even difficult to control. To overcome these problems, custom-made devices are often used in laboratory setups as shown in Appendix Section B.3.

2.3 Software design

The software design process might include the following components:

- Controller for the master and slave robot.
- Communication protocol to interchange information between the master and the slave (or virtual environment).
- Simulation of a virtual environment: this is especially useful in 3D environments or laboratory situations in which a slave system that senses a real environment is not present. For 3D scenes voxmaps are often used (eg. [21])
- Safety-layers, etc.

In [16] MacLean et al. discuss the several possibilities for a system architecture to control haptic media. Subjects like multi-tasking, multi-processor and communication mechanisms are discussed. For each robotic system one has to balance the presented architectures based on the pro's and con's for the particular task under consideration. A detailed study on network based communication protocols can be found in [25].

Many haptic master-slave systems use two independent loops (either on a multiprocessor system or remote computer): a fast haptic controller at 500-1000 Hz and a data exchange rate and graphic loop (both 30 Hz) [10],[19]. The communication is often implemented by using sockets over ethernet protocols, but the latencies inherent to shared network paths make serial and parallel links an increasingly attractive option when the CPU's are physically nearby [16].

2.4 Introducing a new system into the OR

Besides the specifications mentioned in the previous section, a medical robot has to satisfy more demands in order to be accepted in the operation room. Computer Motion Inc. evaluates the appropriateness of new equipment along their so called "four cornerstones of robotic surgery" [36]:

1. **OR Readiness:** the new system should be compatible with existing systems so it can be integrated seamlessly. Areas to consider comprise for example protocols for sterilization, set up procedure for the system, instrument changes and resilience, and patient safety.

2. **Procedural compatibility:** the new system should be compatible with the current OR's and procedure given the typical space constraints given by the OR and the endoscopic surgery procedure. Areas to consider comprise for instance: size of footprint, ease of storage of (modular) parts of the system, obstruction of working space, etc.
3. **Precision and dexterity enhancement:** a robotic system should perform better than the current procedures. Using robotics allows increased precision (eg by filtering hand tremor), motion scaling, a more ergonomic operating environment, etc.
4. **Open architecture and upgradability:** hospitals incorporating robotic equipment should look for products that can be easily upgraded and expanded for maximum flexibility and quality.

Chapter 3

Controller Design

This chapter provides an overview of controller architectures for haptic systems that are described in literature. First, the basic architectures are explained, followed by the different modifications to these structures.

3.1 Classification of controller architectures

In literature haptic control architectures are frequently classified by considering the information streams. By looking at the direction of the commands, the following classification is possible [34]:

- **Unilateral:** communication takes place in merely one direction. Only master motion and/or forces are transmitted to the slave.
- **Bilateral:** communication takes place to both directions.

Classification based on the type of information that is exchanged is also often encountered (e.g. [5]):

- **Impedance control:** the force applied to the haptic device is controlled by detecting the movement commanded by the operator.
- **Admittance control:** the force commanded by the operator is detected by the controlled system and used to control the velocity/displacement of the haptic device.

The classification of a controller into one of the groups mentioned above is not always obvious. Sometimes force is used as an additional input to the impedance controller, or displacement is used as an additional input to the admittance controller. There also exist controller architectures with observers that use the position to estimate the force, or that generate a desired position based on the measured force [5].

3.2 Basic controller architectures

The following bilateral controller architectures are often used during basic haptic experiments ([2],[30] and figure 3.1):

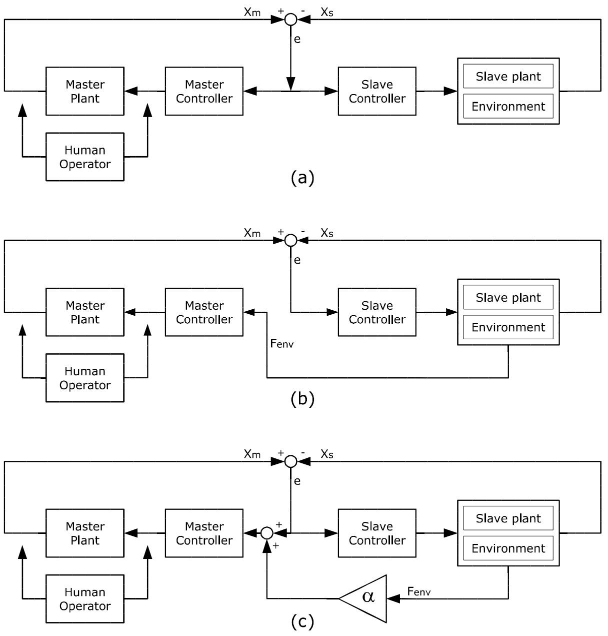

Figure 3.1: (a) PERR, (b) KFF, (c) P+FF

- **PERR (Position Error architecture):** The force send to the master/slave is proportional to the position error between the master and slave. In order to provide good tracking the gain should be set as high as possible, but not to high to avoid actuator saturation. In [3] Hannaford recommends using a PD-controller without an I-action because integral feedback is not desirable in position error based force feedback control for it creates a time varying force feedback under conditions of steady state contact. However, other articles describe PERR architectures that work good with a PID-controller.
  The PERR architecture is in the same as the open-loop impedance control [5], symmetric servo system [30] and force reflection [26].

- **KFF (Kinesthetic Force Feedback architecture):** A force sensor connected to the slave end transmits forces back to the master, while the master position is used to command the slave. This architecture is also referred to as force reflecting servo [30].

- **P+FF (Position and Force Feedback architecture):** The force send back to the master is a linear combination of the position error (PERR) and the interaction force between the slave and the environment (KFF), while the master position is used to command the slave. A special variant is the impedance controller with force feedback [5] in which the interconnections of the signals are slightly different from the normal P+FF structure. By setting the ratio between the position error and force gain, this architecture can vary between a pure PERR and KFF architecture.

In [23] Çavuşoğlu explains how the P+FF structure can be used to investigate which architecture performs best. A so-called alpha curve shows the highest fidelity achievable with a P+FF controller as function of the force gain alpha[1], subject to stability and tracking constraint. The location of the maximum fidelity indicates which controller architecture is the best[2],[3] and if the amount of performance improvement justifies the use of the force sensor.

Adding force sensors not only results in extra costs, but also adds extra mass to the haptic device which alter the dynamics of the device in a negative way (Carignan [5],[23]). The choice may end up being determined by the environment being simulated as well as the characteristics of the haptic device.

A number of articles investigated the performance of the different control architectures. Because of different performance goals and models it is difficult to make a generalized statement of which architecture performs best. One of the major problems with KFF structures is the measurement noise that is present in the force signal[4]. If sensor noise is limited, KFF is often a good choice because of the good force tracking and stability [2],[5],[23].

In [2] Sherman states that control architectures like rate control (based on velocities instead of positions), remote site compliance, and impedance control are not suited for this application because they are designed for situations that will not arise in telesurgery such as manipulating in a large workspace, large time delay, or hard contact tasks.

3.3 Extending the basic architecture

The basic controller structures from the previous section are often used as a starting-point to design new controllers. This section lists some extensions and modifications to these structures.

3.3.1 Modifications

In [12],[26] the KFF architecture is extended with a damping injection term to guarantee passivity. This makes it possible to guarantee intrinsically stability, independent on the choice of parameters and time delay[5].

The Shared Compliance Control structure (SCC) consists of a KFF structure with an extra compliance term in the slave. This extra term results in a smoother mechanical contact interaction between the manipulator and objects [35],[26]. Experiments conducted by Kim et al. demonstrate that the performance of a SCC is significantly better that pure KFF for bigger time delays.

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[1] The defenition of alpha is different from the alpha in figure 3.1

[2] PERR and KFF can be regarded as special cases of the P+FF form: P+FF with force gain $\alpha = 0$ results in PERR, while a force gain $\alpha = 1$ results in KFF.

[3] For example: if the KFF end is the maximum, then it is better to use purely the force sensor output as the source of force feedback. However, if the maximum is located at an intermediate point, it is possible to have better performance by using a combination of position error and the force measurements to generate force feedback. The relative value of the peak value of the curve to the PERR value can be used to judge if the amount of performance improvement justifies the use of the force sensor.

[4] Often noise in force measurents is significant larger than in position measurements.

[5] within certain limits.

3.3.2 Observers

In [8],[9],[7] Kwon et al. add a disturbance observer to a KFF architecture to cancel out non-linear effects of the system due to coupling and friction. The observer uses both master and slave forces and the master position as input signals. The output of the observer is added to the force applied to the operator. Although the proposed control method is not perfect, the operators haptic perception has been increased.

When the force signal for the human operator is not available, an alternative observer can be used as described by Carignan in [5], in which an architecture with two loops is presented. The slave force is measured and a desired tool position is calculated in the outer loop. A servo controller in the inner loop tracks the haptic position with the desired position. The outer loop with difficult (slow) reverse kinematic calculations can be run at a lower rate than the inner loop.

3.4 Other controllers

3.4.1 Model based controllers

Model based controllers are very useful when dealing with large time-delays. The Predictive Controller described in [26] and references therein is similar to the KFF structure, but it uses a Smith predictor to anticipate on the delayed force information from the slave. A model of the dynamics of the slave dynamics is therefore needed in the master controller. Also a prediction method combined with wave variable that enhances the performance of the Smith controller and maintains passivity is described (PCP: Predictive Controller with Passivity).

In the Adaptive Motion/Force controller from Wen-Hong Zhu [26],[34] each manipulator has its own local adaptive position/force controller. Four channels are used to exchange position (or velocity) and force information in both directions. This method guarantees robustness against large time delays and compensates for structured system uncertainties by applying independent parameter adaptation and strong feedback control. Besides, the technique is applicable to both rigid and flexible environments.

3.4.2 Sliding Mode Controller

The Sliding Mode Controller (SMC) presented in [26] and references therein is defined at the slave side in order to achieve a perfect tracking in finite time of the delayed master position, while an impedance controller is used at the master side. This controller offers robustness and can deal with time-delay. Four variables are send from master to slave (delayed position, velocity, force of human operator, delayed force F_{ed}), while only one variable is send from slave to master (force F_{ed}).

3.5 System model

System models are not only needed to simulate the system, but sometimes they are incorporated in the model (e.g. inverse kinematics, Smith predictor) or needed when using design tools like H_∞.

3.5.1 System hardware

The models of the system hardware used in literature are standard dynamic models. Depending on the application the model can vary from simple 1-dof spring/damper system to complex multi-body dynamic models.

3.5.2 Environment model

Although the properties of the remote environment are important for tuning a controller[6], not all authors use environment models to verify the controller design. The environment models encountered in literature vary from simple spring/damper models to complex 3D shapes modelled by voxels (see section 2.3).

In [13] Brouwer et al. present a device to measure vivo tissue properties that can be used in models of the human body (slave environment). In the future a database with gathered properties will be made public on the internet as resource for other engineers.

3.5.3 Human operator

At the master-side the robot interfaces with a human operator that fulfills a sort of external controller function. Therefore also properties of the human operator are important (e.g. stiffness, delays in response, etc.)

Unfortunately, models of the human operator are rarely used in literature. Most systems were tested with an experiment in real-life after the system was build, or forces are treated as external disturbances to the model. In [27] Kammermeier states that this is because in the majority of published research works of human-oriented disciplines, such as physiology and psychology, the analysis methods and arguments are mostly based on verbal descriptions and not on formal engineering language. In the same paper Kammermeier presents a framework for the model of the human operator that is compatible with system engineering models. The proposed systems theoretical framework describes the principles of human perception as a concatenation of nonlinear vector mappings. Although the paper only describes a framework of the model, the technique may become very useful in the future when the unknown parameters of the model are determined by further research projects.

A simpler model is used by Wen-Hong Zhu [34], in which the dynamics of the human operator and the dynamics of the flexible environment are assumed to be second-order mass-damping-stiffness systems with known upper and lower bounds on otherwise unknown parameters.

3.6 Design strategy

Only a minority of the papers accurately describe the design strategy of the controller on forehand. Çavuşoğlu [23] mentions some important design points

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[6] eg. because a soft environment can easily result in instability, this has taken into account when designing a controller.

to come to a good design:

1. It is important to have task-based performance goals rather than trying to achieve a marginally stable, physically unreachable ideal teleoperator response.
2. Teleoperator control design should be explicitly formulated as an optimization to accommodate task-based performance metrics.
3. Design of the teleoperation system must be oriented towards improving performance with respect to human perceptual capabilities. It is necessary to experimentally quantify human perceptual capabilities and to develop control design methodologies which will provide the means to include this in the control design.

When using a robust controller design the stability of the system should first be evaluated by using a robust stability criterion [2]. The set of gains that meet this criterion can then compared based on performance criteria stated by the optimization problem.

Chapter 4

Conclusion

Because of the many advantages of MIS surgery, this technique is becoming more and more popular. This is clearly visible in literature by the increasing number of papers that is written on this subject. With the current state of technology it is also possible to use master-slave robotics that makes performing certain MIS techniques more easily. The first commercial systems are already available.

After studying a number of papers with respect to master-slave systems that are operated by a human operator it became soon obvious that it is very difficult to formulate the system requirements in terms as bandwidth and force levels. This is mainly caused by the fact that human touch is not sensed by a single organ, but by a rather complex mechanism of the nervous, muscular and skeletal system in which each part has it own properties. The minimal required bandwidths for the controllers mentioned in literature vary with the tasks to be performed by the robot. Therefore it seems wise to determine the required system requirements experimental by doing some measurements on the tasks to be performed by the master-slave system (before starting to design the new system).

Although master-slave systems exist for long a long time, most research with respect to haptic systems only took place recently. In the past mainly the basic architectures like PERR, KFF and P+FF were used, sometimes a little modified or extended with an observer. When studying the literature from the last few years, one notices an enormous development in new controller architectures (nice overview by Arcara: [26]). Looking at the new developments it seems like if robust design techniques and incorporating system models is becoming more popular to be able to improve stability and handle with time-delays. Unfortunately it is not possible to tell which controller performs best for this strongly depends on the system under design, the desired specifications and the properties of the remote environment.

One thing that is corrigible is the approach to the design problem. Only occasionally the problem is handled as structured by Çavuşoğlu in [23]. It is also striking to see that models (and simulations) of the human operator are used only occasionally in literature to improve controller performance, while it seems to be important to know how the operator responds to different events. Probably this can be imputed to the fact that most models of the human operators that are available are formulated rather vaguely in words and not in models and transfer functions that are ordinary used frequently by control engineers.

Appendix A

Human operator

This appendix contains an overview of characteristics of human sensing and specifications that a medic robot should met in order to be used successfully for surgery tasks.

A.1 Human sensing

Table A.1 shows the properties of the mechanoreceptors in the glabrous skin of the human hand as discussed in Section 1.3 (source: [32]).

In [15] Jones gives a detailed overview of the possibility of the human kinesthetic system. Some perceptual characteristics are depicted in Table A.2.

According to [31], for the "average user" the index finger can exert 7 N, the middle finger 6 N, and ring fingers 4.5 N without experiencing discomfort or fatigue. Forces on individual fingers should be less than 30-50 N total.

A.2 Surgery tasks

Figure A.1 shows the most common instruments and accessory motions that are used during surgery [8]:

Parameter	**Value**
1. Kinestetic sensing: muscle and joint signals	
Output bandwidth of (voluntary) limb movement	< 10 Hz
2. Cutaneous sensing: mechanoreceptor / nerve endings in the glabrous skin of the human.	
a. Rapid adapting:	
- Small field: RAI - motion/vibration	8-64 Hz
- Large field: RAII - vibration/tickle	> 64 Hz
b. Slowly adapting:	
- Small field: SAI - pressure	2-32 Hz
- Large field: SAII - skin strecth	> 8 Hz

Table A.1: Properties of the mechanoreceptors in the glabrous skin of the human hand [32]

Variable	Resolution	Differential threshold
Limb movement	0.5-1° (over 10-80°/s range)	8% (range: 4-19%)
Limb position	0.8-7° (full range of motion)	7% (range: 5-9%)
Force	0.06 N	7% (range: 5-12%)
Stiffness	Not Available	17% (range: 8-22%)
Viscosity	Not Available	19% (range: 14-34%)
Inertia	Not Available	28% (range: 21-113%)

Table A.2: Perceptual characteristics of kinesthetic system [15]

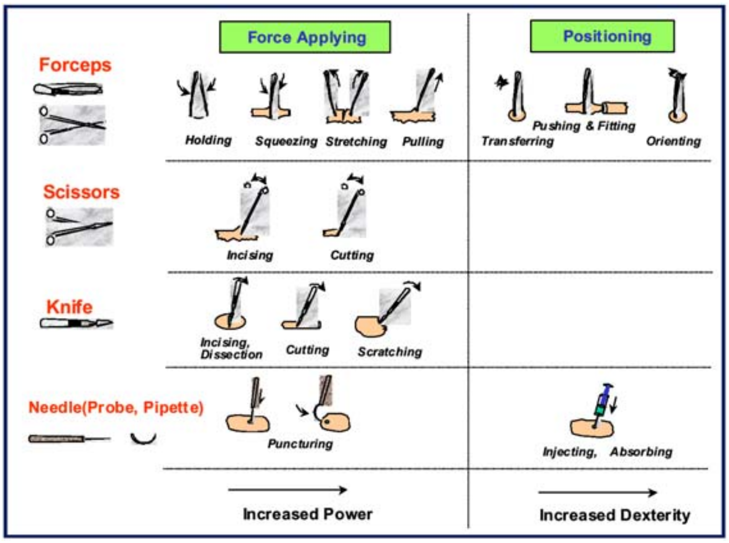


Figure A.1: Modeling of surgical tool motion [8]

- Forceps: hold, pull and stretch tissues.
- Scissors: cut and incise tissue.
- Knife: cut and scratch tissue.
- Needle: puncture and inject.

The forces related to these tasks are depicted in figure A.2.

An overview of the microsurgical environment can be found in Table A.3 (source: [8]).

In [17] Çavuşoğlu et al. obtained the performance goals for suturing a knot by doing measurements on instruments performing suturing in an open surgical setting. The requirements are listed in Table A.3.

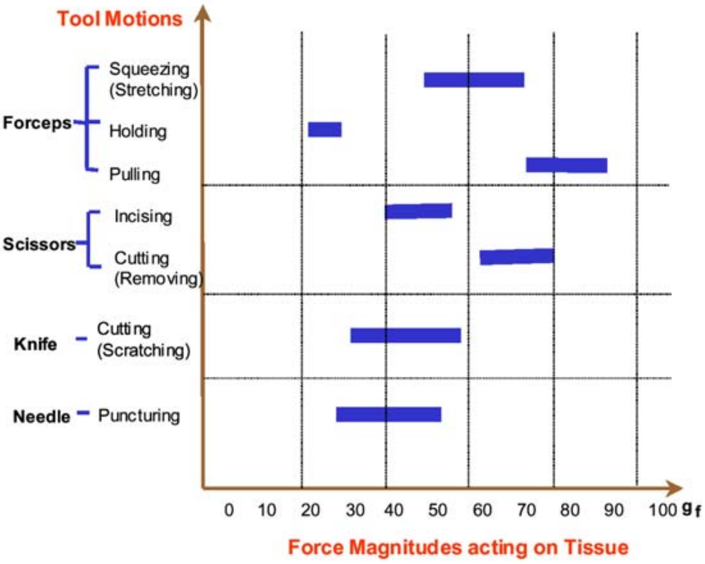
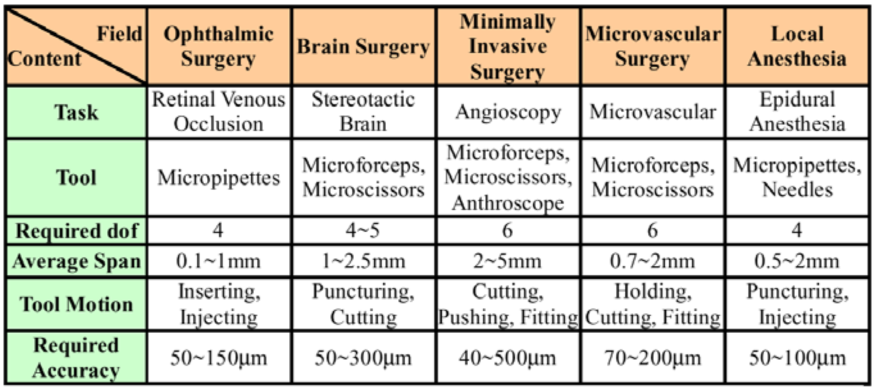


Figure A.2: Sizes of applying force in microsurgery [8] (Note: 1 kgf = 9.806 N)



Field / Content	Ophthalmic Surgery	Brain Surgery	Minimally Invasive Surgery	Microvascular Surgery	Local Anesthesia
Task	Retinal Venous Occlusion	Stereotactic Brain	Angioscopy	Microvascular	Epidural Anesthesia
Tool	Micropipettes	Microforceps, Microscissors	Microforceps, Microscissors, Anthroscope	Microforceps, Microscissors	Micropipettes, Needles
Required dof	4	4~5	6	6	4
Average Span	0.1~1mm	1~2.5mm	2~5mm	0.7~2mm	0.5~2mm
Tool Motion	Inserting, Injecting	Puncturing, Cutting	Cutting, Pushing, Fitting	Holding, Cutting, Fitting	Puncturing, Injecting
Required Accuracy	50~150µm	50~300µm	40~500µm	70~200µm	50~100µm

Figure A.3: Analysis of the microsurgival environment [8]

Parameter	**Value**
Dimension: overall diameter	0-15 mm max
Dimension: wrist joint to grasper	50 mm max
Force: at the point of needle for driving the needle through tissue	1.5 N min
Torque: about grasper axis, for driving needle (assumes curved needle, 15 mm from grasper to needle tip)	100 N/mm min
Torque: wrist exion (yaw)	300 N/mm min
Force: gripping, while driving needle	40 N min
Range of motion: gripper jaw opening	8 mm min
Range of motion: rotation about grasper axis, to drive plus allowance for inclined work surface	270 degrees min
Range of motion: wrist exion, for driving needle	90 degrees min
Range of motion: wrist pronation	720 degrees min
Speed: Grasper, full close in	0.5 sec max
Speed: Wrist roll	540 degrees/sec min
Speed: Wrist exion	360 degrees/sec min
Bandwidth	5 Hz min
Lifetime	6 months min

Table A.3: Performance goals for suturing knots [17]

Appendix B

Medical robotics

This appendix provides an overview of commercially available surgery robots and haptic components.

B.1 Classification of medic robotics

In [9] Kwon et al. present a classification of medical robotics (fig. B.1):

- Robots for surgery:
    - Macrosurgery: conventional surgery with conventional instruments.
    - Microsurgery: not only differs from macro-surgery by the size of the instruments, but also by the modes of operation. The surgeon uses a microscope and miniaturized precision tools. When performing minimally invasive surgery the surgeon even uses remote instruments and a camera that is inserted into the body through a key-hole (Section 1.1).
    - Telesurgery/Telepresence: medical application of a master-slave integrated telerobotic system wich a surgeon uses to operate a patient locally of remotely.
- Human assistant and rehabilitation robots: robots that assist during surgery (eg toolholders) and prostheses.
- Bio-robots: intelligent robots as artificial life form.

B.2 The ZEUS and Da Vinci system

At the moment two master-slave systems are commecially available: the ZEUS robot from Computer Motion Inc. and the Da Vinci from Intuitive Surgical Inc. Both systems are based on conventional MIS techniques: two robot arms control the endoscopic instruments and a third arm to guide the laparoscopic camera. The surgeon operates the robot form the surgeon console in which a (possible 3D) view of the remote site is displayed. Force feedback is not available.

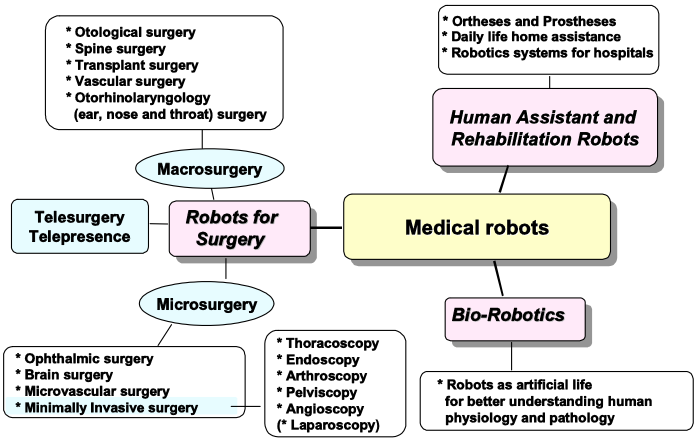


Figure B.1: Classification of medical robotics [9]

B.2.1 Da Vinci robot

The Da Vinci system from Intuitive Surgery Inc. is made up of three components (fig. B.2):

- Tower of video and medical monitors that provide images from the surgical site and other useful information to the assistants.
- Patient-side cart with three robotic arms with surgical instruments that are remotely controlled by a surgeon. The arms are fixed to one console as can be seen in figure B.2. Two arms hold the endoscopic instruments while the third arm holds the endoscope. The instruments that are used in the Da Vinci system have so-called EndoWrist tool-ends that provide two extra degrees of freedom and significantly increase the ease of use of these instruments (fig. B.3).
- Console at which the surgeon sits. The endoscopic tools are controlled by two special controls as depicted in figure B.2. These controlled are handled as if these are pairs of tweezers. A 3D image generated from the multi-lensed camera on the laparoscope that is available in the console.

B.2.2 ZEUS robot

The ZEUS system from Computer Motion Inc. comprises the same components as the Da Vinci system, but some differences exist:

- Three robot arms are fixed to the surgery table (usually after the patient is placed on the table). The arms can be controlled with 3 dof's and have no EndoWrists as are used in the Da Vinci system. This means that the ZEUS system has 2 dof's less than Da Vinci and is therefore more difficult to control.

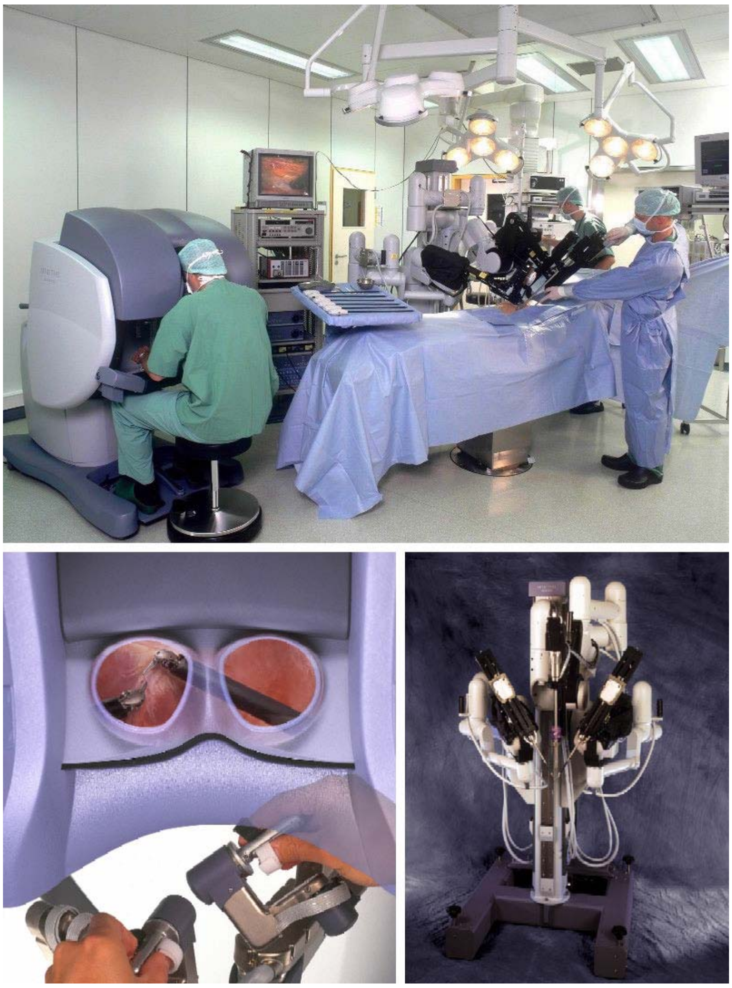


Figure B.2: Surgical site that uses the DaVinci system

Figure B.3: EndowWrist instruments as used by the DaVinci system

Figure B.4: The ZEUS surgical robot

- The surgeon controls the arms remotely from a console. A (pseudo) 3D image is available on a screen that can be viewed with a special pair of glasses. The control handles are controlled in a way that is similar to the handling of a conventional endoscopic instrument. Voice controls are used to control the camera (AESOP subsystem).

B.3 Examples of master-slave components

B.3.1 Master components

The following commercial master components are presented in this section:

- **Sensable PHANToM** (fig.B.5 and table B.1): a series of high performance haptic interfaces that track the user's motion in 6 dof's and provides 3 or 6 dof's force feedback[1]. Because of the highly adaptable setup the device is often used as haptic component in laboratory setups for haptic experiments (e.g. [2],[32]).

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[1] In case of a 6-dof actuater: both force and torque feedback.

Figure B.5: PHANToM 1.5 6-dof

Figure B.6: Immersion Laparoscopic Impulse Engine

- **Immersion Laparoscopic Impulse Engine** (fig. B.6 and table B.2): a haptic interface that simulates the motions and forces from a standard endoscopic instrument. For example used in [24].
- **Immersion Impulse Engine 2000** (fig B.7 and table B.3): highly accurate 2-dof joystick for laboratory use (e.g. used in [6]).
- **6-DOF Delta Haptic Device** (fig B.8 and table B.4): Haptic device form Force Dimension Inc. with a stiff parallel structure. The device is also available in a 3-dof version (e.g. used in [10]).

B.3.2 Slave components

Of course there also exist commercially available slave components:

- **Sensable PHANToM:** by using the feedback forces to move the links of the robot arm.the haptic device can also be used as manipulator as demonstrated in [2].

Parameter	**Value**	
Degrees of freedom	6 for Motion and tracking, 6 for Force feedback	
Motion	**Range**	**Resolution**
Translational	19.5cm x 27cm x 37.5cm	0.03 mm
Yaw/Pitch	335 °	0.0023 °
Roll	260 °	0.0080 °
Maximum forces & torques	**Maximum**	**Continuous**
Translational	8.5 N	1.4 N
Rotational, top 2 axes	515 mNm	188 mNm
Rotational, handle axis	170 mNm	48 mNm
Stiffness and Inertia	**Stiffness**	**Inertia**
Translational	3.5 N/mm	90 g
Rotational, shin	> 5873 mNm/rad	< 108 g
Rotational, middle	> 5873 mNm/rad	< 80 g
Rotational, handle axis	> 5873 mNm/rad	< 40 g
Friction	**Value**	
Translational	0.4 N	
Rotational, shin	14.11 mNm	
Rotational, middle	10.58 mNm	
Rotational, handle axis	7.05 mNm	
Mechanical bandwidth	**Value**	
Translational	...	
Rotational (roughly)	15 kHz	

Table B.1: Specs of the Sensable PHANToM 1.5 6-dof

Parameter	**Value**	
Degrees of freedom	5 Motion and tracking, 3 for Force feedback	
Motion	**Range**	**Resolution**
Pitch/Yaw	±30°	0.012°
Insertion	100 mm	0.012 mm
Rotation	continuous	0.35°
Maximum force output	8.0 N	
Backdrive friction	0.14 N	
Bandwidth	650 Hz (Linear axis), 120 Hz (Rotary axis),	

Table B.2: Specs of the Immersion Laparoscopic Master

Figure B.7: Immersion Impulse Engine 2000

Parameter	**Value**	
Degrees of freedom	2 for Motion and tracking, 2 for Force feedback	
Motion	**Work size**	**Resolution**
X and Y-direction	50 mm x 50 mm	2 μm (1100 dpi)
Maximum force output	8.9 N	
Backdrive friction	0.14 N	
Bandwidth	120 Hz	

Table B.3: Specs of the Immersion Impulse Engine 2000

Figure B.8: Force Dimension 6-DOF DELTA Haptic Device

Parameter	**Value**	
Degrees of freedom	6 for Motion and tracking, 6 for Force feedback	
Motion	**Work size**	**Resolution**
Translation	Cylinder Ø360 mm x L 300 mm	< 0.1 mm
Rotation	±20° for each axis	< 0.04 °
Maximum forces & torques	**Continuous**	
Forces	25 N in the entire workspace	
Rotation	0.2 Nm in the entire workspace	
Bandwidth	....	

Table B.4: Specs of the 6-dof DELTA Haptic Device

Figure B.9: Z-KAT's WAM

- **Whole Arm Manipulator** (fig B.9) from Z-KAT: highly accurate robot that is driven by a back-driven cable drive differential system that is similar to the one used in the PHANToM. (e.g. [1]).
- **Industrial Robots** ([8]): Ordinary industrial robots can be used as placeholders for endoscopic instruments and other palpation devices. These systems are used regularly in laboratory setups where no specialized medic robots are available (or needed).

When performing laboratory experiments highly accurate and expensive commercial solutions are not always needed. In such a case a custom-made design can be used. For example:

- Just two motors with a bar attached to it: [28].
- Force Reflecting Endoscopic Grasper (Fig.B.10, ref. [14]).

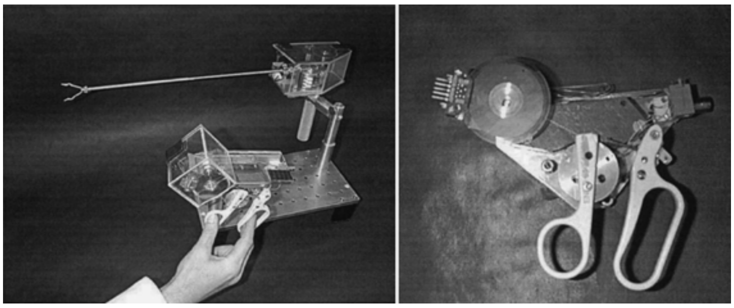

Figure B.10: Custom-made FREG [14]

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