Bimanual Control Of A Multi-Branched Instrument

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BIMANUAL CONTROL OF A MULTI-BRANCHED INSTRUMENT

by

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Long slender instruments used in Endonasal Surgery have two main limitations, the first being that current instruments have a fixed shape so that difficult positioned lesions cannot be reached. The other limitation is caused by the colliding of instrument shafts when multiple shafts are inserted in the surgical corridor, reducing the instrument maneuverability. A Multi-Branched instrument could overcome these problems i.e. an instrument with a single steerable shaft that is inserted through the surgical corridor that at the distal end divides into multiple tool branches that are all steerable. In this research a first step was made to develop a suitable control strategy to operate such an instrument, using a new method for performance testing. Methods: Two interfaces were proposed: A sequential interface that allows the control of a single instrument at a time for each hand, and a simultaneous interface that allows the control of two instruments in parallel for each hand. The simultaneous interface was expected to result in quicker performance. To evaluate their performance, the interfaces were prototyped and connected to a simulation environment containing a virtual Multi-Branched instrument. Results: The sequential interface resulted in around 10% quicker performance than the simultaneous interface. The used methodology to test the control strategies has proven to be successful and enabled further research with relatively low effort to experiment with other instrument configurations and control concepts.

1 Introduction
1.1 Endonasal Surgery

The Skull Base forms the floor of the cranial cavity that separates the brain from the facial compartment (Fig. 1a). It gives access to a lot of important but vulnerable neurovascular structures (i.e. nerves and vessels) that enter and exit trough the cranial base, resulting in a highly complex anatomical area (Fig. 1b). For this reason Skull Base Surgery (SBS) is one of the most challenging fields of surgery and is often referred to as the “no man’s land” of surgery.

Traditionally lesions of the Skull Base were only operated with the so called Open Approaches or Traditional Approaches. Open Skull Base approaches involve the creation of large facial incisions (Fig. 2) to access the area of the lesion. Making such large incisions brings a significant risk of post operative complications such as infections and internal bleedings and leaves visible facial or skull scarring afterward.
Endonasal Surgery is a minimally invasive technique that allows a surgeon to reach the Skull Base through the nose with long slender instruments for the removal or treatment of lesions. Endonasal Approaches provide a less traumatic route: neurological damage is reduced since the brain does not need to be manipulated. Furthermore Endonasal Approaches do not leave visible scarring, have a lower morbidity and mortality rate and a shorter in hospital time and recovery time compared to traditional approaches [3].

The Endoscopic Endonasal Approach (Fig. 3) was developed in the 1990’s [4] by different medical specialists to treat pituitary tumors, positioned in the sella turcica [5] and is now considered the standard procedure for pituitary surgery. The sella turcica is relatively close to the nasal orifice and was therefore a logical first step in Endonasal Surgery. Subsequently the Extended Endonasal Approach was developed to reach deeper into the Skull Base than the Sella Turcica. With the Extended Endonasal Approach almost the complete anterior Skull Base and parts of the middle and posterior Skull Base can currently be reached.

To perform Endonasal Surgery the surgeon needs to be trained in operating with the endoscope and requires a detailed knowledge of the nasal anatomy. Endonasal Surgery is generally performed by a neurosurgeon in close cooperation with an otolaryngologist (Ear-Nose-Throat surgeon).

The first step of Endonasal Surgery is the preparation of the surgical corridor (i.e. the created pathway towards the Skull Base) by debulking of one or both of the nostrils until the needed circumference is obtained. Also both the nostrils (binostril) can be used so that both surgical corridors are used at the same time, improving the maneuverability of the instruments and the access to the lesion. This arrangement allows one surgeon to provide vision with the endoscope and use the suction tube to remove excess fluids through one nostril while the other surgeon can use both hands to resect the tumor via the other nostril [7]. The binostril approach requires partial resection of the posterior of the nasal septum, the bone that separates the airways in the nose [8]. After the preparation of the nostrils, the middle turbinates or nasal conchae (thin bony plates on the wall of the nasal cavity) can be partially resected depending on the surgeons preferences to enlarge the surgical corridor. After these preparations the surgery is continued with a route that depends on the location of the lesion in the Skull Base. The next step for the removal of a pituitary tumor (Fig. 3) would be the drilling of the sphenoid sinus (a cavity in the sphenoid bone) and subsequent drilling of the sellar floor to expose the tumor. Now the tumor can be removed using forceps to grasp the tumor and scissors to cut it away. After removing the tumor the created surgical corridor is closed again (reconstructed).

1.2 Instrumentation

During Endonasal Surgery different long slender instruments are inserted into the nasal corridor. A selection of these instruments relevant to this research will be discussed (Fig. 5).
Fig. 5: A selection of instruments used during endonasal surgery. 
(a) scissors (45 deg) (b) forceps (45 deg) (c) suction tube (d) curette (e) endoscope

The scissors are used to dissect (cut away) tissue. The forceps is used to grasp tissue, or spread tissue by using the beaks to push the tissue outward. The suction tube is used to remove blood, spinal fluid or drill dust that deteriorates the endoscope vision. The curette is used to manipulate tissue e.g. to push tissue away that obstructs the surgical field, or to scrape tissue. The endoscope is an instrument that contains a small camera at the tip providing a view of the surgical field.

Instrument limitations

Endonasal Surgery procedures that reach further than the pituitary gland are still quite uncommon. This is caused by different technical challenges.

The current instruments used in Endonasal Surgery are available in different sizes and angles but remain instruments with a fixed shape that cannot be adapted during surgery [9]. This means that the surgical corridor needs to be perfectly planned, to be able to insert the shape of the instruments. When lesions are positioned further away from the nasal corridor, the surgical corridor and therefore the instruments often need to be routed around vulnerable structures, which is not possible with the current instruments. In such a case the Endonasal Approach cannot be used and a more invasive traditional approach needs to be performed.

The second limitation, the so called "Sword Fighting" [7] of instruments, is caused by spatial constraints of the surgical corridor and the number of instruments shafts that are inserted. The corridor already provides a very limited range of motion for one instrument. With two or more instruments inserted at a time this range of motion is only further limited, especially when the shafts of the instruments collide. This crossing of the instrument shafts called "Sword Fighting" extremely reduces the instrument maneuverability and can be frustrating. Especially in situations where quick reactions are needed, it is difficult for surgeons to anticipate on one an others movements, aggravating the Sword Fighting. When an artery bursts and it needs to be closed quickly the Sword Fighting might have severe consequences for the patient.

Multi-Branched Instrument Concept

Most handheld instruments used in (neuro)surgery work according to the same principle: The surgeon controls the handle of the instrument on the outside of the body so that he or she can manipulate the tip of the instrument inside the body. With the current instruments each instrument has a shaft to cover the distance from the instrument handle through the surgical corridor to the tip of the instrument. However each instrument shaft uses the same surgical corridor and they could therefore be combined. If it would be possible to integrate the shafts of different instruments into a single shaft, then the instrument shafts could not collide and no more "Sword Fighting" would occur.

This line of thinking leads to the proposal of a Multi-Branched instrument (Fig. 6): an instrument with a single shaft that at the end separates into multiple separately steerable branches, each containing a different tool. The single shaft can be inserted through the surgical corridor and the tools on the branches at the distal end of the instrument can be used to treat the lesion. To also be able to reach difficult positioned lesions that cannot be reached with the current fixed-shape instruments, the Multi-Branched instrument is envisioned to be steerable [10]. This resulted in the Multi-Branched instrument concept shown in Fig. 6. In case of e.g a Skull Base tumor, the instrument enters via the nasal corridor and steers towards the tumor, moving around nerves and vessels on its way. Having arrived at the location of the tumor, tool-branches are used to remove the tumor.

Fig. 6: The Multi-Branched Instrument concept [11].

The proposed Multi-Branched instrument will likely have many DOF (Degrees Of Freedom) meaning that there will be many joints that need to be controlled. The motion of these DOF could for example be controlled by devices using wrist movements, finger operated buttons or joysticks. These different control devices need to be incorporated into a potentially complex control interface.
Control Interfaces

Multi-Branched instruments also known as Multi-tasking platforms are already being developed in the fields of SILS (Single Incision Laparoscopic Surgery) and NOTES (Natural Orifice Translumenal Endoscopic Surgery), requiring control interfaces that were recently categorized by E.A. Arkenbout et al. [12].

The authors found that all platforms require at least two operators that must work closely together using complex control interfaces while miscommunication between the operators can lead to dangerous situations. The need for multiple operators is caused by a large number of DOF on the instrument side, requiring the manipulation of many DOF on the control side.

Examples of interfaces belonging to these multi-tasking platforms are depicted in Fig. 7.

Fig. 7a shows a purely mechanical interface that does not seem to be very convenient since it requires four people to operate the platform while working closely together both physically and mentally.

With the MASTER (Master And Slave Translumenal Endoscopic Robot) [15] (Fig. 7b) two surgeons work together using a combined electro-mechanical and mechanical interface. One surgeon is positioned behind an interface on the master side of an electro-mechanical master-slave system manipulating the tissue by controlling the tool-branches, while the other surgeon on the patient side of the platform, positions the main instrument shaft using a mechanical interface. In this way the surgeons are not physically in each others way, but still two human errors are stacked on top of each other while operating the platform and miscommunication can still be dangerous. This system could be used by a single surgeon but would require constant (time consuming) switching between the positioning interface and the tissue manipulation interface, therefore simultaneous operation is not possible.

The third example is the IREP (Insertable Robotic Effector Platform, Fig. 7c) [16] that is completely electro-mechanically operated by a single surgeon. Completely electro-mechanical (computerized) systems are however far from optimal yet due to non-linearities in the kinematical chain and high costs.

None of the Multi-Branched instrument platforms that were categorized have made it into clinical practice yet or have proven to perform better than their minimal invasive counterpart procedure.

For most of the described platforms first the instrument side of the platform was designed and later an interface was added to control the DOF of the instruments. This might result in a mismatch between the instrument and the human operated interface. The instrument might have features that are not practical or possible for a surgeon to control resulting in a situation where the interface and the operator need to adapt to the features of the instrument in stead of the other way around. Therefore this research will focus on the possible control couplings between the Multi-Branched instrument and the interface before the instrument is realized. A clinical expert will be involved in the design process to match the interface and the functionality of the instrument with the requirements of clinical practice.

1.3 Clinical Input

A clinical specialist was approached and we explained the concept of the Multi-Branched instrument. He was asked in what kind of clinical situation he could use such an instrument, what kind of features were needed in the instrument to

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1Using a master-slave system the operator applies a motion on the control device on the master side while the instruments on the slave side follow this motion.

2Wouter van Furth is a Neurosurgeon at the LUMC Leiden with 14 years of working experience as a Neurosurgeon
perform what sort of tasks and how he would like to operate such an instrument if anything was possible.

This resulted in a relevant scenario that can find place at different locations in the Skull Base and is frequently encountered during Endonasal Surgery using the current instruments.

The scenario as it occurs now in clinical practice can be described as follows: The task of a surgeon is to grasp tumor tissue and pull it outwards so that the base of the tumor is exposed and it can be dissected using the scissors. While the surgeon performs this task, two situations often occur. When the vision is not sufficient anymore due to for example a bleeding vessel, another surgeon needs to vacuum the blood flow before the surgeon can continue the dissection. When the endoscope view is obstructed by for example a piece of loose tissue. The second surgeon uses a curette to remove the tissue before the first surgeon can again continue dissecting the tumor.

When one of these situations finds place and the second surgeon is using the suction tube or curette, the first surgeon is often unable to sufficiently move his instruments because of the likely occurrence of Sword Fighting and therefore needs to interrupt his activities. If the two surgeons would operate a Multi-Branched instrument together the Sword Fighting could not occur. They could however still obstruct each others instrument tips due to unanticipated movements of one another. The exact moment that the vision is deteriorated to such an extent that the suction tube needs to be used might differ per surgeon. The first surgeon can of course tell the other surgeon when he finds this necessary, but communicating in stressful situations can be difficult and time consuming, interrupting the surgery.

In the here described scenario with its accompanying limitations and disadvantages it would be beneficial if the surgeon could control all the instruments by himself. He would not need to cope with unexpected movements of the other surgeon and perform the secondary tasks himself at the precise moments that suit him. It is however the question to what extend a human being is capable of controlling up to four instruments by himself. Simultaneous control of four instruments would require the control of two instruments with one hand, which we call a unimanual-simultaneous control strategy. This strategy could provide a time advantage over performing the tasks with a unimanual-sequential control strategy i.e. letting go of an instrument and switch to another. The unimanual-simultaneous strategy would have the practical advantage of controlling up to four instruments simultaneously while not losing time to switch between the controls of different instruments.

**Human Performance and Feasibility**

Simultaneous operation of instruments requires multi-tasking i.e. engaging in two activities at the same time. Humans are not capable of real multi-tasking: only one task can be executed at a time. Time-sharing between tasks is however possible meaning that parts of tasks are sequentially being processed, constantly switching between tasks [17]. There is however a cost since time is wasted due to context switching, depending on the task load [18]. Also more errors might occur during time-sharing due to insufficient attention when the mental workload is high. Humans are better at task management when the workload is moderate, having mental resources left to optimize their task management strategy [19].

Pahsler [20] states that two independent responses, based on unpredictable stimulus input, cannot be selected at the same time. However, while responding to the first stimulus, at the same time the second stimulus is already being perceptually processed or the response to the second stimulus already starts but without proper selection. In case of two simultaneous 2-d cursor parallel positioning tasks this would mean that while the first cursor is placed on the target, the position of the second target is already being processed or the second cursor is already moved in the general direction of the second target, which has not been properly selected yet. It can be concluded that when two tasks are being executed at the same time, one task has the priority and the other is only partially being executed.

Bimanual and unimanual visuomotor coordination tasks activate the same neural networks while performing similar tasks [21]. Researchers have for example let participants vertically position 2 computer cursors on a line using a touch pad. In the first experiment they were allowed to use one finger of each hand while the second time the two cursors needed to be positioned while using the fingers of a single had only. The monitoring of the participants with a fMRI scanner showed that his activated the same neural networks. However unimanual coordination resulted in stronger network activation since unimanual tasks are harder to perform than bimanual tasks due to physical coupling: the two fingers of two different hands are easier to move independently than to independently move the two fingers of one hand since the latter are directly coupled by tendons and muscles. In another example [22] was found that times between letter strokes on a keyboard between the fingers of two hands are shorter than time between strokes that were performed with the fingers of one hand.

As shown, unimanual time-sharing tasks are possible and are neurally processed in the same way as bimanual time-sharing tasks, although at the cost of reduced task performance. Also during unimanual time-sharing, time will be lost due to context switching and the attention must be divided between simultaneous executed tasks, but will however require a higher mental load than bimanual tasks due to physical coupling. Unimanual control will however provide practical advantages since it enables the simultaneous operation of three or four instruments by a single person.

Learning the simultaneous control of multiple instruments might however require some time. After practicing long enough, standard movement patterns for parts of tasks can become engrained in the nervous system by the formation of motor programs [23], resulting in a certain degree of automation and a lower context switching loss.
1.4 Approach

The operating of a Multi-Branched instrument can be divided in two different stages. The first stage is the steering of the main shaft towards the lesion and the deployment of the instrument branches. The second stage considers the operation of the different instruments at the location of the lesion i.e. the treatment of the lesion. This study focuses on exploring the second control stage and in specific on what kind of control couplings can be used between the interface and the DOF of the tools of the Multi-Branched instrument. For example the rotation of a tool branch could be controlled with the rotation of a wheel or the interface or by using two push buttons that both rotate the tool-branch to another direction.

A Multi-Branched instrument is required to test different interface concepts but the designing and building of such an instrument requires a lot of effort and therefore highly limits the different strategies that can be implemented and tested. Therefore is decided to create a virtual computer environment containing the instruments and tasks to which the control interfaces can be connected. In this way a virtual playground is created to explore almost any abstract instrument, combination of DOF or task.

1.5 Research Goal

The following problem statement was formulated:

_During Endonasal Surgery surgeons controlling multiple instruments cannot anticipate on each others movements and the instruments shafts often cross each other, restricting the maneuverability of the instruments, resulting in constant interruption of the procedure._

The proposed solution of a Multi-Branched instrument leads to the following research question:

> What is a suitable control strategy for a single person to operate a Multi-Branched instrument with four tool branches?

Two instruments operated with one hand, could be operated either simultaneous or sequential, resulting in the following hypothesis:

> "Using a unimanual-simultaneous control strategy to operate instruments results in quicker performance than when using a unimanual-sequential control strategy."

To test this hypothesis two control interfaces will be designed with two different control strategies being:

- A unimanual-simultaneous strategy (with one hand two instruments can be simultaneously operated)
- A unimanual-sequential strategy (with one hand two instruments can be operated, but one instrument at a time)

2 Methods

In the following section a new methodology for the testing of medical instruments will be explained. First the software framework used to create the simulation and subsequently the virtual environment based on the clinical scenario will be discussed. Next the design and prototyping of the interfaces will be explained and finally the design of the experiment itself.

2.1 Software

Due to practical considerations we searched for an existing visual and dynamical frame work to support the creation of the simulation. No suitable frame works were found in the medical field that were open-source and could be adapted, hence the scope was widened to another field that makes use of visual computer simulations: the field of robotics. Robotic simulations are used to evaluate the performance of a robot, algorithm or partial system without building the actual machine and therefore require an advanced dynamics engine. Physical interaction with the environment has a higher priority than graphics, which decrease the maximal frame rate and therefore limit the physical accuracy of the simulation. Next to training dexterity surgical simulators can also be used to make the user familiar with the physiological environment, requiring a realistic appearance. For this research however the physical behavior of the instruments has a higher priority than the graphics. Graphics are of course very important to place the user in a more realistic appearing environment, but unrealistic behaving instruments in an amazing looking realistic environment will likely lead to less significant results than the other way around.

After exploring different simulation frameworks\(^5\) V-Rep (Virtual Robot Experimentation Platform) was found to be the most suitable simulation framework. V-rep is a robot simulation framework created with the motto "_create, compose, simulate any robot_." The program has an integrated development environment: CAD models can be imported as rigid bodies and connected to each other with different elements as springs, hinges and more. V-rep comes with 3 different integrated dynamics engines: bullet, ODE and VORTEX. They all have their advantages in specific types of simulations depending on what sort of dynamical calculations need to be made and the needed degree of precision and speed. Vortex is the most realistic and precise dynamics engine, but was in practice found to be too slow for this application resulting in large delays. Comparing ODE and Bullet, Bullet was found in practice to offer the most stable performance. V-REP can communicate with other programs or devices via embedded scripts using its own API (Application Programming Interface). Different languages are supported among others Matlab and C/C++. VREPS closest rival, Gazeboo, also provides most of these functionalities but was found to be more cumbersome to work with.

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Next the the virtual environment will be discussed focusing first on the implementation of the instruments and then on the implementation of the tasks that were described in the clinical scenario.

\(^5\)Gazeboo, Matlab SimMechanics and Matlab VR world
The simulated environment

The Endonasal surgeon receives visual cues via the enlarged endoscope image on the screen and receives haptic feedback from the instruments he holds in his hands. The implementation of haptic feedback is outside the scope of this study. The enhancement of visual feedback though visual cues in the simulation is very well described in literature, and is shortly explained for the readers convenience in Appndix A.

Instruments

The simulation environment contains the four steerable instruments that were mentioned before (Fig.5): the forceps (5 DOF), scissors (5 DOF), suction tube (3 DOF) and curette (3 DOF). The preferred instrument configuration of the clinical specialist is depicted in Fig. 8a which is based on the conventional instrument positions. Every branch has a deflection element to change the horizontal and vertical position of the tip of the tools (2 DOF) and a translation element to control the depth position of the tip of the tools (1 DOF).

The DOF of the virtual forceps are visualized Fig. 9. The deflection element is for every tool-branch created with cylinders with rotation joints in between and the translation element is a translation joint connected to a cylinder. The deflection and translation element can be placed in two configurations: The deflection element can placed at the proximal end of the tool-branch before the translation element, or the other way around with first a translation element followed by a deflection element at the distal end of the tool-branch. With first a deflection and then a translation element, the workspace of the instrument looks like a full dome (Fig 10a). This configuration results in the largest workspace. It is however difficult to accurately control the deflection with this configuration. The reason for this is that displacement of the deflection element will also result in a displacement of the translation element. Therefore the deflection of the tip of the instrument will become larger when the tip is translated forward: the rate of deflection is proportional to the translation. This is hard to anticipate for the user since in the case of a larger translation the instrument will be less precise to control. With the virtual instruments used in the simulation the translation element is placed before the deflection element, resulting in a workspace that looks like a cylinder with a dome on top (Fig.10b), covering less space than the other configuration. With this configuration however a relative change of the control input will always result in the same relative displacement of the tip, resulting in more intuitive tip control, independent from the degree of extension of the translation element. Beside the deflection and translation DOF, the scissors and forceps both have a 4th DOF being an axial rotation to position the tool-branches with respect to the orientation of the objects. The suction tube and curette do not have a rotational DOF since they are both circular shaped and therefore do not need to be rotated. The 5th DOF for two of the tool-branches is the opening and closing of the scissors and forceps.

All the non-transparent elements shown in Fig. 11 can physically interact with each other in the virtual environment by using collision detection. The transparent elements do not have collision detection enabled to minimize the use of the physics engine, requiring less calculations and resulting in a higher frame rate. The arms of the branches (visualized in grey in Fig. 8a, but transparent in Fig. 11) are transparent.
to prevent the branches from visually obstructing the tasks. All the tool-branches are angled inwards under an angle of 12 degrees in the horizontal plane so that the initial positions are directed toward the center of the surgical field.

Task implementation

The simulated tasks that will be discussed in the next paragraphs are abstract versions of the tasks that were described in the introduction: (1) the dissection of tumor tissue by grasping and cutting it, (2) the operation of the suction tube to remove fluids or drill dust and (3) Push away tissue using the curette to create space in the surgical field when the view is obstructed.

Grasping and Cutting the Tissue

The primary task is to grasp and dissect the tumor tissue. The virtual tumor tissue (Fig. 11) is made from cylindrical elements that are linked to each other with virtual force sensors available in the V-REP framework. Force sensors give the possibility to grab, rotate and strain the tissue in all directions. The tissue needs to be grasped at the blue cylinder (Fig. 11a), that will turn purple when grasped correctly (Fig. 11b). The tissue needs to be cut at the green cylinder (while the blue cylinder is still being grasped) after which the tissue disappears and is successfully dissected.

Suction and Obstructing tissue

The suction and obstructing tissue tasks are both implemented as positioning tasks. During the simulation both a red and a yellow sphere are visible that respectively indicate the position where the suction tube and curette need to be positioned. During the simulation the spheres will change position so that the instruments need to be repositioned. When this occurs, the instrument with the corresponding color needs to be placed inside the sphere, that will fade away when the instrument is positioned correctly. When the sphere has disappeared the task has been fulfilled.

2.2 Hardware

For this study two different concept interfaces were developed. The first concept is the unimanual-sequential interface that allows the control of a single instrument with each hand at a time, enabling the operation of two instruments simultaneously with both hands. To operate the other two instruments the thumbs need to switch to a second joystick that is positioned next to the first joystick. The second concept, the unimanual-simultaneous interface, gives the user the opportunity to operate two instruments simultaneously with one hand, or four instruments simultaneously with two hands. For practical reasons will unimanual-simultaneous and unimanual-sequential from now on be referred to as simultaneous and sequential. First the general design choices regarding the shape of the controllers will be discussed after which the chosen control inputs and the control couplings will be explained for both concepts. Performing an elaborate study on ergonomics is not within the scope of this research.
therefore the design of the shape of the controllers is distilled from an existing shape. The Nintendo Wii Nunchuk depicted in Fig.12 was chosen as a starting point for the shape of the controllers since it provides a comfortable and firm one-handed grip. The shape has been adapted to fit in all the physical components. For each tool-branch at least three DOF need to be manipulated, being the deflections (2 DOF) of the branches in the horizontal and vertical direction and the translation (1 DOF) of the branches. The forceps and scissors moreover include two additional DOF to axially rotate the instrument and close the forceps or scissors. The chosen control input device for each DOF will be discussed next.

**Control Couplings**

To connect the interface to the computer simulation, electro-mechanical control couplings are required to manipulate the virtual instruments. Important considerations for the choice of the control couplings are:

1. Compatibility of motions
2. Order of the open loop transfer function
3. Gain
4. Time delay

1) Compatibility of motions [24] Master-slave motions are compatible when the movement of a master system resembles the movement of the slave. An example of incompatibility of motion is when moving a target to the right requires a left moving response or moving a target to the right requires a forward moving response, caused by the misalignment of the control axis. Incompatibility of motion can result in misorientation, experienced when one is for example controlling a radio controlled airplane and the plane flies towards the person in control. Suddenly the lateral movement control is turned 180 degrees while the vertical movements are still controlled with the same control directions, confusing the human controller on the ground. After a while the human will cope with the incompatibility but it will result in a longer learning curve and is therefore unwanted when not necessary. 2) Order of the open loop transfer function: The order of the open loop transfer function from the control input to the followed target determines how well a human can follow the target. A human is very well capable of following 0th and 1st order systems [25]. An example of a 0th order system is the positioning of a flashlight from one target to another, a displacement of the input results in a new position (position control). When using a 1st order system (rate control) a displacement of the input results in a change of the velocity: a displacement of the accelerator in a car results in a new constant velocity. For 2nd order or higher order systems the human cannot fully anticipate on the change of the output, resulting in worse target following, higher delays, more overshoot and a higher mental load [19]. To minimize the mental load on the user and to achieve the best human performance it is best to use 0 or 1st order systems i.e. position or rate controlled systems. 3) Gain: Precise control of the steerable instruments is necessary in the complex and fragile environment of the Skull Base where overshoot might lead to fatal damage. The surgeon however also needs to be able react quickly in crisis situations: every second counts when a main artery bursts and needs to be closed. Therefore the used gains must be a delicate trade off between speed and precision. 4) Time delay: Time delays are harmful in tracking tasks and performance drastically decreases with larger delays. The time delay therefore needs to be kept as small as possible, possibly even by sacrificing graphical or dynamical performance to increase the computational efficiency of the simulation.

**Controlling the Deflections**

To control the deflections of the tool branches different devices are available that are able to control 2 DOF with a single finger being a joystick, touch pad and track ball. Separate devices to control the horizontal and vertical motions require constant switching and are therefore not very practical. The most important advantage of the joystick is that it provides proprioceptive feedback. This is an advantage when the position of the joystick is directly coupled to the position of an tool branch. In that case the user can feel the position of the branch by feeling the joystick. The advantage of the trackball and track pad is that they are not constrained by a finite plane as the joystick is: it is possible to move their inputs infinitely far in all directions providing a control plane as large as is necessary to obtain the most ideal gain. The trackball and touch pad were not found commercially available in sizes small enough to fit into the controller and the production of devices on a scale small enough to be incorporated in a hand held interface is not within the scope of this research. Therefore joysticks were chosen to control the instrument deflections.

For controlling the tool branch deflections with a joystick, both position and rate control can be used. They both require a comparable mental load and which of the two is preferable when using joysticks depends on the application. Position control (Fig.14a) offers little delay and a high accuracy (measurements are close to the target value) resulting in a minimal position error. Position control however results in higher control accelerations i.e. a high velocity error, more overshoot and thus a low precision (measured values are not close to each other). Rate control (Fig. 14b) provides a smoother following curve with less accelerations and thus a high precision but needs more time to reach a certain po-

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6When the motion plane of both the joystick and the tool branch form a square plane, the gain is determined by the width of the motion plane of the branch divided by the width of the motion plane of the joystick.
Fig. 13: (a) The DOF of the instruments. (b) The control inputs of simultaneous interface corresponding to the DOF of the virtual instruments. (c) The coupling between the virtual DOF and the sequential interface. (d) With the simultaneous interface, two joysticks can be controlled simultaneously. (e) With the sequential interface, the thumb can control one joystick at a time. (f) An overview of the functions of the fingers for both concepts.
position resulting in a higher delay and a lower accuracy [19]. This delay of the rate control can off course be lowered by using a higher gain, but not without sacrificing its precision. For this reason in general position control is preferred over velocity control when quick reactions are needed and velocity control is preferred when control accelerations need to be minimized. The choice between position or velocity control also depends on the range of motion of the input device. If for example a cursor needs to be moved accurately over a 2m wide plane, while the available width for the joystick is only 10 mm, then velocity control will be preferred since the high gain required from the position control (an amplification of 200 times) would result in a lot of overshoot. Which strategy performs best is difficult to determine without elaborate experimenting. A experimental study from 1986 suggest that position control is in general superior when using small control devices [26]. Current surgical instruments used in Endonasal Surgery are all position controlled and the skills of the surgeons are based on position control. To not deviate too much from the current surgical situation, and to use the advantage of the proprioceptive feedback provided by the joystick, position control was chosen to couple the deflections of the tool branches to the motions of the joysticks.

The used joysticks (Keyes S-Joys) are normally spring loaded i.e. the joystick returns to its center position when released. When using position control this is an unwanted functionality since the surgeon wants to be able to passively keep an instrument in the same position so that he can let go of the joystick to control another instrument. Since no joysticks without a spring return function were found that could be fitted into the controller, the springs were removed from spring-loaded joysticks. Removing the spring resulted however in a very sensitive joystick with low friction and thus low proprioceptive feedback. To compensate for the sensitivity the joystick motion was damped using a dielectric (electrically insulating) grease.

### Controlling the rotations, translations and opening/closing

The axial rotation of the scissors and forceps are controlled with the rotating motion of a wheel that can be comfortably rotated with a single finger.

The controlling of the translation of the control inputs would be ideally resembled with a translating motion. A translational input was however in practice found to be either too large to control without overstretching the fingers or too small to control precisely (high gain). A rotating wheel provides more precision for the same size since the range of motion of a rotational input is larger than the range of motion of a sliding input with the same size. When the direction of rotation is placed in the same direction of the translation of the instrument it did in practice not seem to create a feeling of misorientation. The translation was implemented with two wheels positioned beneath the joysticks. Because of the size of the components it was not possible to place the translation wheels in a comfortable range of the thumb. Also deep perception turned out to be too difficult in practice with the current simulation. Because of these issues that would likely create too much noise in the experiment, was decided to leave the translations out of this research.

The closing/opening of the scissors and forceps are controlled with a push button that can be operated with a single finger. It behaves as an on/off switch to close the forceps/scissors when pushed or open it when released.

### Finger positioning Sequential Interface

In the first concept (Fig.13e) the sequential control strategy is implemented that allows the user to control a single instrument at the same time with one hand. Therefore with both hands a maximum of two instrument deflections can be controlled simultaneously. See Table 13f for an overview of the function of the fingers for each concept. The thumbs have the highest dexterity and are therefore used for operating the joysticks. The joysticks are placed diagonally so that they are positioned on the circle that is described by the reach of the thumb. The index finger is used to control the axial instrument rotations. The middle finger is assigned to the push button on the front of the controller.

### Finger positioning Simultaneous Interface

The second concept interface gives the user the possibility to operate the four deflections simultaneously using the simultaneous strategy (Fig.13d). This resulted in a ergonomically more challenging concept since four control inputs for the branch deflections instead of two need to be operated simultaneously. The final design is similar to the first concept, but is more slender because the joysticks are now placed in line with the thumb and middle finger instead of both in reach of the thumb. The suction tube and curette require less precise control than the scissors and forceps. Since the middle fingers are less dexterous than the thumbs, they are used to control the curette and suction tube with the joysticks on the front side of the controller. The deflections of the scissors and forceps are controlled with the thumbs on top of the controllers. The index finger is used to rotate the tool-branches and the ring finger is used to control the trigger button. The front joystick can depending on the users preference also be controlled with the index finger requiring switching of the index finger between the joystick and wheel. In that case the middle finger can be used to control the trigger button, freeing the ring finger.

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7Vaseline petroleum jelly

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Fig. 14: (a) Minimized position error, but high velocity error. (b) Minimized velocity error but high position error. Source: [19]
Fig. 15: (a) The inside of the simultaneous interface, showing the components and wiring. (b) The inside of the sequential interface.

2.3 Prototyping

The interiors of the sequential and simultaneous controllers are shown in Figure 24. The bodies are produced with a commercial 3D printer (EnvisionTEC Perfactory 3) using a liquid photo-reactive acrylate (R5 Grey). The joysticks where desoldered and disassembled to remove the springs and to reduce the printed circuit boards in size. The positions of the wheels are measured with potentiometers i.e. a variable resistance which value depends on the position of a rotating contact. The potentiometers and trigger buttons are glued into cavities inside the bodies of the controllers. The joysticks are mounted with screws, all electrical contacts are soldered and the external wiring is protected by a flexible sleeving. The electrical components of the interfaces are connected to the virtual environment via two PLC’s (Programmable Logic Controllers) from Arduino (Arduino MEGA 2560). The Arduino’s measure the voltages of the control devices and send these as a digital value to the simulation via a serial connection i.e. one bit at a time sequentially. Once the simulation receives a complete string, each value in the string is assigned to the corresponding joint variable after which the positions of the virtual instruments are adapted. The joint positions are updated with a refresh rate of 20 Hz. Higher rates resulted in unstable performance, due to desynchronized serial communication between the simulation and the micro-controller.

2.4 Experiments

Participants

Twenty students of the faculty of Mechanical Engineering participated in the experiment with an age varying between 19 and 29 years old (median:23). The students were all Dutch speaking, right handed and played console games less than one hour a week.

Experimental setup

The experimental setup is depicted in Fig. 16. The participant is seated behind a table in front of a 40 inch Samsung TV display. The distance between the participant and the screen is 2.30m. The controllers are placed on the table in front of the participant. To emphasize the control couplings, colored stickers are put on the controllers next to the control inputs with colors corresponding to the virtual instruments.

Tasks

To test the difference in performance between the simultaneous and the sequential strategy, two different scenarios are created:

1. Experiment one contains the earlier described tissue dissection task performed with the forceps and scissors and

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8http://envisontec.com/3d-printing-materials/perfactory-materials/r5-gray/
two positioning tasks (spheres in which the instruments need to be positioned). The goal is to explore how the interfaces are used when bimanually controlling four instruments in a situation comparable to the discussed clinical scenario.

2. Experiment two contains two positioning tasks executed with two instruments operated with only the right controllers of the interfaces. The goal is to create a straightforward scenario to encourage one-handed simultaneous use of instruments.

**Positions of spheres and virtual tissue** The positions of the spheres and the virtual tissue are randomly generated inside the range of the workspaces of the instruments using MATLAB\(^9\) (see appendix B).

**Experimental Procedure**

An overview of the experimental procedure for both experiments is depicted in Figure 17.

![Flowchart](image)

*Fig. 17: An overview of the experimental procedure for the AB group, the other group starts with interface B and so on.*

**Experiment 1.**

The participants are divided into two groups. Group A starts the first session with the *sequential* interface while group B starts the first session with the *simultaneous* interface. Both groups will switch to the other interface for the second session. The first experiment starts with a brief instruction video in Dutch that explains the different control couplings between the interfaces and instruments on the screen. There are deliberately no instructions given about where to put which finger on the controllers. Next the participant is given two minutes to practice the controls in a scene without any tasks present yet. After this first practice round an instruction movie is shown on how to perform the different tasks. Next the participant is given two minutes to practice the given tasks. After this practice phase a last instruction video is shown requesting the participant to stay calm and avoid button bashing i.e. the random pushing of buttons. During the four sessions of the first experiment the participants perform ten rounds of tasks, where each round contains a different positioned tissue dissection task and two different positioning tasks. The four sessions consist of the same ten rounds. After the first session the participant switches to the other control interface and gets two minutes to practice the controls without any tasks in the scene. Next the participant can practice the task again for two minutes after which the second session is started. This process is repeated as depicted in Fig. 17.

**Experiment 2.**

During the second experiment only the right controller of each pair is used. The participant is allowed to only use his or her right hand, operating the curette and suction tube on the right side of the screen. The second experiment starts with an instruction movie that explains the changed controls and the participant is instructed to perform all tasks as quickly as possible. The upper joystick/right joystick is now used to control the curette that is positioned on the upper right corner of the screen while the lower joystick/left joystick is still used to control the suction tube, that is still positioned on the lower right corner of the screen. This experiment is started with the control interface that the participant used first during the first experiment. The participant is given ninety seconds to get used to the controls without performing any tasks, before starting with the first session of the second experiment. Each round contains two positioning tasks need to be fulfilled. Each session consists of thirty rounds that contain three different distances, measured from the sphere of the last round to the sphere of the next round. The shortest and second distance are resp. one third and two third of the largest distance and every distance occurs ten times. Both two sessions contain the same thirty rounds. After the first session the participant is again given ninety seconds to use the other interface without any tasks before starting the second and final session.

**Question form**

After finishing the two experiments the participants were asked to fill in a question form with a few questions about their preferred control interface and possible suggestions they might have for the experiment, simulation or control interfaces.

Data Acquisition and Analysis

During the experiment all the virtual instrument, tissue and sphere positions were measured in the simulation and send to MATLAB via a serial connection. The round completion times of all ten rounds for each of the four sessions and for the thirty rounds of the second session can be calculated from the acquired position data. The simultaneous instrument use is obtained from the data after filtering out the noise using a moving average filter (Appendix C).

Experiment with medical specialist

An additional experiment with a medical specialist was conducted to compare his performance to the student participants and to get additional feedback on the final experiment from an experienced medical specialist.

3 Results
3.1 Experiment 1.
Round completion times

The resulting times for each round of both sessions of the first experiment (Fig. 18) showed a negative trend while the participants progressed. A paired-samples t-test was conducted to evaluate the impact of both the interfaces on the time performance of the participants. There was a significant difference in the total time (all 20 rounds together) between the sequential interface (M = 405.3 sec, SD = 72.0) and the simultaneous interface (M = 169.6 sec, SD = 37.4), (p=0.0026). The sequential interface therefore resulted in faster time performance of the participants. A paired-samples t-test was conducted to evaluate the difference between the first and second session for both interfaces. For the sequential interface there was a significant difference in the total time between the first session (M = 193.1 sec, SD = 35.0 sec) and the second session (M = 169.6 sec, SD = 37.4), (p=0.0026). Also for the simultaneous interface a significant difference was found between the resulting times of the first session (M = 222.9 sec, SD = 53.6) and the second session (M = 182.5 sec, SD = 21.5), (p=0.0001). The performance of the participants over the total four sessions regardless of the interface type is depicted in Fig. 19a. Multiple paired-sample t-tests showed that participants performed significantly better in the second session compared to the first sessions (p=0.001). Also the third session has a significantly lower average time than the second sessions (p=0.010). The difference between the third session (M = 17.7, STD = 1.7) and fourth session (M = 17.5, STD = 2.1) is not significant (p=0.68).

Simultaneous use

The separate and simultaneous use of instruments is depicted in (Fig. 20). Both the bimanual and unimanual simultaneous use of instruments is negligible small (lower than 5%) in the first experiment.

Group Differences

An unpaired-samples t-test was conducted to evaluate the impact of the order in which participants used the two interfaces during the experiment. There was no significant difference in total time for group AB (M = 186.0 sec, SD = 36.4, Median = 190.8 sec) and group BA (M = 197.8 sec , SD = 48.2, Median = 191.7 sec), (p=0.2198).

Use of the trigger buttons

The gripper was on average used more per session (M = 17, SD = 4.1) than the scissors (M = 15, SD = 4.4) (Fig. 19b). This is on average resp. 1.7 and 1.5 times per tissue dissection task.

3.2 Experiment 2.
Task Completion Time

The task completion times are depicted in (Fig. 22). A paired-samples t-test was conducted to evaluate the impact of the different interfaces on the time performance of the participants. There was a significant difference in the total time between the sequential (M = 125.0 sec, SD = 11.7 sec) and the simultaneous interface (M = 139.3 sec , SD = 17.9, p=0.0012).

Simultaneous movements

The general use and simultaneous use of instruments during the second experiment is depicted in Fig. 27. An paired-samples t-test was conducted to evaluate the impact of the different interfaces on the simultaneous use of instruments. There was a significant difference in the simultaneous use of instruments between the sequential interface (M = 9.5%, SD = 4.0) and the simultaneous interface (M = 19.1%, SD = 9.3, p=0.0004). The average cumulative simultaneous use of the instruments of the simultaneous interface during the second experiment (Fig. 21) show a decreasing rate of simultaneous use of instruments after the first 40 seconds of the experiment.

Group differences

An unpaired-samples t-test was conducted to evaluate the impact of the order in which participants used the interfaces during the second experiment. There was no significant difference in total time for group AB (M = 129.9 sec, SD = 20.5) and group BA (M = 131.0 sec , SD = 19.0, p=0.2198).

Question list

The most important findings from the question list are that the simultaneous interface resulted in both a heavier perceived mental and physical load than the sequential interface. The positions of the control inputs on the front side of the simultaneous interface were found be confusing and uncomfortable due to a constant stretch in the fingers. The additional questions (translated from Dutch to English) were:
Fig. 18: The round completion times of the first experiment. The lines are the average times of both the subsequent sessions together.

Fig. 19: (a) The time performance per round for each participant, without taking the interface type in consideration. (b) Average use of the trigger buttons per session of ten rounds.
1. Are you satisfied with your own performance during the experiments? If you are not, why?
   All participants except for one were satisfied with their performance.

2. What did you find difficult during the experiments? Or did you find the experiments too easy?
   Simultaneous operation of instruments is difficult. Experiments were not found to be difficult but were found challenging like a game according to multiple participants.

3. Which interface do you prefer? The simultaneous or sequential interface? Why?
   All participants preferred the sequential interface. The interface was found to be more comfortable to operate and less confusing due to better button/wheel/joystick placement. One participant preferred the simultaneous interface for the first experiment but preferred the simultaneous interface for the second experiment since it felt quicker.

4. Do you have any other remarks concerning the experiment, software, interface or other subjects?
   Joysticks were found to move too easy and require more damping. The joystick, wheel and button placement for simultaneous interface was found to be confusing.
Fig. 22: (a, b) The round completion times of the second experiment. (c, d) The times each of the three distance took to cover. (e) Instrument use of simultaneous interface in percentage of total time. (f) Instrument use in percentage of total time of sequential interface. (g) Simultaneous instrument use of simultaneous interface. (h) Simultaneous instrument use of sequential interface.
4 Discussion

The objective of this research was to find a suitable control strategy for a single person to operate a Multi-Branched instrument containing four tool branches. The following hypothesis was stated in the introduction:

"Using a unimanual-simultaneous control strategy to operate instruments results in quicker performance than when using a unimanual-sequential control strategy."

The results did not support this hypothesis. The sequential interface resulted in better performance for both experiments than the simultaneous interface, however with a relatively small time performance difference of respectively 10.4% and 11.4% for the first and second experiment.

4.1 Limitations

Before describing the results the limitations of the human, software and hardware will be discussed shortly.

Mental Limitations

It was already explained in the introduction that the human is not capable of real multi-tasking, but time-sharing of tasks is possible, although time will be lost due to context switching. Therefore the theoretical limited advantage of the simultaneous strategy with respect to the sequential strategy will be less than 100%. Furthermore multiple targets cannot be selected at the same time, but while responding to the first target a response to a second target can already be processed although without proper selection [20].

Physical Limitations

The control of multiple tool-branches with a single hand will require in theory a higher physical and mental load than bimanual control, due to a stronger physical coupling between the fingers of one hand than the physical coupling between the fingers of two hands.

The index finger has a lower dexterity than the thumb. Therefore the control of joystick with the index fingers will likely result in a lower performance than joysticks that are controlled with the thumbs.

Software

The grasping of the abstract tissue sometimes resulted in unstable behavior. If the tissue was only partly in the beaks of the forceps, or the rotation angle w.r.t the tissue was too high, the tissue could slip out of the beaks of the forceps or start to oscillate. When the tissue was let go, it immediately returned to a stable state. Careful instrument positioning could prevent this instability, but the unstable behavior was nevertheless not a realistic response to incorrect positioning and created some noise on the results.

During the first experiment it was possible to improve performance by first positioning the forceps and only grasps the tissue directly after the positioning of the scissors. This resulted in a lower chance of the tissue slipping out of the forceps, since the tissue is being grasped for a shorter time (The tissue could slip out of the forceps by accidental control movements or by unstable behavior of the dynamical model).

When the simulation was build, the tool-branches positioned on the same height were orientated towards each other to create overlapping work spaces and make it possible to perform a task with two instruments in one area. These overlapping work spaces however resulted in accidental instrument collisions during the experiment. This resulted in noise on the measurement of simultaneous instrument movement, since both instruments move during a collision.

Hardware

All control gains need to be optimized by extensive testing, which was however not within the scope of the current study. The gains were adjusted by reducing the width of the work spaces during the pilot study, using feedback from the participants. The delays were kept as small as possible and were found sufficiently small during the pilot experiment. The joysticks and rotation wheels were except for the joysticks of the simultaneous interface not oriented in the same plane as their corresponding tool-branches in the simulation environment. This did not seem to create a feeling of misorientation for the sequential interface. The different joystick orientations of the simultaneous interface did however felt somewhat confusing to most participants in the beginning and lengthened their learning curve.

The joysticks that were used to control the deflection of the tool-branches were found to be difficult to accurately operate: a lack of damping caused the joysticks to feel sensitive, causing unwanted movements. Also the extreme positions of the joysticks were found to be difficult to control accurately because of the imposed stretch on the fingers, especially when operating the front joystick of the simultaneous interface with the index finger.

The joysticks contain two potentiometers that are used to measure the x and y position of the joysticks. The values of these potentiometers are used to calculate the orientation of the instruments by taking the tangent of those values. These low quality potentiometers do however have a resistance deviation of around 5% which in the exact center position drastically changes the ratio within the tangent and makes the joysticks less accurate as was noticed by some participants.

4.2 Experiments

Experiment 1.

During the first experiment a lowering of the task completion time is seen (Fig. 18) as the participants gain experience. It shows a slight learning curve that seems to stabilize.

Comparing the average times of all four rounds for all participants without taking the type of interface into account (Fig. 19a) shows a negative trend. This might show that participants got better at the virtual tasks, explaining why they started the second round with a higher performance than the first round, although they started the second round with a new interface. The other explanation for this might be that the difference between the interfaces is relatively small and there-
fore experience with one interface also improves the performance in using the other interface.

**Learning curve influences**

These improvements in performance of the virtual tasks or better interface handling cannot be separated. However a part of the improvement in performing the virtual tasks might be identified, since it was possible to switch to a performance increasing strategy by closing the scissors just after the forceps (although was instructed to first grasp the tissue and then position the scissors). The trend of the learning curve might be disturbed by participants that started to use this strategy half way during the experiment, resulting in sudden improvements. If this strategy was however used from the beginning this would only changed the absolute position of the curve and would not disturb the learning curve.

A few participants might have adopted this strategy somewhere in the experiment since the lowest quartile of Fig. 28 (Appendix D) shows that that the 25% participants with the shortest closing times used their forceps between the 10 and 36 seconds per session, which is relatively short and comparable to the scissors closing time, indicating that the forceps was closed just before the scissors.

The adoption of the strategy during the experiment would be characterized by a forceps closing time that is suddenly reduced. The forceps closing times of round four shows that two participants decreased their closing times to around 10 seconds while they started with a closing time in first round that was 63% or 75% higher (Table 1, Appendix D.). It is therefore likely that three of the participants adopted this strategy during the experiment. Their difference in closing times between the first and last session (around the 18 and 26 seconds) might have given them a slight advantage since the average improvement over four sessions is lower (M = 6.3 sec, STD = 12.4, Median = 9.0 sec).

The dynamical instability was however observed around less than 2 times per session and resulted each time in around two seconds time loss. Therefore it is not likely that these two participants influenced the trend of the learning curve very much.

The unstable dynamic behavior of the tissue was during the experiment the most observed in round nine, where the tissue was positioned so far a way that it was challenging to grasp the tissue. This resulted in a drop of performance for the ninth round as is depicted in Fig. 18.

**Simultaneous instrument use**

The simultaneous use of instruments during the first experiment is really low: all instruments were simultaneously used less than 5% of the time. A possible cause is the mental load that was put on the participants by introducing four tasks each round, possibly occupying all their mental resources. The largest part of the small percentage of simultaneous instruments use that was measured is likely caused by collisions of instruments explaining why the sequential and simultaneous interface scored more or less equal on simultaneous use during experiment one.

**Experiment 2.**

The measured data shows a very weak negative correlation between the practice time and round completion time. The spheres in the 30 rounds of the second experiment consisted of 3 different distances measured from the last sphere to the target sphere. It was expected that the rounds involving larger distances would take longer on average than the rounds involving shorter distances. According to Fitts law [27], the time is expected to scale with the logarithm of the distance if the target width is kept constant e.g. a much larger distance will result in only a slightly longer time.

In Fig. 22d the rounds are sorted on distance showing that a shorter distance does not always result in better time performance. The spread on the data is large, especially for the simultaneous interface, and the differences in time between the distances are not significant. This large spread is likely caused by physical factors being the amount of deflection of the joystick and the size of the hands of the participant.

Rounds that resulted in low performance were in most cases a combination of a sphere with an extreme horizontal or vertical position in the work space and a large or medium distance that needed to be covered with the tool branch to reach the sphere. The positions of these spheres required extreme joystick positions and stretched fingers. The amount of stretch however differs per participant due to anatomical differences and combined with the possible fatiguing of participants resulted in noise on the results.

With the shorter distances the luck factor also plays a slightly larger role. When a tool-branch is e.g. left in the last sphere on the right side of the sphere and the next target is positioned to the right then this reduces the smaller distances with a larger factor than it reduces the larger distances (the spheres were about as wide as the smallest distance). This might explain the few lower outliers, but likely had a minor influence on the results.

Looking at the separate instrument in use in Fig. 22f shows that the curette (M = 47.7%, SD = 6.0) controlled with the right joystick of the right sequential controller, was used longer than the suction tube (M = 42.9%, SD = 4.6, p = 0.0027) which is controlled with the left joystick of the right sequential controller). This might indicate that the left joystick of the right sequential controller was operated more effectively, and was easier to operate since similar tasks were performed in a shorter time.

The suction tube, controlled by the joystick of simultaneous interface operated with the index finger, was used less (M = 49.4%, SD = 6.7) than the curette (thumb operated joystick of the simultaneous controller) (M = 54.1%, SD = 8.5, p = 0.014). Therefore it seems that positioning with the index finger was more effective than with the thumb in contrary to the expectations. It could be that participants were so focused on the difficult index finger position, that they switched their fingers such that the front joystick was comfortable to control but at the expense of the thumb position. Another theory is that the orientation of the front joystick which was aligned with the orientation of the tool-branches resulted in better positioning because the thumb joystick created a feel-
ing of misorientation caused by the ninety degree difference in orientation between the joysticks and tool-branches.

**Simultaneous instrument use**
The simultaneous control strategy is more likely to have an advantage in the second experiment than in the first experiment since the second experiment only contains two positioning tasks. Fig. 27 shows that simultaneous control of the suction tube and the curette during the second experiment (median:16.8%) occurred a lot more than during the first experiment (median:2.9%). This is however still relatively low. Multiple participants mentioned afterwards that they tried to use the instruments simultaneously in the beginning of the second experiment, but soon found it too challenging and switched to a sequential strategy. This behavior can also be seen in Fig. 21 that shows the cumulative simultaneous use of instruments over time. The simultaneous use increases more than average starting around t = 10 sec until around t = 40 sec. After 40 seconds the simultaneous strategy seems to be abandoned and the simultaneous use stabilizes to a more or less constant rate which is likely caused by tool-branch collisions.

**Learning curves of both experiments**
The time performance over all rounds of the experiment one shows a slight learning curve that seems to stabilize, while the learning curve for experiment two is almost non existing. This last flat part of the learning curve of experiment one and the missing of a trend for the second experiment might be an indication that the participants have gone through the largest part of their learning process and says something about the final time performance when using a sequential strategy for both interfaces.

However when participants have more time to practice, the simultaneous use of the instruments will probably increase and will further improve the time performance. Especially when movement patterns will become engrained in the nervous system by the formation of motor programs [23], this might theoretically improve the simultaneous performance close to 100% compared to the sequential strategy.

During the second experiment one strategy was observed when simultaneously using the positioning instruments: The participant moved one instrument in the general direction of a sphere while his or her focus was on the other sphere. When the participants successfully removed the first sphere they had less distance to cover to reach the last sphere. This is in agreement with the time-sharing strategy that was described by Pahsler [20] stating that a response to a second target is already being processed without proper selection, while responding to the first target.

### 4.3 Hardware

Participants were in practice not able to use the advantage of the simultaneous control strategy. The participants however still had to cope with the more physically and mentally challenging finger positioning of the simultaneous controllers, as was learned from the additional questions.

Most participants experienced slight discomfort and three participants experienced light pain in their hands using the simultaneous interface, however none of the participants could not finish the experiment or accepted the offer of a short break of one minute. Especially the index finger was found to fatigue a lot and extreme positions of the front joystick were found to be difficult to control.

**Finger positioning**

During the experiments no instructions were given on what finger to use for which control input. For the simultaneous interface two different strategies were observed.

With the first strategy fours fingers (thumb, middle, index and ring finger) were constraint to positions. Some participants using this four-finger strategy placed their fingers beside the rotation wheel or push button to rest and therefore required extra time to displace their finger to a control input when needed.

With the second three-finger strategy, only the middle and index finger were used to control the three control inputs on the front side of the interface, freeing the ring finger. This three-finger strategy could be useful since the rotation wheel use was relatively low.

However repositioning of the finger when the wheel needed to be used caused extra mental effort and sometimes confused participants. This is caused by the positioning of the joystick in between the trigger button and rotation wheel: the participant needs to let go of the joystick with his or her index finger to control the wheel. If the rotation wheel and trigger button would be both positioned beneath the joystick, the middle finger could be used to switch between these less frequently used functions of the trigger and wheel and the index finger could be used solely to control the joystick. This positioning of the control inputs was however not possible due to the size of the potentiometer attached to the wheel.

The medical specialist mentioned after performing the experiments that the rotation of instruments is used less often in reality than during the simulation, therefore the three-finger strategy might be applicable in practice.

With the sequential interface every participant used his thumbs to control the joysticks, index finger to turn the wheel and middle finger to control the trigger. The sequential interface was found the most comfortable to use of the two since participants found the control input placement more comfortable and intuitive. The sequential interface was however found a little too wide for the under average sized hands causing a constant stretch to be able to reach the wheel and trigger button. Smaller components would enable a sleeker more comfortable design.

### 4.4 Experiment with clinical expert

The proposed interfaces will in the end be used by medical specialists, skilled experts with highly developed psychomotor skills and years of experience. Not every person with the right educational background can become a neurosurgeon. Just like jet fighter pilots neurosurgical students are selected to pick out the applicants with the above average set
of skills, the freaks of nature.

Since this experiment was performed with average people that might deviate a lot in psychomotor skill from the typical neurosurgeon (who is likely superior because of the selection process and professional experience) performing the same experiment with neurosurgeons will likely give different results, likely starting with a higher performance level.

An additional experiment was performed with a single neurosurgeon to compare his performance with the student participants and to get general feedback on the simulation environment and control interfaces. It has to be noted that due to practical considerations the environment was more distracting and the experiment was performed on a smaller screen than during the original experiment (20” in stead of 40”). Therefore it is not completely fair to compare the results, although being quite remarkable.

The neurosurgeon performed a little above average during the first experiment. In the second experiment, the neurosurgeon however turned out to be an above average performing multi-tasker. Only one participant of the original experiment scored higher on simultaneous use of instruments (37.1%) than the neurosurgeon (35.0%) but the neurosurgeon performed far better (session time = 124.6 seconds) than that participant (session time = 186.5 seconds). The other closest two best multitasking participants performed similar to the neurosurgeon, using their instruments resp. 34.8% and 33.1% with session times of resp. 128.9 seconds and 121.6 seconds (See also Fig. 27 again for a spread of the simultaneous use during the second experiment).

The neurosurgeon was the only participant that performed the second experiment clearly better with the simultaneous interface (124.6 sec) than with the sequential interface (137.1 sec). There was only one other person in the experiment that performed the second experiment better with the simultaneous interface than with the sequential interface (107.2 sec vs 137.2 sec) but with a relatively low simultaneous instrument usage of 10.2 %.

M. Watson and L. Strayer described in 2010 a group of supertaskers: people that not seem to lose time due to context switching while time-sharing tasks. In the experiment 200 participants were tested in a high-fidelity driving simulator in both single- and dual-task conditions. A small group (2.5% of the participants) showed absolutely no performance decrement with respect to performing single and dual tasks and surprisingly also showed superior performance in single task conditions [28].

It is possible that neurosurgeons belong to this group of outstanding multi-taskers. It is possible that the same experiments conducted with only neurosurgeons will result in more simultaneous use of instruments. It however seems unlikely that no performance decrement will be noticed for the so called supertaskers when the multi-tasking occurs with the same perceptual systems as is the case for the experiments of this research (e.g. driving while performing secondary auditory tasks it not the same as for example performing two auditory tasks at the same time).

It however has to be stressed that this was learned from the observation of a single surgeon and the described result might therefore be irrelevant. Further research needs to be conducted to find out if this was an incidental measurement or perhaps a pattern in the skill set of neurosurgeons in general.

4.5 Recommendations

The method used in this research created a flexible playground enabling further research with relatively low efforts and costs. The simulation can be adapted for future use to experiment with other DOF, instruments, scenarios, control couplings, control devices, (3D-printed) interface shapes and different instrument configurations.

Interfaces

Because of the size of the used parts it was not possible to make both the interfaces smaller or to get the finger positions closer to each other or in a better configuration. The use of smaller components will make it possible to make more comfortable interfaces.

The improved simultaneous interface could be operated using a sequential strategy in higher mental load situations with a smaller performance degradation than with the current control input configuration. In lower mental load situations the interface could be used with a simultaneous strategy when beneficial.

The control input configuration for the simultaneous interface needs to changed to make the three-finger strategy more viable by placing the wheel and trigger under the joystick, so they can both be controlled with the middle finger, and the index finger can be used solely to operate the front joystick. This configuration can be accomplished by using a smaller potentiometer that is partially integrated in the wheel. To reduce the number of fingers needed to operate the simultaneous interface the push button could be integrated in the front joystick or rotation wheel. This requires less finger switching.

The used joysticks still moved to easily after applying the di-electric grease. Therefore another smaller sized joystick with more movement damping needs to be developed. This will result in more control and less accidental movements of the joysticks.

For this experiment position control was used to couple the movements of the joystick to the simulation environment. Further research is needed to experiment with velocity control, position control or an hybrid version that combines the two. Velocity control can for example be used to displace the origin of the work space so that the movable work space can be kept very small resulting in low position control gains. This can be implemented as follows: the joystick is position controlled, but when the instrument is positioned near the edge of the work space, the origin of the work space begins to displace in that direction with a constant or joystick deflection dependent velocity. In this way still mainly position control is used for fine control, but the joystick gain can be minimized, while covering a larger tool-branch work space.

The joysticks were easier to control in their middle position: the outer position result in more stretch of the fingers.
and less accurate positioning. Therefore a displacing origin could enable to use joysticks with a smaller range of motion while still being able to accurately control the tool-branches.

The work space origin could also be displaced by using a force sensor in the joystick: when the joystick is pushed above a certain force at its extreme positions it starts to move the origin of the work space in that direction with a constant velocity or a velocity dependent on the applied force. Since the threshold force can be adjusted, there will be a lower chance of accidentally moving the work space, by accidentally positioning the joystick in an extreme position.

In stead of using a force sensor also the outer range of the joystick motion can be stiffened (with springs or an elastic material): If the joystick is pushed hard enough it will enter the outer range and the work space origin starts to move.

The writer recommends the development of a joystick without a spring return function, with a damped motion and with a smaller range of motion that requires less stretching of the thumb, combined with a force activated work space displacement. If higher accuracy potentiometers are used to measure the joystick positions, the center in-sensitivity might become unnoticeable small. Such joysticks will likely result in better control and more comfort.

The translation was not successfully implemented and needs to be implemented yet. Smaller control components will enable more comfortable positions for the translations wheels. Also other ways to implement the translations need to be investigated. Perhaps the translation of the branches can be coupled to the translation of on of the interfaces. For example: translation of the left controller is coupled to the translation of the forceps and scissors, while the right controller is coupled to the suction tube and curette. Two wheels can be used to enable relative translation between those instruments. Also velocity control could be used for the translation, controlling the translations for example with small levers.

Experiments

The tasks used in the experiment can be improved and elaborated together with medical experts. A first step would be to improve the dynamical behavior of the basic simulation. In stead of using collision detection grasping could be achieved by virtually attaching the object to the forceps when it is closed. This implementation will result in more stable grasping behavior, although requiring some tuning to approach realistic behavior. With the current grasping method the forceps-tissue interaction is continuously calculated and is sometimes inaccurate. This is probably caused by contact surfaces that become infinitely small in the dynamical simulation model, causing extremely high force peaks.

The depth perception of the simulations needs to be improved by a more realistic graphical appearance or possibly by unnatural exaggeration of visual cues to enable the use of translation in the simulation.

The NASA TLX questionnaire (appendix D) was used to provide information about the perceived workloads during the experiments. The pilot experiments took however longer than ninety minutes, which was longer than expected, while the goal was to test at least twenty participants. Therefore was decided to only use one questionnaire for the complete experiment to only identify extremes, in stead of one questionnaire for each interface, to compare their relative performance. It was decided that the question form would provide enough information about the relative perceived mental and physical performance of the participants. The NASA TLX would however provide more accurate information. It is recommended to put more emphasis on measuring the mental aspect of the experiment.

The anatomical differences of the hands of the participants likely created some noise in the experiment. Measuring the dimensions of the hands of participants would provide valuable information, especially when adapting the size of the interfaces.

The instrument positions were measured by using information of the instrument positions in the simulation. This provided information with a relatively low rate of 20Hz. Direct measurement of the joysticks could provide higher frequency more accurate information about the movement patterns of each joystick. The joystick positions could be measured by connecting parallel wires to the potentiometer signals and measure the signals with a third PLC.

The experiments took in total around 75 minutes which seemed to be too short to learn the simultaneous operation of instruments. Prolongued experiments will be required to give more insight about the simultaneous use. Longer experiments will also provide more information about the ergonomics of the interface which will be very important for a final interface design since most Endonasal Procedures take longer than three hours.

The tasks of the second experiment were identical tasks resulting in a symmetrical division of the work load: in reality two simultaneous performed task will often not be equally occupying. The strategy of processing the next task while the first task is being executed, might then be observed more frequently. Therefore it is recommended to also implement simultaneous tasks with asymmetrical work loads to test the unimanual-simultaneous performance of a single controller.

The suction and curette task were both implemented as a positioning task. This implementation is similar to the behavior of the suction tube during real procedures: The suction tube needs to be positioned so that it gradually removes the targeted fluid or material. This is however not true for the obstructing tissue. Tissue that obstructs the endoscope vision is in reality pushed away, which can be seen as a unidirectional positioning task, since the tissue needs to be pushed away in the correct direction until a certain position has been reached.

The tissue obstruction task was first implemented with a target that needed to be pushed away but sometimes resulted in dynamic instability. When the dynamic behavior is improved this task could be used again since it is a clinically relevant example of an asymmetrical task.

The simultaneous operation of two instruments with one hand provides practical advantages. However the exact clinical relevancy needs to be further investigated together with clinical experts, using more realistic scenarios and different
instruments for supporting me during this challenging adventure.

5 Conclusion

The goal of this research was to find a suitable control strategy to allow a single person to operate a Multi-Branched instrument i.e. a surgical instrument with a single shaft that at the end divided into four branches, each containing a different tool. Two control interfaces were designed. The first interface made use of a sequential strategy that allowed the control of a single instrument at a time with each hand. In the second interface a simultaneous strategy was implemented that allowed the simultaneous control of two instruments with each hand. The simultaneous strategy was expected to result in quicker performance. The interfaces where prototyped and a virtual environment was created to evaluated their performance in two different experiments. The first experiment was a virtual version of a relevant surgical scenario containing four instruments. Every round virtual tissue needed to be dissected using a forceps and a pair of scissors while two other instruments needed to be positioned inside spheres, simulating the positioning of a suction tube during conventional Endonasal Surgery. The second experiment contained each round solely two sphere positioning tasks to create more suitable circumstances for the simultaneous use of two instruments with a single hand. The first experiment resulted in a 10% time performance difference in favor of the sequential interface. Simultaneous use of instruments with the simultaneous interface was negligible small. Also the second experiment resulted in better performance (12%) of the sequential interface. The second experiment resulted however in significantly more simultaneous instrument use (median: 16.8% vs 2.9%) but was still relatively low. The simultaneous interfaces was therefore mainly used with a sequential strategy but resulted in a relatively small performance degradation compared to the sequential interface.

With this research a first step was made in the development of a suitable control strategy for a Multi-Branched instrument. The used research methodology for performance evaluation has proven to be successful. A modular virtual playground was created that makes the steps for further research small. The simulation and interfaces can be changed with relatively low effort to experiment with other control couplings between the virtual instruments and interfaces, and to further experiment with different tool and DOF configurations in other virtual scenarios.

Acknowledgements

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This research would not have been possible if not for the great enthusiasm of my supervisors. Therefore I would like to thank Paul Breedveld, Ewout Arkenbout en Paul Henselmanns for supporting me during this challenging adventure while keeping me sharp with many fruitful discussions (and coffee). Also I would like to thank neurosurgeon Wouter van Furth for the pleasant cooperation and the unique opportunity to attend an Endonasal Procedure. His professional input and drive for innovation was of great importance for this research. I want to thank DEMO (Dienst Elektronische en Mechanische Ontwikkeling) for helping me with the high quality 3D printing of the interfaces.

Furthermore I would of course like to thank my parents, brother, family and friends for supporting me during this year of hard but satisfying work.

References


Appendix A: Visual Feedback

The endoscope image that a neurosurgeon sees while performing surgery is displayed in only two dimensions. The human can however see depth by using depth perception to trick the human visual system [29]. The visual system gets information from the environment in the form of object properties such as color, texture, shape, size, position and motion. Depth perception in general is created using this information in the form of binocular and monocular cues. Binocular cues are cues in 3 dimensions that are based on information from both eyes while monocular cues can be based on the information of a single eye. Since displays used in the operation room as well as in the simulation - using a monocular endoscope - do not provide a stereoscopic image, only the monocular cues can be used by the surgeon to perceive depth of image.

These monocular depth perception cues are:

- **Occlusion**
- **Shading**
- **Size**
- **Linear perspective**
- **Surface texture**
- **Motion parallax**
- **Kinetic depth perception**

**Occlusion** occurs when objects overlap each other, the overlapping object is the nearest to the observer. The **shadow** of an object can give its relative position to a light source with respect to another object. Knowing the **size** of an object the brain can compare the sensed size to the actual size of the object, giving information about the distance to the object. **Linear perspective** can be seen when looking down at a straight road where the parallel sides meet each other in the horizon. The **surface texture** of an object can be seen better when the object is closer, smoother objects are interpreted to be further away. **Motion parallax** is created by changing the difference to an object by either moving the head or the object so that angle to object slightly varies. If an object is closer, the change of the angle will be larger. **Kinetic depth perception** is created when an object in motion becomes smaller as it appears to be moving away.

**Occlusion, size, linear perspective and kinetic depth perception**, where already implemented in the graphical engine of V-rep. **Shadow** is created by using a light source in the simulation although shadows are not present in most endoscope images. Since the light source is located at the tip of the endoscope, a ring of light is created around the endoscope
that increases the image brightness but does almost not create any visible shadowing. It is however possible in practice with commercially available products to introduce an extra different positioned light source to improve the depth perception [30]. **Rough texture** is applied on the tissue used to further improve the depth perception in the simulation. **Motion parallax** is created in a very limited form by the surgeon by slightly changing the position of the endoscope in the little available space. In the simulation the position of the endoscope can however not be changed.

The simulation environment is constrained by a cavity on which a texture is applied to approach a more realistic appearance.

**Appendix B: Task positions**

The positions and orientations of the virtual tissue and the positions of the spheres in the experiments where randomly created using MATLAB.

**Pseudo code** : Each workspace can be represented by a cylinder with a dome attached to it as depicted in Fig.10. A cylinder can be described by a height perpendicular to the ground plane and a radius at each height position.

For the positions of the spheres used in the positioning task, first a random height was chosen and next a random radius was chosen, resulting in a random point in the workspace that was used for the positioning tasks.

For the virtual tissue task this process was repeated for the workspace of the forceps and the scissors. Then the distance between the to found points was calculated. If this was a distance that could be cleared by the tissue, then a random tissue position was found. This is a rather simple and brute force algorithm but resulted in ten random tissue positions within three minutes (Fig. 23). Other algorithms that where used at first where quicker but resulted in less uniform distributed positions.

**Appendix C: Filtering**

The object and joint positions in the simulation are updated with a frequency of 20 Hz. These positions were measured by Matlab with an inserted delay that resulted in a high frequency of 60 Hz. The result of this high sample frequency is that when for example a joint is constantly rotated, and 3 samples are taken, only one sample will measure a displacement, since after the first sample the simulation 3 times slower simulation has not updated the joint position yet. These peaks belonging to the same motion needed to be grouped to be able to measure the time that instruments were used simultaneously. It occurred when two joysticks were moved simultaneously, the displacement peaks did not always occur in the same sample probably caused by noise somewhere in the electro-mechanical components, serial connection or connection between Matlab and V-REP.

Although the exact origin of the problem was found, it was solved by using a moving average filter to group the peaks that belong to one motion. The moving average filter takes for every sample the average of together: the 3 samples before the sample + the sample + the 3 samples after that sample. The filter was tested in a situation where no joysticks are moved and another situation where 2 joysticks are constantly moved.

Without the filter (Fig. 24c) while constantly moving two joysticks, a simultaneous percentage of 30.34 % was measured. Applying the filter on the same data (Fig. 24c) resulted in a percentage of simultaneous movement of 99.59%, which is closer to the expected value of 100%. When the joysticks were not moved at all this resulted with the filter applied in a simultaneous use of 0.17%.

**Appendix D: Additional Data**
Fig. 24: (a) The displacement peaks when simultaneously moving two joysticks, but without applying the filter. The black lines indicate simultaneous movement. (b) Applying the filter on the same data shows an almost continuously black line of simultaneous movement. (c) Separate instrument movement with the sequential interface, when no instruments collisions occur: The filter groups the peaks belonging to the same movement.

Table 1: The difference in gripper closing time between the first and last round

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Fig. 25: (a) The total time the participants took to complete experiment 1. for both interfaces. (b) The total time the participants took to complete experiment 2. for both interfaces.

Fig. 26: (a) Experiment 1: the round difference for the unimanual-sequential interface. (b) Experiment 1: the round difference for the unimanual-simultaneous interface.

Fig. 27: (a) Experiment 1. Difference AB - BA group. (b) Experiment 2. Difference AB - BA group.
Fig. 28: The average time the scissors and gripper were closed during all sessions of experiment 1.

Fig. 29: The results of the NASA TLX questionnaire, one questionnaire for each participant.